Expanding the Capabilities of DOE's EnergyPlus™ Building Energy Simulation Program

Final Technical Report

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ABSTRACT

EnergyPlus™ is a new generation analysis tool that is being developed, tested, and commercialized to support DOE's Building Technologies (BT) Program in terms of whole-building, component, and systems R&D (<http://www.energyplus.gov>). It will also support evaluation and decision making of zero energy building (ZEB) energy efficiency and supply technologies during new building design and existing building retrofits. Version 1.0 of EnergyPlus was released in April 2001, followed by six updated versions over the ensuing three-year period.

This report summarizes work performed by the University of Central Florida's Florida Solar Energy Center (UCF/FSEC) to expand the capabilities of EnergyPlus. The project tasks involved implementing, testing, and documenting the following new features:

- A model for energy recovery ventilation equipment that transfers both sensible (temperature) and latent (moisture) energy between building exhaust air and incoming outdoor ventilation air
- A model to account for the degradation of cooling coil dehumidification performance at part-load conditions
- A model for cooling coils augmented with air-to-air heat exchangers for improved dehumidification
- A heat transfer coefficient calculator and automatic sizing algorithms for the existing EnergyPlus cooling tower model

UCF/FSEC located existing mathematical models for these features and incorporated them into EnergyPlus. The software models were written using Fortran-90 and were integrated within EnergyPlus in accordance with the EnergyPlus Programming Standard and Module Developer's Guide. Each model/feature was thoroughly tested and identified errors were repaired. Upon completion of each model implementation, the existing EnergyPlus documentation (Input Output Reference and Engineering Document) was updated with information describing the new model/feature.

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1.0 INTRODUCTION

In April 2001 the U.S. Department of Energy released EnergyPlus™ Version 1.0, a new building performance simulation program. This program combines the best capabilities and features of its parent programs (DOE-2 and BLAST) along with new capabilities and flexibility. EnergyPlus has innovative simulation capabilities, including simulation time steps of less than one hour, modular systems modules that are integrated with a heat balance-based zone simulation, and input and output data structures tailored to facilitate third party interface development. The integrated systems modules/heat balance solution technique allows for evaluation of interactions between various building components and subsystems, a key deficiency in the earlier programs, but absolutely necessary to enable whole-building optimization.

When EnergyPlus Version 1.0 was released, it had many unique simulation capabilities to foster the design of high-performance buildings. However, certain key features were needed to simplify program input requirements, enhance the program's ability to accurately predict indoor humidity levels, and model certain commercially-available HVAC technologies that have extremely high potential for energy savings and improved comfort. These key features were:

- Models for energy recovery ventilation equipment and associated controls
- A model to account for the degradation of cooling coil dehumidification performance at part-load conditions
- A model for cooling coils augmented with air-to-air heat exchangers for improved dehumidification
- A heat transfer coefficient calculator to simplify cooling tower input data requirements
- Automatic sizing algorithms for the existing EnergyPlus cooling tower model

Through this DOE-sponsored project, the University of Central Florida's Florida Solar Energy Center (UCF/FSEC) added these modeling features to EnergyPlus. As each new feature was implemented it was included in the next version of the simulation program, and all of the features will be included in EnergyPlus Version 1.2, scheduled for release in April 2004. This report summarizes the models selected for implementation, the model testing that was performed, and the documentation that was developed for program users to understand the model inputs, outputs and modeling methodology.

2.0 EXPERIMENTAL

This section briefly describes the mathematical models that were selected for implementation in EnergyPlus.

Task 1 – Add Models for Energy Recovery Ventilation Equipment

The outdoor air ventilation requirements prescribed by ASHRAE Standard 62 (ASHRAE 2001, ASHRAE 2003) have significant impacts on HVAC system energy use, equipment sizing, energy costs and indoor humidity levels. Various technologies have been developed in an effort to mitigate the impacts of these ventilation requirements. One such technology is energy recovery ventilation (ERV) equipment that is now being offered by numerous manufacturers as a method for meeting ventilation requirements while minimizing the energy and economic impacts. ERV equipment recovers energy from building exhaust air and uses this energy to precondition the incoming outdoor ventilation air.

EnergyPlus version 1.0 included a heat recovery model for air-to-air plate heat exchangers that transfer sensible (temperature) energy. Effectiveness-NTU formulas are used to model the plate heat exchanger. While the existing heat recovery module represented a good first step in modeling ERV equipment, there were many additional types of ERV equipment and ERV control strategies that needed to be added to allow a full evaluation of the potential for ERVs by users of the software program.

A new ERV model was therefore selected for implementation in EnergyPlus. This new model was derived from an existing model developed by UCF/FSEC and others for the U.S. Environmental Protection Agency's "Indoor Humidity Assessment Tool" (<http://www.epa.gov/iaq/schooldesign/toolbox.html>). This model provides several improvements over the existing EnergyPlus model for air-to-air plate heat exchangers, including:

- Heat exchanger performance can be specified to transfer sensible (temperature) energy, latent (moisture) energy or both between the supply and exhaust air streams
- Performance is defined by specifying sensible and/or latent effectiveness at 75% and 100% of the nominal (rated) supply air flow rate at two operating conditions (ARI 2001). This performance information is readily available from ERV manufacturers.
- The heat exchanger can be used in conjunction with a conventional air-side economizer, whereby heat exchange is suspended whenever the air-side economizer is active (i.e., air flow is bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped). Heat exchange between the incoming outdoor ventilation air and the building exhaust air can also be suspended for the purpose of providing free cooling operation in the absence of a conventional air-side economizer.
- The model includes four methods for controlling or eliminating frost buildup on the heat exchanger during winter weather
- The heat exchanger can be controlled to maintain a fixed supply air outlet temperature to avoid overheating the conditioned zone
- The model can be used to simulate an ERV used as part of a central air distribution system, or as part of stand-alone equipment which conditions outdoor ventilation air and supplies it directly to an occupied zone within the building

Task 2 – Add an Existing Model to Account for Dehumidification Degradation at Part-Load Conditions

The latent (dehumidification) capacity of a direct-expansion (DX) cooling coil is strongly affected by part-load, or cyclic, operation. This is especially true in applications where the supply air fan operates continuously while the cooling coil cycles on and off to meet the cooling load. During constant fan operation, moisture condenses on the cooling coil when the compressor operates, but part or all of the moisture that is held by the coil evaporates back into the airstream when the cooling coil is deactivated. The net effect is that the amount of moisture removed from the air is degraded at part-load conditions as compared to steady-state conditions when the compressor operates continuously.

The latent degradation model selected for implementation in EnergyPlus is based on algorithms developed by Henderson and Rengarajan (1996). The model is applicable to single-stage cooling units, like residential and small commercial air conditioners or heat pumps with less than 19 kW (5.3 tons) of nominal cooling capacity. The model currently works in tandem with the existing DX cooling coil model previously added to EnergyPlus by UCF/FSEC, although it could readily be adapted for use with other DX cooling coil models. The existing DX cooling coil model first calculates the dehumidification performance for steady-state operation (no cycling losses). The Henderson and Rengarajan model then determines the dehumidification degradation based on the maximum coil cycling rate, the coil runtime fraction, the moisture holding capacity of the cooling coil, and the initial moisture evaporation rate from the cooling coil when the compressor first turns off.

Task 3 – Add an Existing Model for Cooling Coils with Air-to-Air Heat Exchangers for Improved Dehumidification

An air-to-air heat exchanger can be used to enhance the dehumidification performance of a conventional cooling coil. The air-to-air heat exchanger precools the air entering the cooling coil, and reuses this energy to reheat the supply air leaving the cooling coil. This heat exchange process improves the latent removal performance of the cooling coil by allowing it to dedicate more of its cooling capacity toward dehumidification (lower sensible heat ratio).

The model selected for implementation utilizes existing EnergyPlus models for both direct expansion (DX) and chilled-water cooling coils. Existing EnergyPlus models for air-to-air heat exchangers, including the model implemented as part of Task 1 (described above), are also used. Modeling of the heat exchanger-assisted cooling coil is performed by consecutively modeling the air-to-air heat exchanger and the cooling coil until convergence on a solution is achieved.

Task 4 – Implement a Heat Transfer Coefficient Calculator and AutoSizing for the Cooling Tower Model

The existing EnergyPlus cooling tower model, implemented by UCF/FSEC in 2001, is based on Merkel's theory (Merkel 1925), which is also the basis for the tower model included in ASHRAE's HVAC1 Toolkit for primary HVAC system energy calculations (ASHRAE 1999, Bourdouxhe et al. 1994). Cooling tower performance is modeled using effectiveness-NTU relationships for counterflow heat exchangers. The model can be used to simulate the

performance of both single speed and two speed mechanical-draft cooling towers. The model will also account for tower performance in the “free convection” regime, when the tower fan is off but the water pump remains on. For part-load operation, the model assumes a simple linear interpolation between two steady-state regimes without accounting for any cycling losses.

Originally, inputs to the model required the user to specify tower performance using the "UA and Design Water Flow Rate" method. While most of the model inputs were readily available from manufacturer's data, the heat transfer coefficient-area product (UA) was much more difficult to obtain and likely required the user to derive this value using other manufacturer's performance information. To alleviate this obstacle UCF/FSEC, during this DOE/NETL project, added an alternate input method for specifying tower performance called the “Nominal Capacity” method. This method reduces the number of model inputs and all inputs are readily available from manufacturer's data. Performance information for the cooling tower is entered by the user for standard rating conditions (CTI 2002), and this information is used to calculate the heat transfer coefficient-area product (UA) that is subsequently used by the cooling tower model to simulate tower performance at off-design conditions.

One of EnergyPlus' numerous features is its ability to calculate zone cooling/heating loads based on design weather conditions and schedules, and then use this information to automatically size the components for the heating, ventilation and air-conditioning (HVAC) system that the user has chosen to model. The average software user will not want, or will not be able, to size the components themselves. Also, parametric analyses would be extremely difficult to perform without the autosizing feature since all of the system sizing information would need to be recalculated and modified by the user for each simulation run.

UCF/FSEC worked with another EnergyPlus developer from Lawrence Berkeley National Laboratory (LBNL) to implement the autosizing feature for the EnergyPlus cooling tower model. The LBNL developer initially implemented algorithms for automatically determining appropriate values for most of the numeric input fields for the original cooling tower model that was added by UCF/FSEC in 2001. UCF/FSEC reviewed the initial autosizing algorithms, and implemented some refinements based on manufacturer's data and expanded the algorithms to include additional existing numeric input fields. In addition, UCF/FSEC added the autosizing feature to the new numeric fields that were added as part of this DOE/NETL project for specifying tower performance using the “Nominal Capacity” method.

3.0 RESULTS AND DISCUSSION

Each new feature outlined in Section 2.0 was implemented in EnergyPlus, with the order of implementation determined in consultation with the DOE Technology Development Officer (Dru Crawley) and other members of the EnergyPlus development team. Table 1 below summarizes the date of source code completion and the version of EnergyPlus that included the new feature.

Table 1. New Feature Implementation Schedule

Description	Date Completed ¹	EnergyPlus Version ²
<i>Task 1: Add Models for Energy Recovery Ventilation Equipment³</i>	March 2003	1.1.0
	June/July 2003	1.1.1
<i>Task 2: Add an Existing Model to Account for Dehumidification Degradation at Part-Load Conditions</i>	Oct 2003	1.2.0
<i>Task 3: Add an Existing Model for Cooling Coils with Air-to-Air Heat Exchangers for Improved Dehumidification</i>	Oct 2003	1.2.0
<i>Task 4: Implement a Heat Transfer Coefficient Calculator and AutoSizing for the Cooling Tower Model</i>	Oct 2002	1.0.3

Notes: ¹Date that the computer source code was checked in to the official DOE repository (StarTeam)

²Version of EnergyPlus that included this new feature.

³A basic ERV model for sensible/latent energy exchange in a central air distribution system was completed in March 2003. The stand-alone version, winter frost controls, coordination with air-side economizer and other controls were completed several months later in June/July 2003.

Implementation of each new feature included the following:

- Locating an appropriate existing mathematical model
- Writing new software source code and integrating it into the existing EnergyPlus building simulation program
- Fully testing the models and documenting the test results
- Modifying the EnergyPlus user documentation to include information regarding the new feature/model

The models selected for implementation were described previously in Section 2.0 of this report. Well-documented Fortran-90 software modules were developed and integrated into the existing EnergyPlus program in accordance with the EnergyPlus Programming Standard and the Module Developer's Guide. The computer source code was uploaded to DOE's central electronic repository for all EnergyPlus-related work (StarTeam). NETL recognizes that submission of the completed source code to the official DOE central repository fulfills the contract requirements for this deliverable (see Appendix A). Each new feature was fully tested, and the test results were documented and presented at EnergyPlus team meetings as appropriate.

EnergyPlus user documentation includes an Input Output Reference and an Engineering Document. The Input Output Reference provides the user with a brief description of each simulation model and fully describes the data input requirements, as well as the output variables available for reporting the simulation results. The Engineering Document gives a complete model description including key mathematical equations and a description of how the equipment controls are modeled. After completing source code development and testing for each new feature, appropriate user documentation was developed to describe the new feature which was suitable for inclusion in the current EnergyPlus software documentation. The new and/or revised documentation sections were completed prior to the release of the EnergyPlus version that included each new feature. The user documentation sections that were developed and/or revised under this contract are provided in Appendices B through E.

4.0 CONCLUSION

EnergyPlus™ is a new generation analysis tool that is being developed, tested and commercialized to support DOE's Building Technologies (BT) Program in terms of whole-building, component and systems R&D (<http://www.energyplus.gov>). It will also support evaluation and decision making of zero energy building (ZEB) energy efficiency and supply technologies during new building design and existing building retrofits. Version 1.0 of EnergyPlus was released in April 2001, followed by six updated versions over the ensuing three-year period.

One of DOE's near-term milestones is to complete the incorporation of current technologies, systems, and controls into EnergyPlus to support energy codes and standards. Energy standards, such as ASHRAE Standard 90.1, ASHRAE Standard 90.2, California Title 24, and the Florida Energy Code were developed with whole-building simulation tools and future improvements to these standards cannot be developed without analysis tools. New and currently available technologies cannot be considered in a standard unless the tool used to produce the standard can properly model that technology.

The work completed under this contract provides significant progress toward this milestone. With increased outdoor ventilation requirements being prescribed to improve indoor air quality in commercial, institutional and residential buildings, energy recovery ventilation equipment is being required by an increasing number of energy codes and standards as a method for mitigating the energy consumption and cost impacts. In humid climates, the increased ventilation requirements can also result in elevated indoor humidity levels. With the model added during this project for cooling coil dehumidification degradation at part-load conditions, building design professionals will be able to more accurately evaluate the impacts of their design choices on indoor humidity levels. If high indoor humidity levels are predicted, the model added for cooling coils with air-to-air heat exchangers for improved dehumidification can be evaluated to determine the benefits and cost effectiveness of this currently-available energy-efficiency technology. Modifications to the cooling tower model implemented during this project will assist users with determining model input parameters and the autosizing improvements will be particularly useful for parametric analyses that are routinely performed to support energy codes and standards development.

5.0 REFERENCES

References used throughout this report (including Appendices) are summarized here.

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Appendix A

NETL Memo Regarding Closeout Requirements

U.S. Department of Energy

National Energy Technology Laboratory

January 7, 2004

MEMORANDUM FOR THE FILE

FROM: ANDREA L. GYORKE
CONTRACT SPECIALIST

SUBJECT: DE-FC26-01NT41249: Requirements for Closeout

Project number DE-FC26-01NT41249 with the University of Central Florida concluded on 12/30/03, and the Project Investigator, Don Shirey, was contacted regarding the reporting requirements for closeout of the award. He was reminded that the Hazardous Waste Report and Termination or Completion Inventory Report were both due 12/31/03 and should be completed as soon as possible. In addition, the final technical report is due by 3/29/04.

Regarding the delivery of the EnergyPlus Software to NETL: The Statement of Project Objectives and the Reporting Requirements Checklist contained in the award emphasized that the delivery of this software to NETL/DOE was integral to the performance of the project. However, it was understood that the end user of this product was EE headquarters personnel, and, consequently, the software ultimately would be sent to the DOE-approved central repository (StarTeam). While the software was never submitted to NETL, correspondence between EE headquarters and NETL has confirmed that all of the software has been submitted to StarTeam. Therefore, we have concluded that the University of Central Florida has satisfied the software deliverable requirements of this award.

Andrea L. Gyorke
Contract Specialist

Appendix B

EnergyPlus Documentation for Energy Recovery Ventilation Equipment

This appendix contains the EnergyPlus documentation (Input/Output Reference and Engineering Manual) for the energy recovery ventilation equipment that was added as part of this project.

Input Output Reference for Heat Exchanger:Air to Air:Generic

The generic air-to-air heat exchanger is an HVAC component typically used for exhaust or relief air heat recovery (Figure 1). Heat exchanger performance can be specified to transfer sensible energy, latent energy or both between the supply and exhaust air streams. The input requires no geometric data. Performance is defined by specifying sensible and/or latent effectiveness at 75% and 100% of the nominal (rated) supply air flow rate at two operating conditions as shown in Table 2.

Figure 1. Schematic of the Generic Air-to-Air Heat Exchanger

Table 2. Operating Conditions for Defining Heat Exchanger Performance

Parameter	Conditions	
	Heating	Cooling
Entering supply air temperature:		
Dry-bulb	1.7°C (35°F)	35°C (95°F)
Wet-bulb	0.6°C (33°F)	26°C (78°F)
Entering exhaust air temperature:		
Dry-bulb	21°C (70°F)	24°C (75°F)
Wet-bulb	14°C (58°F)	17°C (63°F)

Note: Conditions consistent with the Air-Conditioning and Refrigeration Institute's (ARI) Standard 1060-2001.

This object models the basic operation of an air-to-air heat exchanger. Heat exchange between the supply and exhaust air streams occurs whenever the unit is scheduled to be available (Availability schedule) and supply/exhaust air flow is present. This heat exchanger

object can be used in conjunction with a conventional air-side economizer (i.e., specify ECONOMIZER in the Controller:Outside Air object), whereby heat exchange is suspended whenever the air-side economizer is active (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped). This object is also able to suspend heat exchange for the purpose of providing free cooling operation in the absence of a conventional air-side economizer (i.e., specify BYPASS in the Controller:Outside Air object).

During winter weather, humid exhaust air entering the heat exchanger can form frost on the cold heat exchanger surfaces, which can reduce air flow and the amount of energy recovery. Several methods are used to control or eliminate frost formation, and the following types can be modeled for this heat exchanger object: supply air preheat, minimum exhaust air temperature, exhaust air recirculation and exhaust only. For preheat frost control, a separate heating coil object must be placed in the supply inlet air stream to keep the air temperature above the frost threshold temperature. The other frost control types are modeled within this object itself (i.e., do not require a separate object to be defined) based on alpha and numeric inputs to this heat exchanger object.

Air-to-air heat exchangers are sometimes controlled to maintain a fixed supply air outlet temperature to avoid overheating. To model this control in EnergyPlus, a set point manager object is used to establish a temperature set point at the supply air outlet node of the heat exchanger. Wheel speed modulation or plate supply air bypass is used to control the supply air exiting conditions to this set point. The set point for supply air temperature control should be set at the minimum economizer temperature set point if an air-side economizer is also being used by the air system. If frost control and supply air outlet temperature control are used, frost control takes precedence over supply air temperature control (e.g., frost control defrost time fraction is determined as if wheel speed modulation or plate supply air bypass is not used).

To model a generic air-to-air heat exchanger located in an air loop, the input data file should include the following objects:

- OUTSIDE AIR SYSTEM
- CONTROLLER:OUTSIDE AIR
- OUTSIDE AIR MIXER
- HEAT EXCHANGER:AIR TO AIR:GENERIC
- COIL:WATER:SIMPLEHEATING, COIL:ELECTRIC:HEATING or COIL:GAS:HEATING (if preheat frost control is to be modeled)
- SET POINT MANAGER:SCHEDULED (if supply air outlet temperature control is used)

The generic air-to-air heat exchanger can also be used in a number of other applications, including conditioning outdoor ventilation air and supplying it directly to a zone without an air loop. See object ENERGY RECOVERY VENTILATOR:STAND ALONE for further details on this specific application.

A description of each input field for this object is provided below.

Field: Heat exchanger name

A unique user-assigned name for a particular air-to-air generic heat exchanger unit. Any reference to this unit by another object will use this name.

Field: Availability schedule name

The name of the schedule (ref: Schedule) that denotes whether the unit can operate during a given hour. A schedule value greater than 0 (usually 1 is used) indicates that the unit can operate during the hour. A value less than or equal to 0 (usually 0 is used) denotes that the unit will not operate (i.e., no heat exchange will take place).

Field: Nominal supply air flow rate

The nominal primary side (supply) air flow rate in cubic meters per second. The actual supply and exhaust air flow rates must be between 50% and 130% of this value or a warning will be issued.

Field: Sensible effectiveness at 100% airflow heating condition

The sensible heat exchange effectiveness at the *heating* condition defined in Table 2 above with both the supply and exhaust air volume flow rates equal to 100% of the nominal supply air flow rate specified in the previous input field. The default value for this field is 0.

Field: Latent effectiveness at 100% airflow heating condition

The latent heat exchange effectiveness at the *heating* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 100% of the nominal supply air flow rate. Specify this value as 0.0 if the heat exchanger does not transfer latent energy. The default value for this field is 0.

Field: Sensible effectiveness at 75% airflow heating condition

The sensible heat exchange effectiveness at the *heating* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 75% of the nominal supply air flow rate. The default value for this field is 0.

Field: Latent effectiveness at 75% airflow heating condition

The latent heat exchange effectiveness at the *heating* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 75% of the nominal supply air flow rate. Specify this value as 0.0 if the heat exchanger does not transfer latent energy. The default value for this field is 0.

Field: Sensible effectiveness at 100% airflow cooling condition

The sensible heat exchange effectiveness at the *cooling* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 100% of the nominal supply air flow rate. The default value for this field is 0.

Field: Latent effectiveness at 100% airflow cooling condition

The latent heat exchange effectiveness at the *cooling* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 100% of the nominal supply air flow rate. Specify this value as 0.0 if the heat exchanger does not transfer latent energy. The default value for this field is 0.

Field: Sensible effectiveness at 75% airflow cooling condition

The sensible heat exchange effectiveness at the *cooling* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 75% of the nominal supply air flow rate. The default value for this field is 0.

Field: Latent effectiveness at 75% airflow cooling condition

The latent heat exchange effectiveness at the *cooling* condition defined in Table 2 with both the supply and exhaust air volume flow rates equal to 75% of the nominal supply air flow rate. Specify this value as 0.0 if the heat exchanger does not transfer latent energy. The default value for this field is 0.

Field: Supply air inlet node name

The name of the HVAC system node from which the unit draws its supply (primary) inlet air.

Field: Supply air outlet node name

The name of the HVAC system node to which the unit sends its supply (primary) outlet air.

Field: Exhaust air inlet node name

The name of the HVAC system node from which the unit draws its exhaust (secondary) inlet air.

Field: Exhaust air outlet node name

The name of the HVAC system node to which the unit sends its exhaust (secondary) outlet air.

Field: Nominal electric power

The electric consumption rate of the unit in watts. Electric power is considered constant whenever the unit operates. This numeric input can be used to model electric power consumption by controls (transformers, relays, etc.) and/or a motor for a rotary heat exchanger. None of this electric power contributes thermal load to the supply or exhaust air streams. The default value for this field is 0.

Field: Supply air outlet temperature control

This alpha field determines if the heat exchanger's supply air outlet is controlled to a temperature set point. The choices for this input field are "yes" or "no", with the default being "no". When supply air outlet temperature control is used, the wheel rotational speed modulates or supply air is bypassed around the plate heat exchanger to maintain the desired set point temperature. A set point manager object is required to establish the desired set point at the supply air outlet node (reference: SET POINT MANAGER:SCHEDULED). When an air-side economizer is also being modeled for this air system, the set point for the supply air outlet temperature control should be equal to the economizer outdoor air temperature lower limit (reference: CONTROLLER: OUTSIDE AIR, field Temperature Lower Limit).

Field: Heat exchanger type

This alpha field denotes the type of heat exchanger being modeled: plate (e.g., fixed plate) or rotary (e.g., rotating cylinder or wheel). The default choice for this field is "plate". The heat exchanger type affects the modeling of frost control options and supply air outlet temperature control. For rotary heat exchangers, rotational speed is varied to control frost formation or the supply air outlet temperature. For plate exchangers, air bypass around the heat exchanger is used to obtain the desired effect.

Field: Frost control type

This alpha field has four choices: none, exhaust air recirculation, exhaust only and minimum exhaust temperature. If this field is left blank, the default frost control type is "none". For modeling preheat frost control, specify "none" for this input field and insert a separate heating coil object in the supply inlet air stream to keep the air temperature above the desired frost threshold temperature.

Exhaust air recirculation: dampers are used to direct exhaust air back into the zone through the supply side of the heat exchanger when the supply (outdoor) air inlet temperature falls below a threshold temperature (defined in the next input field). The fraction of time that exhaust air is circulated through the supply side of the heat exchanger is dependent on the supply (outdoor) air inlet temperature with respect to the threshold temperature, the initial defrost time fraction, and the rate of change of defrost time fraction (see *Field: Rate of defrost time fraction increase*). When exhaust air is being recirculated, no supply (outdoor ventilation) air is being provided through the heat exchanger unit (which may or may not be acceptable regarding ventilation for occupants).

Exhaust only (supply air bypass): this control cycles off the supply air flow through the heat exchanger for a certain period of time while the exhaust air continues to flow through the exhaust side of the heat exchanger. The fraction of time that the supply flow through the heat exchanger is cycled off is dependent on the supply (outdoor) air inlet temperature with respect to the threshold temperature, the initial defrost time fraction, and the rate of change of

defrost time fraction (see *Field: Rate of defrost time fraction increase*). When implemented in real applications, provisions are usually made to avoid building depressurization when this frost control is operating (automatic or pressure-operated dampers, or a bypass air damper around the supply side of the heat exchanger). For this frost control type, it is assumed that the supply air is bypassed around the heat exchanger during frost control operation (i.e., the total supply flow is not reduced during defrost, but merely bypassed around the heat exchanger).

Minimum exhaust temperature: the temperature of the exhaust air leaving the heat exchanger is monitored and the heat exchanger effectiveness is decreased (by slowing heat exchanger rotation or bypassing supply air around the plate exchanger) to keep the exhaust air from falling below the threshold temperature.

Field: Threshold temperature

This numeric field defines the dry-bulb temperature of air which is used to initiate frost control. The default value is 1.7°C. For exhaust air recirculation and exhaust-only frost control, the threshold temperature defines the supply (outdoor) air inlet temperature below which frost control is active. For minimum exhaust temperature frost control, heat exchanger effectiveness is controlled to keep the exhaust air outlet temperature from falling below this threshold temperature value.

The appropriate threshold temperature varies with exhaust (inlet) air temperature and humidity, frost control type, heat exchanger type, and whether the heat exchanger transfers sensible energy alone or both sensible and latent energy (enthalpy). Typical threshold temperatures are provided in Table 3 below. However, it is recommended that the user consult manufacturer's information for the specific air-to-air heat exchanger being modeled.

Table 3. Typical threshold temperatures

Frost control type	Heat exchanger type	Energy exchange	Threshold temperature (°C)
Exhaust air recirculation	Plate	Sensible-only	-1.1°C (30°F)
		Sensible + latent	-12.2°C (10°F)
	Rotary	Sensible-only	-12.2°C (10°F)
		Sensible + latent	-23.3°C (-10°F)
Exhaust only	Plate	Sensible-only	-1.1°C (30°F)
		Sensible + latent	-12.2°C (10°F)
	Rotary	Sensible-only	-12.2°C (10°F)
		Sensible + latent	-23.3°C (-10°F)
Minimum exhaust temperature	Plate	Sensible-only	1.7°C (35°F)
		Sensible + latent	1.7°C (35°F)
	Rotary	Sensible-only	1.7°C (35°F)
		Sensible + latent	1.7°C (35°F)
Preheat**	Plate	Sensible-only	-1.1°C (30°F)
		Sensible + latent	-12.2°C (10°F)
	Rotary	Sensible-only	-12.2°C (10°F)
		Sensible + latent	-23.3°C (-10°F)

Source: Indoor Humidity Assessment Tool, U.S. Environmental Protection Agency,
<http://www.epa.gov/iaq/schooldesign/saves.html>

** To model preheat frost control, specify frost control type as “None” and place a heating coil in the supply inlet air stream controlled to keep the air temperature above the frost threshold temperature.

Field: Initial defrost time fraction

This numeric field defines the fraction of the simulation time step when frost control will be invoked when the threshold temperature is reached. This field is only used for the exhaust air recirculation and exhaust-only frost control types. The value for this field must be ≥ 0 and ≤ 1 . The default time fraction is 0.083 (e.g., 5 min / 60 min) which is typical for exhaust air recirculation frost control. Higher initial defrost time fractions (e.g., $0.167 = 10 \text{ min} / 60 \text{ min}$) are typically required for exhaust-only frost control. For best results, the user should obtain this information from the manufacturer.

Field: Rate of defrost time fraction increase

This numeric field defines the rate of increase in the defrost time fraction as the supply (outdoor) air inlet temperature falls below the threshold temperature. This field is only used for the exhaust air recirculation and exhaust-only frost control types. The value for this field must be ≥ 0 . The default value is 0.012 (e.g., 0.72 min / 60 min per degree C temperature difference) which is typical for exhaust air recirculation frost control. Higher values (e.g., $0.024 = 1.44 \text{ min} / 60 \text{ min}$ per degree C temperature difference) are typically required for exhaust-only frost control. For best results, the user should obtain this information from the manufacturer.

This value is used to determine the total defrost time fraction as follows:

Total defrost time fraction = Initial defrost time fraction +

$$\text{Rate of defrost time fraction increase} * (T_{\text{threshold}} - T_{\text{supply air inlet}})$$

The model does not allow the total defrost time fraction to exceed 1.0 or be less than 0.

The full IDD specification follows:

```
HEAT EXCHANGER:AIR TO AIR:GENERIC,  
  \memo This object models an air-to-air heat exchanger using effectiveness relationships.  
  \memo The heat exchanger can transfer sensible energy, latent energy, or both between the  
  \memo supply (primary) and exhaust (secondary) air streams.  
  \min-fields 19  
A1, \field Heat exchanger name  
  \required-field  
  \type alpha  
A2, \field Availability schedule name  
  \required-field  
  \type object-list  
  \object-list ScheduleNames  
N1, \field Nominal supply air flow rate  
  \required-field  
  \type real  
  \minimum> 0.0  
  \units m3/s  
N2, \field Sensible effectiveness at 100% airflow heating condition  
  \type real  
  \units dimensionless  
  \minimum 0.0  
  \maximum 1.0  
  \default 0.0  
N3, \field Latent effectiveness at 100% airflow heating condition  
  \type real  
  \units dimensionless  
  \minimum 0.0  
  \maximum 1.0  
  \default 0.0
```

```

N4, \field Sensible effectiveness at 75% airflow heating condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
N5, \field Latent effectiveness at 75% airflow heating condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
N6, \field Sensible effectiveness at 100% airflow cooling condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
N7, \field Latent effectiveness at 100% airflow cooling condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
N8, \field Sensible effectiveness at 75% airflow cooling condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
N9, \field Latent effectiveness at 75% airflow cooling condition
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.0
A3, \field Supply air inlet node name
\required-field
\type alpha
A4, \field Supply air outlet node name
\required-field
\type alpha
A5, \field Exhaust air inlet node name
\required-field
\type alpha
A6, \field Exhaust air outlet node name
\required-field
\type alpha
N10, \field Nominal electric power
\type real
\units W
\ip-units W
\minimum 0.0
\default 0.0
A7, \field Supply air outlet temperature control
\type choice
\key No
\key Yes
\default No
A8, \field Heat exchanger type
\type choice
\key Plate
\key Rotary
\default Plate
A9, \field Frost control type
\type choice
\key None
\key Exhaust air recirculation
\key Exhaust only
\key Minimum exhaust temperature
\default None

```

```

N11,\field Threshold temperature
\type real
\units C
\default 1.7
\note Supply (outdoor) air inlet temp threshold for exhaust air recirculation and
\note exhaust only frost control types. Exhaust air outlet threshold temperature for
\note minimum exhaust temperature frost control type.
N12,\field Initial defrost time fraction
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.083
\note Fraction of the time when frost control will be invoked at the threshold temp.
\note This field only used for exhaust air recirc and exhaust-only frost control types.
N13;\field Rate of defrost time fraction increase
\type real
\units 1/K
\minimum 0.0
\default 0.012
\note Rate of increase in defrost time fraction as actual temp falls below threshold temp.
\note This field only used for exhaust air recirc and exhaust-only frost control types.

```

Following is an example input for this heat exchanger object:

```

HEAT EXCHANGER:AIR TO AIR:GENERIC,
  OA Heat Recovery 1,      !- Heat exchanger name
  FanAndCoilAvailSched,   !- Availability schedule
  0.4333, !- Nominal supply air flow rate {m3/s}
  .75,    !- Sensible effectiveness at 100% airflow heating condition
  .68,    !- Latent effectiveness at 100% airflow heating condition
  .79,    !- Sensible effectiveness at 75% airflow heating condition
  .74,    !- Latent effectiveness at 75% airflow heating condition
  .75,    !- Sensible effectiveness at 100% airflow cooling condition
  .68,    !- Latent effectiveness at 100% airflow cooling condition
  .79,    !- Sensible effectiveness at 75% airflow cooling condition
  .74,    !- Latent effectiveness at 75% airflow cooling condition
  Outside Air Inlet Node,  !- Supply air inlet node
  Heat Recovery Outlet Node, !- Supply air outlet node
  Relief Air Outlet Node,  !- Secondary air inlet node
  Heat Recovery Secondary Outlet Node, !- Secondary air outlet node
  0.0,    !- Nominal electric power {W}
  No,     !- Supply air outlet temperature control
  Rotary, !- Heat exchanger type
  None;   !- Frost control type

```

Heat Exchanger:Air to Air:Generic Outputs

```

HVAC,Average,Heat Exchanger Sensible Heating Rate[W]
HVAC,Sum,Heat Exchanger Sensible Heating Energy[J]
HVAC,Average,Heat Exchanger Latent Heating Rate[W]
HVAC,Sum,Heat Exchanger Latent Heating Energy[J]
HVAC,Average,Heat Exchanger Total Heating Rate[W]
HVAC,Sum,Heat Exchanger Total Heating Energy[J]
HVAC,Average,Heat Exchanger Sensible Cooling Rate[W]
HVAC,Sum,Heat Exchanger Sensible Cooling Energy[J]
HVAC,Average,Heat Exchanger Latent Cooling Rate[W]
HVAC,Sum,Heat Exchanger Latent Cooling Energy[J]
HVAC,Average,Heat Exchanger Total Cooling Rate[W]
HVAC,Sum,Heat Exchanger Total Cooling Energy[J]
HVAC,Average,Heat Recovery Electric Power[W]
HVAC,Sum,Heat Recovery Electric Consumption[J]
HVAC,Average,Heat Recovery Sensible Effectiveness[-]
HVAC,Average,Heat Recovery Latent Effectiveness[-]
HVAC,Average,Heat Recovery Supply Air Bypass Mass Flow [kg/s]
HVAC,Average,Heat Recovery Exhaust Air Bypass Mass Flow [kg/s]
HVAC,Average,Heat Recovery Defrost Time Fraction[-]

```

Field: Heat Exchanger Sensible Heating Rate [W]

This output is the sensible heating rate of the supply air by the heat exchanger in Watts. This rate is determined using the supply air mass flow rate through the heat exchanger unit, the supply air inlet and outlet conditions, and the specific heat of the inlet supply air. A positive value is reported if the supply air is heated by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Sensible Heating Energy [J]

This output is the sensible heating energy added to the supply air by the heat exchanger in Joules over the time step being reported.

Field: Heat Exchanger Latent Heating Rate [W]

This output is the latent heating rate (humidification) of the supply air by the heat exchanger in Watts. This rate is determined by taking the difference between the Heat Exchanger Total Heating Rate and the Heat Exchanger Sensible Heating Rate. A positive value is reported if the supply air is humidified by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Latent Heating Energy [J]

This output is the latent heating energy added to the supply air by the heat exchanger in Joules over the time step being reported.

Field: Heat Exchanger Total Heating Rate [W]

This output is the total heating rate of the supply air by the heat exchanger in Watts. This rate is determined using the supply air mass flow rate through the heat exchanger unit, and the enthalpy of the supply air entering and leaving the unit. A positive value is reported if the enthalpy of the supply air is increased by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Total Heating Energy [J]

This output is the total heating energy added to the supply air by the heat exchanger in Joules over the time step being reported. This output is also added to a report meter with ResourceType = EnergyTransfer, EndUseKey = HeatRecoveryforHeating, GroupKey = System (ref. Report Meter).

Field: Heat Exchanger Sensible Cooling Rate [W]

This output is the sensible cooling rate of the supply air by the heat exchanger in Watts. This rate is determined using the supply air mass flow rate through the heat exchanger unit, the supply air inlet and outlet conditions, and the specific heat of the inlet supply air. A positive value is reported if the supply air is cooled by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Sensible Cooling Energy [J]

This output is the sensible cooling energy added to the supply air by the heat exchanger in Joules over the time step being reported.

Field: Heat Exchanger Latent Cooling Rate [W]

This output is the latent cooling rate (dehumidification) of the supply air by the heat exchanger in Watts. This rate is determined by taking the difference between the Heat Exchanger Total Cooling Rate and the Heat Exchanger Sensible Cooling Rate. A positive value is reported if the supply air is dehumidified by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Latent Cooling Energy [J]

This output is the latent cooling energy added to the supply air by the heat exchanger in Joules over the time step being reported.

Field: Heat Exchanger Total Cooling Rate [W]

This output is the total cooling rate of the supply air by the heat exchanger in Watts. This rate is determined using the supply air mass flow rate through the heat exchanger unit, and the enthalpy of the supply air entering and leaving the unit. A positive value is reported if the enthalpy of the supply air is decreased by the heat exchanger, else the rate is set to zero.

Field: Heat Exchanger Total Cooling Energy [J]

This output is the total cooling energy added to the supply air by the heat exchanger in Joules over the time step being reported. This output is also added to a report meter with ResourceType = EnergyTransfer, EndUseKey = HeatRecoveryforCooling, GroupKey = System (ref. Report Meter).

Field: Heat Recovery Electric Power [W]

This output is the electric consumption rate of the unit in Watts. This rate is applicable whenever the unit operates (i.e., whenever the unit is scheduled to be available and supply and exhaust air flows exist).

Field: Heat Recovery Electric Consumption [J]

This output is the electric consumption of the unit in Joules for the time step being reported. This output is also added to a report meter with ResourceType = Electricity, EndUseKey = HeatRecovery, GroupKey = System (ref. Report Meter).

Field: Heat Recovery Sensible Effectiveness [-]

This output is the average sensible effectiveness of the heat exchanger (excluding bypass air, if any) over the time step being reported.

Field: Heat Recovery Latent Effectiveness [-]

This output is the average latent effectiveness of the heat exchanger (excluding bypass air, if any) over the time step being reported.

Field: Heat Recovery Supply Air Bypass Mass Flow [kg/s]

This output is the average mass flow rate in kg/second of the supply (primary) air stream that is bypassing the heat exchanger over the time step being reported. This flow rate is equal to the total supply mass flow rate through the heat exchanger **unit** minus the amount passing through the supply side of the heat exchanger **core**.

Field: Heat Recovery Exhaust Air Bypass Mass Flow [kg/s]

This output is the average mass flow rate in kg/second of the exhaust (secondary) air stream that is bypassing the heat exchanger over the time step being reported. This flow rate is equal to the total exhaust mass flow rate through the heat exchanger **unit** minus the amount passing through the exhaust side of the heat exchanger **core**.

Field: Heat Recovery Defrost Time Fraction [-]

This output is the average fraction of the reporting time step when frost control is being implemented.

Engineering Document for Heat Exchanger:Air to Air:Generic

Overview

The generic air-to-air heat exchanger is an HVAC component that consists of a heat exchanger and primary/secondary air bypass dampers. The specific configuration of the component is shown in Figure 2 below.

Figure 2. Schematic of the Generic Air-to-Air Heat Exchanger

The generic air-to-air heat exchanger is typically used for exhaust or relief air heat recovery. Heat exchanger performance can be specified to transfer sensible energy, latent energy or both between the supply and exhaust air streams. The input requires no geometric data. Performance is defined by specifying sensible and/or latent effectiveness at 75% and 100% of the nominal (rated) supply air flow rate in both heating and cooling conditions (Table 2).

Table 4. Operating Conditions for Defining Heat Exchanger Performance

Parameter	Conditions	
	Heating	Cooling
Entering supply air temperature:		
Dry-bulb	1.7°C (35°F)	35°C (95°F)
Wet-bulb	0.6°C (33°F)	26°C (78°F)
Entering exhaust air temperature:		
Dry-bulb	21°C (70°F)	24°C (75°F)
Wet-bulb	14°C (58°F)	17°C (63°F)

Note: Conditions consistent with the Air-Conditioning and Refrigeration Institute's Standard 1060 (ARI 2001).

Heat exchange between the supply and exhaust air streams occurs whenever the unit is scheduled to be available (Availability schedule) and supply/exhaust air flows are present. This heat exchanger object can be used in conjunction with a conventional air-side economizer (i.e., specify ECONOMIZER in the Controller:Outside Air object), whereby heat exchange is suspended whenever the air-side economizer is active (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped). This object is also able to suspend heat exchange for the purpose of providing free cooling operation in the absence of a conventional air-side economizer (i.e., specify BYPASS in the Controller:Outside Air object).

Several methods of frost control are available to warm the heat exchanger core to prevent frost formation. Available methods are preheat, exhaust only, exhaust air recirculation, and minimum exhaust temperature. Preheat frost control uses a separate heater object placed in the supply inlet air stream to keep the air temperature above the frost threshold temperature. All other frost control methods are modeled within this heat exchanger object.

This heat exchanger object can also control the supply air outlet temperature to a set point when a set point manager and temperature schedule are used. This temperature control is accomplished through wheel speed modulation or bypassing supply air around the heat exchanger to maintain the desired set point and avoid overheating the supply air.

Model Description

The heat exchanger object models energy transfer between the supply air stream and the exhaust air stream according to the effectiveness values that are specified by the user in the input data file (see IO Reference Document, Heat Exchanger:Air to Air:Generic). The operating volumetric air flow rate through the heat exchanger (i.e., the average of the actual supply and exhaust air flow rates for the simulation time step) should be between 50% and 130% of the nominal supply air flow rate specified for the heat exchanger. Operating air flow rates outside this range result in a warning message and a recommendation to adjust air flow rates to within the appropriate range.

The user must enter the sensible and latent effectiveness of the heat exchanger for heating and cooling conditions (Table 2) with balanced air flow (supply flow equal to the exhaust flow) at two flow rates: 75% and 100% of the nominal supply air flow rate. Heat exchanger manufacturers can typically provide this performance information, and it is also available for equipment contained in ARI's Certified Product Directory for Air-to-Air Energy Recovery Ventilation Equipment (ARI 2003). Values may be entered for sensible effectiveness, latent effectiveness, or both. The model assumes default values of 0.0 for sensible and latent effectiveness, thus requiring the user to input representative values for the heat exchanger being modeled.

To obtain the "operating" effectiveness of the heat exchanger at different air flow rates, the model first calculates the average volumetric air flow rate through the heat exchanger (average of the supply and exhaust air flow rates) for each simulation time step. Air flows through the heat exchanger may be unbalanced (supply greater than exhaust, or vice versa), but an unbalanced air flow ratio greater than 2:1 results in a fatal warning message and program termination. The model determines the operating effectiveness of the heat exchanger by linear interpolation or extrapolation of the 100% flow and 75% flow effectiveness values specified in the input data file, using the average volumetric air flow rate through the heat exchanger. Extrapolation is allowed down to 50% and up to 130% of the nominal supply air flow rate (beyond this range a warning message is issued).

$$e_{operating,sensible} = e_{sensible,75\% flow} + (e_{sensible,100\% flow} - e_{sensible,75\% flow}) \left(\frac{HX_{flowratio} - 0.75}{1 - 0.75} \right) \quad (0.1)$$

$$e_{operatinglatent} = e_{latent,75\% flow} + (e_{latent,100\% flow} - e_{latent,75\% flow}) \left(\frac{HX_{flowratio} - 0.75}{1 - 0.75} \right) \quad (0.2)$$

where:

$e_{operating,sensible}$ = operating sensible effectiveness of the heat exchanger

$e_{operatinglatent}$ = operating latent effectiveness of the heat exchanger

$e_{sensible,75\% flow}$ = sensible effectiveness at 75% airflow condition

$e_{sensible,100\% flow}$ = sensible effectiveness at 100% airflow condition

$e_{latent,75\% flow}$ = latent effectiveness at 75% airflow condition

$e_{latent,100\% flow}$ = latent effectiveness at 100% airflow condition

$HX_{flowratio}$ = the ratio of the average operating volumetric air flow rate [(supply flow plus exhaust flow) / 2.0] to the nominal supply air flow rate

If the heat exchanger's supply air inlet temperature is less than the exhaust air inlet temperature, the operating sensible and latent effectivenesses are calculated using the 75% and 100% heating condition values; otherwise, the 75% and 100% cooling effectiveness values are used in Equations (0.1) and (0.2).

The supply air conditions leaving the heat exchanger are determined using the heat exchanger operating effectiveness calculated above, the ratio of the air stream with the minimum heat capacity rate to the supply air stream heat capacity rate, and the difference in temperature or humidity ratio between the supply and exhaust inlet air:

$$\dot{m}_{Cp,min} = MIN(\dot{m}_{Cp,sup}, \dot{m}_{Cp,exh})$$

$$T_{SupAirOut} = T_{SupAirIn} + e_{operating,sensible} \left(\frac{\dot{m}_{Cp,min}}{\dot{m}_{Cp,sup}} \right) (T_{ExhAirIn} - T_{SupAirIn})$$

$$W_{SupAirOut} = W_{SupAirIn} + e_{operatinglatent} \left(\frac{\dot{m}_{Cp,min}}{\dot{m}_{Cp,sup}} \right) (W_{ExhAirIn} - W_{SupAirIn})$$

where:

$\dot{m}_{Cp,min}$ = minimum heat capacity rate (W/K)

$\dot{m}_{Cp,sup}$ = heat capacity rate of the supply air stream (W/K)

$\dot{m}_{Cp,exh}$ = heat capacity rate of the exhaust air stream (W/K)

$T_{SupAirOut}$ = supply air temperature leaving the heat exchanger (°C)

$T_{SupAirIn}$ = supply air inlet temperature (°C)

$T_{ExhAirIn}$ = exhaust air inlet temperature (°C)

$W_{SupAirOut}$ = supply air humidity ratio leaving the heat exchanger (kg/kg)

$W_{SupAirIn}$ = supply air inlet humidity ratio (kg/kg)

$W_{ExhAirIn}$ = exhaust air inlet humidity ratio (kg/kg)

Using the supply air outlet temperature and humidity ratio, the enthalpy of the supply air leaving the heat exchanger is calculated.

$$h_{SupAirOut} = PSYHTW(T_{SupAirOut}, W_{SupAirOut})$$

where:

$h_{SupAirOut}$ = enthalpy of the supply air leaving the heat exchanger (J/kg)

$PsyHFnTdbW$ = psychrometric routine calculating air enthalpy as a function of temperature and humidity ratio

If the predicted conditions of the supply air leaving the heat exchanger exceed the saturation curve (>100% RH), then the temperature and humidity ratio of the air are reset to saturated conditions (= 100% RH) at the enthalpy condition calculated above ($h_{SupAirOut}$).

Next, the sensible and total heat recovery rates of the heat exchanger are calculated:

$$\dot{Q}_{Sensible} = \left(\dot{m} c_{p,sup} \right) (T_{SupAirIn} - T_{SupAirOut}) \quad (0.3)$$

$$\dot{Q}_{Total} = \dot{m}_{SupAir} (h_{SupAirIn} - h_{SupAirOut}) \quad (0.4)$$

where:

$\dot{Q}_{Sensible}$ = sensible heat recovery rate (W)

$\dot{Q}_{Total}$ = total heat recovery rate (W)

$h_{SupAirIn}$ = supply air inlet enthalpy (J/kg)

$\dot{m}_{SupAir}$ = mass flow rate of the supply air stream (kg/s)

The conditions of the exhaust (secondary) air leaving the heat exchanger are then calculated:

$$T_{ExhAirOut} = T_{ExhAirIn} + \frac{\dot{Q}_{Sensible}}{\dot{m} c_{p,exh}}$$

$$h_{ExhAirOut} = h_{ExhAirIn} + \frac{\dot{Q}_{Total}}{\dot{m}_{ExhAir}}$$

$$W_{ExhAirOut} = PSYWTH(T_{ExhAirOut}, h_{ExhAirOut})$$

where:

$T_{ExhAirOut}$ = exhaust air temperature leaving the heat exchanger (°C)

$h_{ExhAirOut}$ = exhaust air enthalpy leaving the heat exchanger (J/kg)

$\dot{m}_{ExhAir}$ = mass flow rate of the exhaust air stream (kg/s)

$W_{ExhAirOut}$ = exhaust air humidity ratio leaving the heat exchanger (kg/kg)

$PsyWFNTdbH$ = psychrometric routine calculating air humidity ratio as a function of temperature and enthalpy

As was done for the supply air, calculated exhaust air conditions beyond the saturation curve are reset to saturation conditions at the calculated air enthalpy value.

Once the air conditions leaving each side of the heat exchanger (supply and exhaust) are calculated, this air is blended with any bypass air that was directed around the heat

exchanger core to determine the final air conditions leaving the heat exchanger unit. These outlet air conditions are used in Equations (0.3) and (0.4) to determine the sensible and total heat recovery rate for the overall heat exchanger unit. The latent heat recovery rate for the overall unit is then calculated as the difference between the total and sensible heat recovery rates:

$$\dot{Q}_{Latent} = \dot{Q}_{Total} - \dot{Q}_{Sensible}$$

Heat recovery electric power is the electric consumption rate of the unit in watts. The nominal electric power rate for the heat exchanger is specified in the input data file, and can be used to model controls (transformers, relays, etc.) and/or a motor for a rotary heat exchanger. The model assumes that this electric power is consumed whenever the heat exchanger is scheduled to operate and supply/exhaust air flow rates exist. The electric power is assumed to be zero for all other times or if heat exchange is suspended to provide free cooling (economizer operation). None of this electric power is assumed to contribute thermal load to either of the heat exchanger air streams.

At the end of each HVAC simulation time step, this object reports the sensible, latent and total heat recovery rates for the overall unit as calculated above. The heat recovery rates are reported separately for times when the supply air is heated and when it is cooled (Ref: Heat Exchanger:Air To Air: Generic in the EnergyPlus Input Output Reference). The heat recovery electric power is also reported for each simulation time step. In addition to the heat recovery rates and electric power, heating/cooling energy transferred to the supply air and the electric energy consumption by the heat exchanger unit are calculated for the time step being reported as follows:

$$Q_{SensibleCooling} = \dot{Q}_{SensibleCooling} * TimeStepSys * 3600.$$

$$Q_{LatentCooling} = \dot{Q}_{LatentCooling} * TimeStepSys * 3600.$$

$$Q_{TotalCooling} = \dot{Q}_{TotalCooling} * TimeStepSys * 3600.$$

$$Q_{SensibleHeating} = \dot{Q}_{SensibleHeating} * TimeStepSys * 3600.$$

$$Q_{LatentHeating} = \dot{Q}_{LatentHeating} * TimeStepSys * 3600.$$

$$Q_{TotalHeating} = \dot{Q}_{TotalHeating} * TimeStepSys * 3600.$$

$$E_{HXUnit} = P_{HXUnit} * TimeStepSys * 3600.$$

where:

$Q_{SensibleCooling}$ = output variable 'Heat Exchanger Sensible Cooling Energy, J'

$\dot{Q}_{SensibleCooling}$ = output variable 'Heat Exchanger Sensible Cooling Rate, W' = $\dot{Q}_{Sensible}$
during times when the supply air is cooled

$TimeStepSys$ = HVAC system simulation time step, hr

$Q_{LatentCooling}$	= output variable 'Heat Exchanger Latent Cooling Energy, J'
$\dot{Q}_{LatentCooling}$	= output variable 'Heat Exchanger Latent Cooling Rate, W' = $\dot{Q}_{Latent}$ during times when the supply air is dehumidified
$Q_{TotalCooling}$	= output variable 'Heat Exchanger Total Cooling Energy, J'
$\dot{Q}_{TotalCooling}$	= output variable 'Heat Exchanger Total Cooling Rate, W' = $\dot{Q}_{Total}$ during times when the supply air enthalpy is reduced
$Q_{SensibleHeating}$	= output variable 'Heat Exchanger Sensible Heating Energy, J'
$\dot{Q}_{SensibleHeating}$	= output variable 'Heat Exchanger Sensible Heating Rate, W' = $\dot{Q}_{Sensible}$ during times when the supply air is heated
$Q_{LatentHeating}$	= output variable 'Heat Exchanger Latent Heating Energy, J'
$\dot{Q}_{LatentHeating}$	= output variable 'Heat Exchanger Latent Heating Rate, W' = $\dot{Q}_{Latent}$ during times when the supply air is humidified
$Q_{TotalHeating}$	= output variable 'Heat Exchanger Total Heating Energy, J'
$\dot{Q}_{TotalHeating}$	= output variable 'Heat Exchanger Total Heating Rate, W' = $\dot{Q}_{Total}$ during times when the supply air enthalpy is increased
E_{HXUnit}	= output variable 'Heat Recovery Electric Consumption, J'
P_{HXUnit}	= output variable 'Heat Recovery Electric Power, W'

Frost Control Methods

In cold weather, frost can form on the heat exchanger causing a reduction in air flow and heat recovery performance. Various strategies can be employed to limit frost formation. Heat exchangers that transfer total energy (sensible plus latent) usually have a lower frost threshold temperature than sensible-only heat exchangers. Frost threshold temperatures for sensible-only heat exchangers may be -1°C to -12°C for plate and rotary heat exchangers respectively, while those for comparable total (sensible plus latent) heat exchangers may be 10°C lower. The frost threshold temperature for a specific application is dependent on the exhaust air dry-bulb temperature and relative humidity, heat exchanger type (e.g., sensible-only or total heat exchange, flat plate or rotary), and the heat exchanger effectiveness. Consult manufacturer's literature to obtain specific frost threshold temperatures for the heat exchanger being modeled.

Four frost control strategies can be modeled for this air-to-air heat exchanger unit. Each of these four strategies is discussed in detail below.

Preheat

One method to control frost formation is to preheat the cold outdoor (supply) air entering the heat exchanger. When a preheat coil is used for frost control, a separate heating coil object must be placed in the supply air stream at the inlet to the heat exchanger (COIL:WATER:SIMPLEHEATING, COIL:ELECTRIC:HEATING or COIL:GAS:HEATING). The preheat coil should be controlled to maintain a minimum supply air inlet temperature thereby eliminating frost buildup on the heat exchanger core. When modeling preheat frost control, specify "None" as the frost control method in the heat exchanger object. When modeling this

heat exchanger as part of an air loop, refer to the objects OUTSIDE AIR SYSTEM and SET POINT MANAGER:SCHEDULED in the EnergyPlus Input Output Reference for additional information on specifying a preheat coil and controlling its supply air temperature. This frost control method is not currently available when this heat exchanger is being used as part of the compound object Energy Recovery Ventilator:Stand Alone.

Exhaust Only

This method of frost control bypasses the incoming supply air around the heat exchanger core thereby warming the core using the exiting exhaust air. This method is similar to 'supply air off' frost control where the supply air fan is turned off for a predetermined period of time while the exhaust air fan continues to operate. For the 'supply air off' method, the supply air flow is stopped for a period of time thereby reducing the ventilation air supplied to the zone(s). In addition, the building may be negatively pressurized for the period of time that the supply air flow is stopped since the exhaust air fan continues to operate. On the other hand, the 'exhaust only' method of frost control modeled by EnergyPlus continues to provide outdoor ventilation air to the zone(s), but this air is simply bypassed around the heat exchanger core for a portion of the time and the potential problem with negatively pressurizing the building is avoided. Since the supply airflow rate through the heat exchanger core is purposely reduced to control frost formation, average volumetric airflow rates below 50% of nominal are allowed when this frost control is active and no warning message is issued.

The user enters a threshold temperature, an initial defrost time fraction, and a rate of defrost time fraction increase. When the temperature of the supply air (e.g., outdoor air) entering the heat exchanger is equal to or below the specified threshold temperature, the fractional amount of time that the supply air is bypassed around the heat exchanger core is determined from the following equation:

$$X_{DefrostTime} = X_{Initial} + X_{RateofIncrease} (T_{Threshold} - T_{SupAirIn})$$

where:

$$X_{DefrostTime} = \text{Fractional time period for frost control } (0 \leq X_{DefrostTime} \leq 1)$$

$$X_{Initial} = \text{Initial defrost time fraction}$$

$$X_{RateofIncrease} = \text{Rate of defrost time fraction increase (K}^{-1}\text{)}$$

$$T_{Threshold} = \text{Threshold temperature (}^{\circ}\text{C)}$$

$$T_{SupAirIn} = \text{Supply air inlet temperature (}^{\circ}\text{C)}$$

During the defrost time, supply air flow is fully bypassed around the heat exchanger core and no heat transfer takes place. For the remainder of the time period, no air is bypassed and full heat exchange is achieved. The average supply air flow bypassed around the heat exchanger core is calculated as follows:

$$\dot{m}_{SupAirBypass} = (X_{DefrostTime}) \dot{m}_{SupAir}$$

To determine the average heat transfer rates for the simulation time step, the supply air outlet conditions are first calculated as if the heat exchanger were not in defrost mode (see previous section, Model Description). The sensible and total heat transfer rates are then calculated and multiplied by the fractional time period that the heat exchanger is not in defrost mode $(1 - X_{DefrostTime})$.

$$\dot{Q}_{Sensible} = (1 - X_{DefrostTime}) \left(\dot{m}_{Cp,sup} \right) (T_{SupAirIn} - T_{SupAirOut})$$

$$\dot{Q}_{Total} = (1 - X_{DefrostTime}) \dot{m}_{SupAir} (h_{SupAirIn} - h_{SupAirOut})$$

Once the average heat transfer rates are determined, the average conditions of the supply air exiting the overall heat exchanger unit are calculated as follows:

$$T_{SupAirOut} = T_{SupAirIn} - \frac{\dot{Q}_{Sensible}}{\dot{m}_{Cp,sup}}$$

$$h_{SupAirOut} = h_{SupAirIn} - \frac{\dot{Q}_{Total}}{\dot{m}_{SupAir}}$$

$$W_{SupAirOut} = PSYWTH(T_{SupAirOut}, h_{SupAirOut})$$

As described previously, if the predicted conditions of the exiting supply air exceed the saturation curve (>100% RH), then the temperature and humidity ratio of the air are reset to saturated conditions (= 100% RH) at the enthalpy condition calculated above ($h_{SupAirOut}$). If the supply air temperature is reset, the average sensible heat transfer rate is recalculated before the exhaust air outlet conditions are determined:

$$T_{ExhAirOut} = T_{ExhAirIn} + \frac{\dot{Q}_{Sensible}}{\dot{m}_{Cp,exh}}$$

$$h_{ExhAirOut} = h_{ExhAirIn} + \frac{\dot{Q}_{Total}}{\dot{m}_{ExhAir}}$$

$$W_{ExhAirOut} = PSYWTH(T_{ExhAirOut}, h_{ExhAirOut})$$

Exhaust Air Recirculation

This method of frost control routes exhaust (outlet) air back through the supply side of the heat exchanger to warm the core. Since this method routes exhaust air back into the building, the building is typically not depressurized when this frost control is active. However, the incoming supply (outdoor ventilation) air flow is stopped for the fractional period of time that frost control is active. If significant periods of time exist when outdoor temperatures are below the selected threshold temperature and outdoor ventilation air is continuously required, an alternative method of frost control should be considered.

The user enters a threshold temperature, an initial defrost time fraction, and a rate of defrost time fraction increase. When the temperature of the inlet supply air (e.g., outdoor air) is equal to or below the specified threshold temperature, the fractional amount of time that this heat exchanger frost control strategy is active is determined from the following equation:

$$X_{DefrostTime} = X_{Initial} + X_{RateofIncrease} (T_{Threshold} - T_{SupAirIn})$$

The air mass flow rate of the supply air leaving the heat exchanger unit is then calculated using the defrost time fraction calculated above the mass flow rates of supply and exhaust air entering the unit.

$$\dot{m}_{SupAirOut} = (1 - X_{DefrostTime}) \dot{m}_{SupAirIn} + X_{DefrostTime} \dot{m}_{ExhAirIn}$$

The model assumes that no heat exchange occurs during defrost, and the average supply air conditions are simply a blend of the conditions when the unit is not in defrost and the exhaust air inlet conditions during defrost operation:

$$T_{SupAirOut} = \frac{(1 - X_{DefrostTime}) \dot{m}_{SupAirIn} T_{SupAirOutNoDefrost} + X_{DefrostTime} \dot{m}_{ExhAirIn} T_{ExhAirIn}}{\dot{m}_{SupAirOut}}$$

$$W_{SupAirOut} = \frac{(1 - X_{DefrostTime}) \dot{m}_{SupAirIn} W_{SupAirOutNoDefrost} + X_{DefrostTime} \dot{m}_{ExhAirIn} W_{ExhAirIn}}{\dot{m}_{SupAirOut}}$$

$$h_{SupAirOut} = PSYHTW(T_{SupAirOut}, W_{SupAirOut})$$

The operating effectivenesses of the heat exchanger are initially calculated according to Equations (0.1) and (0.2) assuming no defrost operation. Since the supply air flow across the heat exchanger core is not reduced during defrost operation, the sensible and latent effectiveness are therefore derated (for reporting purposes) in direct proportion to the fraction of time that frost control is not active.

$$e_{operating,sensible} = (1 - X_{DefrostTime}) e_{operating,sensible}$$

$$e_{operatinglatent} = (1 - X_{DefrostTime}) e_{operatinglatent}$$

Since the exhaust outlet air is recirculated through the supply side of the heat exchanger core, the incoming supply air and exiting exhaust air flows are stopped for the fraction of the time when frost control is active. The average air mass flow rate at the supply air inlet and the exhaust air outlet nodes are therefore reduced accordingly.

$$\dot{m}_{SupAirIn} = (1 - X_{DefrostTime}) \dot{m}_{SupAirIn}$$

$$\dot{m}_{ExhAirOut} = (1 - X_{DefrostTime}) \dot{m}_{ExhAirOut}$$

The conditions of the exiting (outlet) exhaust air (temperature, humidity ratio and enthalpy) are reported as the values when frost control is not active (i.e., the conditions when exhaust air is actually leaving the unit).

Minimum Exhaust Temperature

With this frost control method, frost formation is avoided by continuously maintaining the temperature of the exhaust air leaving the heat exchanger core above a specified set point. The minimum exhaust air temperature is maintained by modulating heat exchanger rotational speed or by bypassing supply air around a plate heat exchanger. For this frost control method, the user must only enter the threshold (minimum) temperature.

For the case of modulating heat exchanger rotation, the operating effectivenesses and outlet air conditions are first calculated as if the heat exchanger is not in defrost mode (see Model Description). If the resulting temperature of the exhaust air leaving the heat exchanger core is below the specified threshold temperature, then the operating effectivenesses are reduced as follows:

$$X_{DefrostTime} = \frac{(T_{Threshold} - T_{ExhAirOut})}{(T_{ExhAirIn} - T_{ExhAirOut})}$$

$$e_{operating,sensible} = (1 - X_{DefrostTime})e_{operating,sensible}$$

$$e_{operatinglatent} = (1 - X_{DefrostTime})e_{operatinglatent}$$

The supply air and exhaust air outlet conditions are then recalculated using these reduced effectiveness values. Finally the sensible, latent and total heat recovery rates are calculated along with the unit's electric power and electric consumption.

The calculation procedure is slightly different for the case of a plate heat exchanger where the supply air is bypassed around the heat exchanger core. Since the volumetric air flow rate through the heat exchanger core is reduced when frost control is active, an iterative process is used to determine the operating effectiveness of the heat exchanger. The operating effectivenesses and outlet air conditions are first calculated as if the heat exchanger is not in defrost mode (see Model Description). If the resulting temperature of the exhaust air leaving the heat exchanger core is below the specified threshold temperature, then the fractional defrost time is calculated as follows:

$$X_{DefrostTime} = \frac{(T_{Threshold} - T_{ExhAirOut})}{(T_{ExhAirIn} - T_{ExhAirOut})}$$

The iteration process then begins to determine the heat exchanger effectiveness and the exhaust air outlet temperature as if frost control were active. The operating mass flow rate through the supply side of the heat exchanger core is calculated.

Beginning of iteration process:

$$\dot{m}_{SupAirCore} = (1 - X_{DefrostTime})\dot{m}_{SupAirIn}$$

$$\dot{m}_{SupAirBypass} = (X_{DefrostTime})\dot{m}_{SupAirIn}$$

The ratio of average volumetric flow rate through the heat exchanger core to heat exchanger's nominal volumetric flow rate ($HX_{flowratio}$) is then determined and used to calculate the operating effectiveness of the heat exchanger using Equations (0.1) and (0.2). Since the supply airflow rate through the heat exchanger core is purposely reduced to control frost formation, average volumetric airflow rates below 50% of nominal are allowed and no

warning message is issued. Supply air outlet temperature (leaving the heat exchanger core), sensible heat transfer, and exhaust air outlet temperature are then calculated using the revised heat exchanger effectiveness.

$$T_{SupAirOut} = T_{SupAirIn} + e_{operatingsensible} \left(\frac{\dot{m} c_{p,min}}{\dot{m} c_{p,sup}} \right) (T_{ExhAirIn} - T_{SupAirIn})$$

$$\dot{Q}_{Sensible} = (1 - X_{DefrostTime}) \left(\dot{m} c_{p,sup} \right) (T_{SupAirInlet} - T_{SupAirOutlet})$$

$$T_{ExhAirOut} = T_{ExhAirIn} + \frac{\dot{Q}_{Sensible}}{\dot{m} c_{p,exh}}$$

The error between the exhaust outlet temperature and the threshold temperature for frost control and a new defrost time fraction are subsequently calculated.

$$Error = T_{ExhAirOut} - T_{Threshold}$$

$$X_{DefrostTime} = X_{DefrostTime} \left(\frac{T_{ExhAirIn} - T_{ExhAirOut}}{T_{ExhAirIn} - T_{Threshold}} \right)$$

End of iteration process:

The iteration process ends when the calculated error is within an error tolerance of 0.001. The air streams passing through the heat exchanger core and bypassing the core through the bypass damper are then blended together to provide the air conditions leaving the heat exchanger unit. Finally the sensible, latent and total heat recovery rates are calculated along with the unit's electric power and electric consumption.

Economizer Operation

A conventional air-side economizer may be used in conjunction with this heat exchanger object. The air-side economizer is specified through the use of an outside air controller (see object: CONTROLLER:OUTSIDE AIR). Specify "economizer" as the economizer choice, and provide the required control points and air flow rates as defined in the outside air controller object. Energy transfer provided by the heat exchanger will be suspended whenever free cooling is available (i.e., when the air-side economizer is activated). For plate heat exchangers, heat transfer is suspended by fully bypassing the supply and exhaust air around the heat exchanger core. For rotary heat exchangers, air flows continue through the core but it is assumed that heat exchanger rotation is stopped.

Heat exchange can also be suspended for the purposes of providing free cooling operation in the absence of a conventional air-side economizer. In this case specify "bypass" as the economizer choice and again provide the required control points as defined in the outside air controller object. Energy transfer provided by the heat exchanger will be suspended whenever free cooling is available, however the supply air flow rate will remain at the minimum value specified in the outside air controller object.

If economizer operation is not required, specify "no economizer" as the economizer choice in the outside air controller object. The heat exchanger will operate according to its availability schedule and free cooling will not be provided.

Supply Air Outlet Temperature Control

This heat exchanger object can also control the supply air outlet temperature to a set point to avoid overheating. This temperature control is accomplished through wheel speed modulation or bypassing supply air around the heat exchanger. To model this temperature control, the user must specify 'Yes' for the Supply Air Outlet Temperature Control field in this heat exchanger object, and a separate set point manager (see object: SET POINT MANAGER:SCHEDULED) and temperature schedule (see object: SCHEDULE) must be specified for the heat exchanger unit's supply air outlet node.

This control strategy is typically used in conjunction with economizer operation (see object CONTROLLER:OUTSIDE AIR), and an example control profile is shown in the figure below. When the outdoor air temperature falls to the specified maximum limit for economizer operation, heat exchange is suspended (air is fully bypassed around the heat exchanger core or heat exchanger rotation is stopped). The figure below shows economizer operation being initiated based on outdoor temperature but other triggers can be used (e.g. differential temperature [outdoor temperature with respect to exhaust air temperature], single point enthalpy or differential enthalpy). Heat exchange remains suspended until the outdoor temperature falls to the minimum temperature (temperature lower limit) for economizer control. The setpoint for the supply air outlet temperature control should match the economizer temperature lower limit.

As the outdoor air temperature falls further below the setpoint for the supply air outlet temperature (same as the economizer lower temperature limit), the heat exchanger bypass dampers will modulate closed to maintain the desired supply air temperature for a plate heat exchanger. For a rotary heat exchanger the rotary heat exchanger speed will gradually increase to maintain the desired supply air temperature. Modulation of heat exchanger performance will continue until the supply air temperature set point can no longer be maintained.

Figure 3. Air to Air Heat Exchanger with Supply Air Temperature Control

References

ARI 2001. Rating Air-to-Air Heat Exchangers for Energy Recovery Ventilation Equipment. <http://www.ari.org/std/individual/>. Arlington, Virginia: Air-Conditioning & Refrigeration Institute.

ARI 2003. Certified Product Directory for Air-to-Air Energy Recovery Ventilation Equipment. <http://www.ari.org/directories/erv/>. Arlington, Virginia: Air-Conditioning & Refrigeration Institute.

Input Output Reference for Energy Recovery Ventilator:Stand Alone

The stand alone energy recovery ventilator (ERV) is a single-zone HVAC component used for exhaust air heat recovery (Figure 4). This compound object consists of 3 required components: a generic air-to-air heat exchanger (see object Heat Exchanger:Air to Air:Generic), a supply air fan, and an exhaust air fan (see object Fan:Simple:OnOff). An optional controller (see object Controller:Stand Alone ERV) may be used to simulate economizer (free cooling) operation.

Figure 4. Schematic of the Energy Recovery Ventilator:Stand Alone compound object

This compound object models the basic operation of supply and exhaust air fans and an air-to-air heat exchanger. The stand alone ERV operates whenever the unit is scheduled to be available (Availability schedule). The stand alone ERV object can be used in conjunction with an economizer feature whereby heat exchange is suspended whenever free cooling is available (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped).

To model a stand alone ERV connected to a single zone, the input data file should include the following objects:

- ENERGY RECOVERY VENTILATOR:STAND ALONE
- HEAT EXCHANGER:AIR TO AIR:GENERIC
- FAN:SIMPLE:ONOFF (supply air)
- FAN:SIMPLE:ONOFF (exhaust air)

- CONTROLLER:STAND ALONE ERV (if economizer [free cooling] operation is desired)
- SET POINT MANAGER:SCHEDULED (if supply air outlet temperature control is used, Ref. Heat Exchanger:Air to Air:Generic for additional guidance)
- CONTROLLED ZONE EQUIP CONFIGURATION
- ZONE EQUIPMENT LIST
- OUTSIDE AIR INLET NODE LIST

A description of each input field for this compound object is provided below.

Field: Stand alone ERV name

A unique user-assigned name for the stand alone ERV unit. Any reference to this unit by another object will use this name.

Field: Availability schedule name

The name of the schedule (ref: Schedule) that denotes whether the unit can operate during a given hour. A schedule value greater than 0 (usually 1 is used) indicates that the unit can operate during the hour. A value less than or equal to 0 (usually 0 is used) denotes that the unit will not operate.

Field: Heat exchanger name

The user-assigned name corresponding to the air-to-air heat exchanger used in this compound object. The heat exchanger type must be HEAT EXCHANGER:AIR TO AIR:GENERIC.

Field: Supply air flow rate

The supply air flow rate through the ERV unit in cubic meters per second at standard temperature and pressure (dry air at 20° C drybulb). The program uses local barometric pressure to account for altitude using the equation for "standard atmospheric" pressure on p 6.1 of the ASHRAE 1997 HOF (SI edition) to initialize the air systems being simulated.

$$p = 101325 * (1 - 2.25577E - 05 * Z) ** 5.2559$$

where p=pressure in Pa and Z=altitude in m

Note that this flow rate must be within the valid air flow range for the heat exchanger (ref: HEAT EXCHANGER:AIR TO AIR:GENERIC in the Engineering Document). In addition, this flow rate must match the supply fan air flow rate (FAN:SIMPLE:ONOFF). If the supply air flow rate is less than the exhaust air flow rate, the zone infiltration (ref: INFILTRATION) should be specified accordingly (the infiltration induced by imbalanced air flows is not accounted for automatically).

Field: Supply air inlet node name

The name of the HVAC system node from which the unit draws its supply inlet air. This node must be an outside air node (defined in an OUTSIDE AIR INLET NODE LIST) and the node name must match the supply air inlet node name specified for the air-to-air heat exchanger (HEAT EXCHANGER:AIR TO AIR:GENERIC).

Field: Supply air outlet node name

The name of the HVAC system node to which the unit sends its supply outlet air. This node should be a zone inlet node (ref: NODE LIST and CONTROLLED ZONE EQUIP CONFIGURATION). This node name must also match the outlet node name specified in the supply air fan object.

Field: Exhaust air flow rate

The exhaust air flow rate through the ERV unit in cubic meters per second at standard temperature and pressure (dry air at 20° C drybulb). The program uses local barometric

pressure to account for altitude using the equation for "standard atmospheric" pressure on p 6.1 of the ASHRAE 1997 HOF (SI edition) to initialize the air systems being simulated.

$$p=101325*(1-2.25577E-05*Z)**5.2559$$

where p=pressure in Pa and Z=altitude in m

Note that this flow rate must be within the valid air flow range for the heat exchanger (ref: HEAT EXCHANGER:AIR TO AIR:GENERIC in the Engineering Document). In addition, this flow rate must match the exhaust fan air flow rate (FAN:SIMPLE:ONOFF). If the exhaust air flow rate is greater than the supply air flow rate, the zone infiltration (ref: INFILTRATION) should be specified accordingly (the infiltration induced by imbalanced air flows is not accounted for automatically).

Field: Exhaust air inlet node name

The name of the HVAC system node from which the unit draws its exhaust inlet air. This node should be a zone exhaust node (ref: NODE LIST and CONTROLLED ZONE EQUIP CONFIGURATION). This node name must match the exhaust air inlet node name specified for the air-to-air heat exchanger (HEAT EXCHANGER:AIR TO AIR:GENERIC).

Field: Exhaust air outlet node name

The name of the HVAC system node to which the unit sends its exhaust outlet air. This node name must match the outlet node specified in the exhaust fan object.

Field: Supply air fan name

The name of the supply air fan used in this object. Fan type must be FAN:SIMPLE:ONOFF.

Field: Exhaust air fan name

The name of the exhaust air fan used in this object. Fan type must be FAN:SIMPLE:ONOFF.

Field: ERV controller name

The name of the controller used by this compound component if economizer (free cooling) mode operation is desired. Controller type must be CONTROLLER:STAND ALONE ERV.

The full IDD specification follows:

```
ENERGY RECOVERY VENTILATOR:STAND ALONE,  
  \memo This compound component models a stand-alone energy recovery ventilator (ERV)  
  \memo that conditions outdoor ventilation air and supplies that air directly to a zone.  
  \memo The ERV unit is modeled as a collection of components: generic air-to-air heat exchanger,  
  \memo supply air fan, exhaust air fan and an optional controller to avoid overheating  
  \memo of the supply air (economizer or free cooling operation).  
  \min-fields 11  
A1, \field Stand alone ERV name  
  \required-field  
  \type alpha  
A2, \field Availability schedule name  
  \required-field  
  \type object-list  
  \object-list ScheduleNames  
A3, \field Heat exchanger name  
  \required-field  
  \type alpha
```



```

N1, \field Supply air flow rate
    \required-field
    \type real
    \minimum> 0.0
    \units m3/s
    \note This flow rate must match the supply fan air flow rate.
A4, \field Supply air inlet node name
    \required-field
    \type alpha
A5, \field Supply air outlet node name
    \required-field
    \type alpha
N2, \field Exhaust air flow rate
    \required-field
    \type real
    \minimum> 0.0
    \units m3/s
    \note This flow rate must match the exhaust fan air flow rate.
A6, \field Exhaust air inlet node name
    \required-field
    \type alpha
A7, \field Exhaust air outlet node name
    \required-field
    \type alpha
A8, \field Supply air fan name
    \required-field
    \type alpha
A9, \field Exhaust air fan name
    \required-field
    \type alpha
A10; \field ERV controller name
    \type alpha

```

Following is an example input for this compound object and associated objects that may be defined:

```

ENERGY RECOVERY VENTILATOR:STAND ALONE,
    Stand Alone ERV 1,                !- Stand alone ERV name
    FanAndCoilAvailSched,             !- Availability schedule name
    OA Heat Recovery 1,               !- Heat exchanger name
    0.05,                             !- Supply air flow rate {m3/s}
    ERV Outside Air Inlet Node,        !- Supply air inlet node name
    Stand Alone ERV Supply Fan Outlet Node, !- Supply air outlet node name
    0.05,                             !- Exhaust air flow rate {m3/s}
    Zone 1 Exhaust Node,              !- Exhaust air inlet node name
    Stand Alone ERV Exhaust Fan Outlet Node, !- Exhaust air outlet node name
    Stand Alone ERV Supply Fan,        !- Supply air fan name
    Stand Alone ERV Exhaust Fan,       !- Exhaust air fan name
    ERV OA Controller 1;              !- ERV controller name

OUTSIDE AIR INLET NODE LIST,
    OutsideAirInletNodes; !- 1st Node name or node list name

NODE LIST,
    OutsideAirInletNodes, !- Node List Name
    ERV Outside Air Inlet Node; !- Node_ID_1

```

```

CONTROLLED_ZONE_EQUIP_CONFIGURATION,
  RESISTIVE_ZONE,      !- Zone Name
  Zone1Equipment,      !- List Name: Zone Equipment
  Zone1Inlets,          !- List Name: Zone Inlet Nodes
  Zone1Exhausts,        !- List Name: Zone Exhaust Nodes
  Zone_1_Node,          !- Zone Air Node Name
  Zone_1_Outlet_Node;   !- Zone Return Air Node Name

ZONE_EQUIPMENT_LIST,
  Zone1Equipment,      !- Name
  ENERGY_RECOVERY_VENTILATOR:STAND_ALONE, !- KEY--Zone Equipment Type 1
  Stand_Alone_ERV_1,    !- Type Name 1
  1, !- Cooling Priority
  1; !- Heating Priority

NODE_LIST,
  Zone1Inlets, !- Node List Name
  Stand_Alone_ERV_Supply_Fan_Outlet_Node; !- Node_ID_1

NODE_LIST,
  Zone1Exhausts, !- Node List Name
  Zone_1_Exhaust_Node; !- Node_ID_1

CONTROLLER:STAND_ALONE_ERV,
  ERV_OA_Controller_1, !- ERV controller name
  0.05, !- Outside air flow rate {m3/s}
  19., !- Temperature high limit {C}
  14., !- Temperature low limit {C}
  0.0, !- Enthalpy high limit {J/kg}
  ERV_Outside_Air_Inlet_Node, !- Supply air inlet node name
  Zone_1_Exhaust_Node, !- Exhaust air inlet node name
  NO_EXHAUST_AIR_TEMP_LIMIT, !- Exhaust air temperature limit
  NO_EXHAUST_AIR_ENTHALPY_LIMIT; !- Exhaust air enthalpy limit

HEAT_EXCHANGER:AIR_TO_AIR:GENERIC,
  OA_Heat_Recovery_1, !- Heat exchanger name
  FanAndCoilAvailSched, !- Availability schedule name
  0.05, !- Nominal supply air flow rate {m3/s}
  .76, !- Sensible effectiveness at 100% airflow heating condition
  .68, !- Latent effectiveness at 100% airflow heating condition
  .81, !- Sensible effectiveness at 75% airflow heating condition
  .73, !- Latent effectiveness at 75% airflow heating condition
  .76, !- Sensible effectiveness at 100% airflow cooling condition
  .68, !- Latent effectiveness at 100% airflow cooling condition
  .81, !- Sensible effectiveness at 75% airflow cooling condition
  .73, !- Latent effectiveness at 75% airflow cooling condition
  ERV_Outside_Air_Inlet_Node, !- Supply air inlet node name
  Heat_Recovery_Outlet_Node, !- Supply air outlet node name
  Zone_1_Exhaust_Node, !- Exhaust air inlet node name
  Heat_Recovery_Secondary_Outlet_Node, !- Exhaust air outlet node name
  50.0, !- Nominal electric power {W}
  Yes, !- Supply air outlet temperature control
  Rotary, !- Heat exchanger type
  Minimum_Exhaust_Temperature, !- Frost control type
  1.7; !- Threshold temperature

FAN:SIMPLE:ONOFF,
  Stand_Alone_ERV_Supply_Fan, !- Fan Name
  FanAndCoilAvailSched, !- Available Schedule
  0.5, !- Fan Total Efficiency
  75.0, !- Delta Pressure {Pa}
  0.05, !- Max Flow Rate {m3/s}
  0.9, !- Motor Efficiency
  1.0, !- Motor In Airstream Fraction
  Heat_Recovery_Outlet_Node, !- Fan_Inlet_Node
  Stand_Alone_ERV_Supply_Fan_Outlet_Node; !- Fan_Outlet_Node

```

```

FAN:SIMPLE:ONOFF,
  Stand Alone ERV Exhaust Fan,          !- Fan Name
  FanAndCoilAvailsSched,                !- Available Schedule
  0.5,                                  !- Fan Total Efficiency
  75.0,                                 !- Delta Pressure {Pa}
  0.05,                                 !- Max Flow Rate {m3/s}
  0.9,                                  !- Motor Efficiency
  1.0,                                  !- Motor In Airstream Fraction
  Heat Recovery Secondary Outlet Node,    !- Fan_Inlet_Node
  Stand Alone ERV Exhaust Fan Outlet Node; !- Fan_Outlet_Node

SET POINT MANAGER:SCHEDULED,
  Heat Exhchanger Supply Air Temp Manager, !- Name
  TEMP, !- Control variable
  Heat Exchanger Supply Air Temp Sch, !- Schedule Name
  Heat Exchanger Supply Air Nodes; !- Name of the set point Node List

NODE LIST,
  Heat Exchanger Supply Air Nodes, !- Node List Name
  Heat Recovery Outlet Node; !- Node_ID_1

```

Energy Recovery Ventilator:Stand Alone Outputs

```

HVAC,Average,Stand Alone ERV Electric Power[W]
HVAC,Sum,Stand Alone ERV Electric Consumption[J]
HVAC,Average,Stand Alone ERV Zone Total Cooling Rate[W]
HVAC,Sum,Stand Alone ERV Zone Total Cooling Energy[J]
HVAC,Average,Stand Alone ERV Zone Total Heating Rate[W]
HVAC,Sum,Stand Alone ERV Zone Total Heating Energy[J]
HVAC,Average,Stand Alone ERV Zone Sensible Cooling Rate[W]
HVAC,Sum,Stand Alone ERV Zone Sensible Cooling Energy[J]
HVAC,Average,Stand Alone ERV Zone Sensible Heating Rate[W]
HVAC,Sum,Stand Alone ERV Zone Sensible Heating Energy[J]
HVAC,Average,Stand Alone ERV Zone Latent Cooling Rate[W]
HVAC,Sum,Stand Alone ERV Zone Latent Cooling Energy[J]
HVAC,Average,Stand Alone ERV Zone Latent Heating Rate[W]
HVAC,Sum,Stand Alone ERV Zone Latent Heating Energy[J]

```

Field: Stand Alone ERV Electric Power [W]

This output is the electric consumption rate of the stand alone energy recovery ventilator in Watts. This rate includes the electric consumption by the supply air fan, exhaust air fan and the generic air-to-air heat exchanger.

Field: Stand Alone ERV Electric Consumption [J]

This output is the electric consumption of the stand alone energy recovery ventilator in Joules for the time step being reported. This value includes the electric consumption by the supply air fan, exhaust air fan and the generic air-to-air heat exchanger.

Field: Stand Alone ERV Zone Total Cooling Rate [W]

This output is the total cooling rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone. This value is calculated using the supply air outlet mass flow rate, and the enthalpy of the supply outlet and exhaust inlet air streams. This value is calculated for each HVAC system time step being simulated, and the results (cooling only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Total Cooling Energy [J]

This output is the total cooling energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported. This value is calculated using the supply air outlet mass flow rate, the enthalpy of the supply outlet and exhaust inlet air streams, and the HVAC system time step. This value is calculated for each HVAC system

time step being simulated, and the results (cooling only) are summed for the time step being reported.

Field: Stand Alone ERV Zone Total Heating Rate [W]

This output is the total heating rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone. This value is calculated using the supply air outlet mass flow rate, and the enthalpy of the supply outlet and exhaust inlet air streams. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Total Heating Energy [J]

This output is the total heating energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported. This value is calculated using the supply air outlet mass flow rate, the enthalpy of the supply outlet and exhaust inlet air streams, and the HVAC system time step. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are summed for the time step being reported.

Field: Stand Alone ERV Zone Sensible Cooling Rate [W]

This output is the sensible cooling rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone. This value is calculated using the supply air outlet mass flow rate, and the enthalpy of the supply outlet and exhaust inlet air streams at a constant humidity ratio. This value is calculated for each HVAC system time step being simulated, and the results (cooling only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Sensible Cooling Energy [J]

This output is the sensible cooling energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported. This value is calculated using the supply air outlet mass flow rate, the enthalpy of the supply outlet and exhaust inlet air streams at a constant humidity ratio, and the HVAC system time step. This value is calculated for each HVAC system time step being simulated, and the results (cooling only) are summed for the time step being reported.

Field: Stand Alone ERV Zone Sensible Heating Rate [W]

This output is the sensible heating rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone. This value is calculated using the supply air outlet mass flow rate, and the enthalpy of the supply outlet and exhaust inlet air streams at a constant humidity ratio. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Sensible Heating Energy [J]

This output is the sensible heating energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported. This value is calculated using the supply air outlet mass flow rate, the enthalpy of the supply outlet and exhaust inlet air streams at a constant humidity ratio, and the HVAC system time step. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are summed for the time step being reported.

Field: Stand Alone ERV Zone Latent Cooling Rate [W]

This output is the latent cooling rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone. This value is calculated as the difference between the Stand Alone ERV Zone Total Cooling Rate and the Stand Alone ERV Zone Sensible Cooling Rate. This value is calculated for each HVAC system time step being simulated, and the results (cooling only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Latent Cooling Energy [J]

This output is the latent cooling energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported. This value is calculated as the difference between the Stand Alone ERV Zone Total Cooling Energy and the Stand Alone ERV Zone Sensible Cooling Energy. This value is calculated for each HVAC system time step being simulated, and the results (cooling only) are summed for the time step being reported.

Field: Stand Alone ERV Zone Latent Heating Rate [W]

This output is the latent heating rate (in Watts) supplied by the stand alone energy recovery ventilator to the zone (humidification). This value is calculated as the difference between the Stand Alone ERV Zone Total Heating Rate and the Stand Alone ERV Zone Sensible Heating Rate. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are averaged for the time step being reported.

Field: Stand Alone ERV Zone Latent Heating Energy [J]

This output is the latent heating energy (in Joules) supplied by the stand alone energy recovery ventilator to the zone for the time step being reported (humidification). This value is calculated as the difference between the Stand Alone ERV Zone Total Heating Energy and the Stand Alone ERV Zone Sensible Heating Energy. This value is calculated for each HVAC system time step being simulated, and the results (heating only) are summed for the time step being reported.

Engineering Document for Energy Recovery Ventilator:Stand Alone

The stand alone energy recovery ventilator (ERV) is a single-zone HVAC component used for exhaust air heat recovery (see figure below). This compound object consists of 3 required components: a generic air-to-air heat exchanger (see object Heat Exchanger:Air to Air:Generic), a supply air fan, and an exhaust air fan (see object Fan:Simple:OnOff). An optional controller (see object Controller:Stand Alone ERV) may be used to simulate economizer (free cooling) operation.

Figure 5. Schematic of the Energy Recovery Ventilator:Stand Alone compound object

This compound object models the basic operation of supply and exhaust air fans and an air-to-air heat exchanger. The stand alone ERV operates whenever the unit is scheduled to be available (Availability schedule). The stand alone ERV object can be used in conjunction with an economizer feature whereby heat exchange is suspended whenever free cooling is available (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped).

To model a stand alone ERV connected to a single zone, the input data file should include the following objects:

- ENERGY RECOVERY VENTILATOR:STAND ALONE
- HEAT EXCHANGER:AIR TO AIR:GENERIC
- FAN:SIMPLE:ONOFF (supply air)
- FAN:SIMPLE:ONOFF (exhaust air)
- CONTROLLER:STAND ALONE ERV (if economizer [free cooling] operation is desired)
- SET POINT MANAGER:SCHEDULED (if supply air outlet temperature control is used, Ref. Heat Exchanger:Air to Air:Generic for additional guidance)
- CONTROLLED ZONE EQUIP CONFIGURATION
- ZONE EQUIPMENT LIST
- OUTSIDE AIR INLET NODE LIST

Model Description

The purpose of this compound component is to simply call the individual component models and optional controller for each energy recovery ventilator. Since this equipment is not associated with an air loop, the compound object sets the supply and exhaust air mass flow rates through the ventilator. This compound object is also used to report the total, sensible and latent energy supplied to the zone, as well as the total electrical energy consumed by all of the individual components (supply air fan, exhaust air fan and heat exchanger parasitics).

During each simulation time step, the air mass flow rate at the supply air and exhaust air inlets is set based on the stand alone ERV's availability schedule and the specified volumetric air flow rates as follows:

IF (availability schedule value > 0) THEN

$$\dot{m}_{Supply} = \dot{rV}_{Supply}$$

$$\dot{m}_{Exhaust} = \dot{rV}_{Exhaust}$$

ELSE

$$\dot{m}_{Supply} = \dot{m}_{Exhaust} = 0.0$$

where:

$$\dot{m}_{Supply} = \text{mass flow rate of the supply air stream, kg/s}$$

$$\dot{m}_{Exhaust} = \text{mass flow rate of the exhaust air stream, kg/s}$$

ρ = density of dry air at local barometric pressure (adjusted for altitude) and 20 °C, kg/m³

$\dot{V}_{Supply}$ = volumetric flow rate of the supply air stream, m³/s

$\dot{V}_{Exhaust}$ = volumetric flow rate of the exhaust air stream, m³/s

With the supply and exhaust inlet air mass flow rates set, the compound object then calls the generic air-to-air heat exchanger model to determine its supply air and exhaust air exiting conditions based on the inputs specified in the heat exchanger object. The supply air and exhaust air fans are then modeled to determine the final conditions of the air streams exiting the stand alone energy recovery ventilator. The heat exchanger and fan models are described in detail elsewhere in this document (reference: Heat Exchanger:Air to Air:Generic and Fan:Simple:OnOff).

The sensible heat transfer rate to the zone by the stand alone ventilator is then calculated as follows:

$$\dot{Q}_{Sensible} = \dot{m}_{Supply} (h_{SupplyOutlet} - h_{ExhaustInlet})_{HR\ min}$$

where:

$\dot{Q}_{Sensible}$ = sensible energy transfer rate to the zone, W

$\dot{m}_{Supply}$ = mass flow rate of the supply air stream, kg/s

$h_{SupplyOutlet}$ = enthalpy of the air being supplied to the zone, J/kg

$h_{ExhaustInlet}$ = enthalpy of the air being exhausted from the zone through the ventilator, J/kg

HR_{min} = enthalpies evaluated at a constant humidity ratio, the minimum humidity ratio of the supply air outlet or the exhaust air inlet

The resulting sensible energy transfer rate is passed to the zone equipment manager and added to the zone load to be met by other heating or cooling equipment. Since the stand alone ERV is intended to reduce the outdoor air load through heat exchange and not meet that load completely, the stand alone heat exchanger must be modeled first in the list of zone equipment. This is accomplished by setting the stand alone ERV priority for cooling and heating higher than that of other zone cooling or heating equipment (reference: ZONE EQUIPMENT LIST).

When economizer (free cooling) operation is desired, a controller is coupled to the stand alone ERV by providing the name of the controller object in the ERV Controller input field. This controller determines when the air-side economizer is active (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped) based on the controller inputs (Ref. Controller:Stand Alone ERV).

At the end of each HVAC simulation time step, this compound object reports the heating or cooling rate and energy delivered to the zone, as well as the electric power and consumption by the ventilator. In terms of thermal energy delivered to the zone, the sensible, latent and total energy transfer rate to the zone is calculated as follows:

$$\dot{Q}_{Total} = \dot{m}_{Supply} (h_{SupplyOutlet} - h_{ExhaustInlet})$$

$$\dot{Q}_{Sensible} = \dot{m}_{Supply} (h_{SupplyOutlet} - h_{ExhaustInlet})_{HR\ min}$$

$$\dot{Q}_{Latent} = \dot{Q}_{Total} - \dot{Q}_{Sensible}$$

where:

$$\dot{Q}_{Total} = \text{total energy transfer rate to the zone, W}$$

$$\dot{Q}_{Sensible} = \text{sensible energy transfer rate to the zone, W}$$

$$\dot{Q}_{Latent} = \text{latent energy transfer rate to the zone, W}$$

$$\dot{m}_{Supply} = \text{mass flow rate of the supply air stream, kg/s}$$

$$h_{SupplyOutlet} = \text{enthalpy of the air being supplied to the zone, J/kg}$$

$$h_{ExhaustInlet} = \text{enthalpy of the air being exhausted from the zone through the ventilator, J/kg}$$

$$HR_{min} = \text{enthalpies evaluated at a constant humidity ratio, the minimum humidity ratio of the supply air outlet or the exhaust air inlet}$$

Since each of these energy transfer rates can be calculated as positive or negative values, individual reporting variables are established for cooling and heating and only positive values are reported. The following calculations are representative of what is done for each of the energy transfer rates:

IF ($\dot{Q}_{Total} < 0.0$) THEN

$$\dot{Q}_{TotalCooling} = \text{ABS} (\dot{Q}_{Total})$$

$$\dot{Q}_{TotalHeating} = 0.0$$

ELSE

$$\dot{Q}_{TotalCooling} = 0.0$$

$$\dot{Q}_{TotalHeating} = \dot{Q}_{Total}$$

where:

$$\dot{Q}_{TotalCooling} = \text{output variable 'Stand Alone ERV Zone Total Cooling Rate, W'}$$

$$\dot{Q}_{TotalHeating} = \text{output variable 'Stand Alone ERV Zone Total Heating Rate, W'}$$

In addition to heating and cooling rates, the heating and cooling energy supplied to the zone is also calculated for the time step being reported. The following example for total cooling

energy is representative of what is done for the sensible and latent energy as well as the heating counterparts.

$$\dot{Q}_{TotalCooling} = \dot{Q}_{TotalCooling} * TimeStepSys * 3600.$$

where:

$\dot{Q}_{TotalCooling}$ = output variable 'Stand Alone ERV Zone Total Cooling Energy, J'

$TimeStepSys$ = HVAC system simulation time step, hr

Input Output Reference for Controller:Stand Alone ERV

This controller object is used exclusively by the stand alone energy recovery ventilator (ENERGY RECOVERY VENTILATOR:STAND ALONE,

Figure 6). The purpose of this controller is to simulate economizer operation for the stand alone ERV and provide free cooling whenever possible. If all of the limits are satisfied, the controller activates economizer mode (fully bypassing the fixed-plate air-to-air heat exchanger or stopping the rotation of a rotary heat exchanger). If any of the selected limits are exceeded, economizer operation is terminated.

Figure 6. Schematic of the Energy Recovery Ventilator:Stand Alone compound object

Field: ERV controller name

A unique user-assigned name for the stand alone ERV controller. Any reference to this controller by another object will use this name.

Field: Outside air flow rate

The outside (supply) air flow rate in cubic meters per second. This value should match the supply air flow rate specified in the ENERGY RECOVERY VENTILATOR:STAND ALONE object.

Field: Temperature high limit

The input for this field is the outside air temperature high limit (°C) for economizer operation. If the outside air temperature is above this limit, economizer (free cooling) operation is terminated. The minimum value for this field is 0°C. This temperature limit is checked if the input value is greater than to 0°C. If this input field is set equal to 0°C this limit is not checked.

Field: Temperature low limit

The input for this field is the outside air temperature low limit (°C) for economizer operation. If the outside air temperature is below this limit, economizer (free cooling) operation is terminated. The minimum value for this field is 0°C. This temperature limit is checked if the input value is greater than to 0°C. If this input field is set equal to 0°C this limit is not checked.

Field: Enthalpy high limit

The input for this field is the outside air enthalpy limit (in J/kg) for economizer operation. If the outside air enthalpy is above this value, economizer (free cooling) operation is terminated. The minimum value for this field is 0.0 J/kg. This limit is checked if the input value is greater than to 0.0 J/kg. If this input field is set equal to 0.0 J/kg this limit is not checked.

Field: Supply air inlet node name

The name of the HVAC system node from which the Stand Alone ERV object draws its supply inlet air. This node must be an outdoor air node (defined in an OUTSIDE AIR INLET NODE LIST) and the name must match the supply air inlet node name specified in the object ENERGY RECOVERY VENTILATOR: STAND ALONE.

Field: Exhaust air inlet node name

The name of the HVAC system node from which the ENERGY RECOVERY VENTILATOR: STAND ALONE object draws its exhaust inlet air. This name must match the exhaust air inlet node name specified in the object ENERGY RECOVERY VENTILATOR: STAND ALONE

Field: Exhaust air temperature limit

This input establishes whether or not there is a limit control on the exhaust air temperature. The choices are EXHAUST AIR TEMP LIMIT or NO EXHAUST AIR TEMP LIMIT. If EXHAUST AIR TEMP LIMIT is chosen, the controller deactivates economizer mode whenever the outside air temperature is greater than the exhaust air temperature. If NO EXHAUST AIR TEMP LIMIT is chosen, no limit check on the exhaust air temperature is performed.

Field: Exhaust air enthalpy limit

This input establishes whether or not there is a limit control on the exhaust air enthalpy. The choices are EXHAUST AIR ENTHALPY LIMIT or NO EXHAUST AIR ENTHALPY LIMIT. If EXHAUST AIR ENTHALPY LIMIT is chosen, the controller deactivates economizer mode whenever the outside air enthalpy is greater than the exhaust air enthalpy. If NO EXHAUST AIR ENTHALPY LIMIT is chosen, no limit check on the exhaust air enthalpy is performed.

The full IDD specification follows:

```

CONTROLLER:STAND ALONE ERV,
    \memo This controller is used exclusively by the object ENERGY RECOVERY VENTILATOR:STAND ALONE
    \memo to allow economizer (free cooling) operation when possible.
    \min-fields 7
A1 , \field ERV controller name
    \required-field
    \type alpha
N1 , \field Outside air flow rate
    \required-field
    \type real
    \units m3/s
    \minimum> 0
N2 , \field Temperature high limit
    \required-field
    \units C
    \minimum 0.0
    \default 0.0
    \note Value set to zero means this limit is not checked.
N3 , \field Temperature low limit
    \units C
    \minimum 0.0
    \default 0.0
    \note Value set to zero means this limit is not checked.
N4 , \field Enthalpy high limit
    \units J/kg
    \minimum 0.0
    \default 0.0
    \note Value set to zero means this limit is not checked.
A2 , \field Supply air inlet node name
    \required-field
    \type alpha
A3 , \field Exhaust air inlet node name
    \required-field
    \type alpha
A4 , \field Exhaust air temperature limit
    \type choice
    \key EXHAUST AIR TEMP LIMIT
    \key NO EXHAUST AIR TEMP LIMIT
    \default NO EXHAUST AIR TEMP LIMIT
A5 , \field Exhaust air enthalpy limit
    \type choice
    \key EXHAUST AIR ENTHALPY LIMIT
    \key NO EXHAUST AIR ENTHALPY LIMIT
    \default NO EXHAUST AIR ENTHALPY LIMIT

```

Following is an example input for this heat exchanger object:

```

CONTROLLER:STAND ALONE ERV,
    ERV OA Controller 1,           !- ERV controller name
    0.05,                          !- Outside air flow rate {m3/s}
    19.,                           !- Temperature high limit {C}
    14.,                           !- Temperature low limit {C}
    0.0,                           !- Enthalpy high limit {J/kg}
    ERV Outside Air Inlet Node,    !- Supply air inlet node name
    Zone 1 Exhaust Node,          !- Exhaust air inlet node name
    NO EXHAUST AIR TEMP LIMIT,     !- Exhaust air temperature limit
    NO EXHAUST AIR ENTHALPY LIMIT; !- Exhaust air enthalpy limit

```

Engineering Document for Controller:Stand Alone ERV

The stand alone energy recovery ventilator (ERV) controller is used solely in conjunction with a stand alone energy recovery ventilator (see figure below).

Figure 7. Schematic of the Energy Recovery Ventilator:Stand Alone compound object

This controller object mimics virtually all of the control logic available for a conventional air-side economizer as embodied in the object Controller:Outside Air. However, this controller only signals the object Heat Exchanger:Air to Air:Generic that favorable conditions are available for free cooling and heat exchange should be suspended (i.e., air flow is fully bypassed around a fixed-plate heat exchanger or the rotation of a rotary heat exchanger is stopped). The air flow rate through the stand alone ERV remains the same regardless of whether the controller is signaling for economizer (free cooling) operation or not. In this way, this controller is very similar to Controller:Outside Air with the field EconomizerChoice set to "BYPASS". However, this controller is only used with the stand alone energy recovery ventilator object (dedicated to serving a single zone, without a traditional air distribution system) while the Controller:Outside Air is used with systems that utilize an air loop to provide conditioned air to one or more zones.

Controller Logic

In many ways, the logic for this controller follows that established for the object Controller:Outside Air. Nearly the same computations (source code) are used for this controller as for Controller:Outside Air, except the addition of a few calculations that are unique for this stand alone ERV controller. In some instances local variables used in the Controller:Outside air computations are set to specific values for Controller:Stand Alone ERV to allow the same computations and logic to be used for both controllers. The logic that is being applied for Controller:Stand Alone ERV is presented below.

As explained above the controller senses when air conditions are such that heat exchange by the air-to-air heat exchanger should be suspended to provide free cooling to the zone, thereby reducing the amount of mechanical cooling that needs to be provided by other equipment. The inputs for this controller specify temperature and/or enthalpy conditions that are used to trigger economizer operation.

The user can enter a high and low temperature limit for economizer operation. When the supply inlet (outdoor) air is between these two values, heat exchange is suspended while air flow rates remain unchanged. This logic represents a conventional single-point temperature economizer control. If the user wishes to model differential temperature control, EXHAUST AIR TEMP LIMIT should be specified in the proper input field. In this case, heat exchange is suspended whenever the temperature of the exhaust air is greater than the temperature of the outdoor air. The user still needs to set the low temperature limit to restart the heat exchange process when the outdoor temperature falls too low.

Similar logic can be used with air enthalpy. The user can enter a high enthalpy limit, and heat exchange between the supply and exhaust air streams will be suspended when the outdoor air enthalpy falls below this value. This logic represents single-point enthalpy economizer control. If the user wishes to model differential enthalpy control, EXHAUST AIR ENTHALPY LIMIT should be specified in the proper input field. Regardless of modeling single-point enthalpy or differential enthalpy control, the user still needs to set the low temperature limit to restart the heat exchange process when the outdoor temperature falls too low.

The model is flexible, and checks all limits established by the user in the object's input data. The model initially assumes that heat exchange should be suspended, and then checks each one of the limits that the user has set (single-point temperature control, differential temperature control, single-point enthalpy and differential point enthalpy). If any of the limits entered by the user is exceeded, then economizer operation is terminated and heat exchange between the supply and exhaust air streams is modeled:

```
EconomizerOperationFlag = TRUE
IF (Outdoor Air Temp < Temperature Low Limit) EconomizerOperationFlag = FALSE
IF (Outdoor Air Temp > Temperature High Limit) EconomizerOperationFlag = FALSE
IF (Outdoor Air Enthalpy > Enthalpy High Limit) EconomizerOperationFlag = FALSE
IF (EXHAUST AIR TEMP LIMIT .AND. Outdoor Air Temp > Exhaust Air Temp) THEN
    EconomizerOperationFlag = FALSE
IF (EXHAUST AIR ENTHALPY LIMIT .AND. Outdoor Air Enthalpy > Exhaust Air Enthalpy)
    THEN EconomizerOperationFlag = FALSE
```

Appendix C

EnergyPlus Documentation for Degradation of Cooling Coil Dehumidification at Part-Load Conditions

This appendix contains the EnergyPlus documentation (Input/Output Reference and Engineering Manual) for the cooling coil dehumidification degradation model that was added as part of this project.

Input Output Reference for Coil:DX:CoolingBypassFactorEmpirical

This DX cooling coil model and input are quite different from that for the heating and cooling water coils. The simple water coils use an NTU-effectiveness heat exchanger model. The CoolingBypassFactorEmpirical DX coil model uses performance information at rated conditions along with curve fits for variations in total capacity, energy input ratio and part-load fraction to determine performance at part-load conditions. Sensible/latent capacity splits are determined by the rated sensible heat ratio (SHR) and the apparatus dew point/bypass factor (ADP/BF) approach. This approach is analogous to the NTU-effectiveness calculations used for sensible-only heat exchanger calculations, extended to a cooling and dehumidifying coil.

The DX cooling coil input requires an availability schedule, the rated total cooling capacity, the rated SHR, the rated COP, and the rated air volume flow rate. The latter 4 inputs determine the coil performance at the rating point (air entering the cooling coil at 26.7°C drybulb/19.4°C wetbulb and air entering the outdoor condenser coil at 35°C drybulb/23.9°C wetbulb). The rated air volume flow rate should be between .00004699 m³/s and .00006041 m³/s per watt of rated total cooling capacity (350 to 450 cfm/ton).

This model requires 5 curves as follows:

1. The total cooling capacity modifier curve (function of temperature) is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The output of this curve is multiplied by the rated total cooling capacity to give the total cooling capacity at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures).
2. The total cooling capacity modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated total cooling capacity and the total cooling capacity modifier curve (function of temperature) to give the total cooling capacity at the specific temperature and air flow conditions at which the coil is operating.
3. The energy input ratio (EIR) modifier curve (function of temperature) is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The output of this curve is multiplied by the rated EIR (inverse of the rated COP) to give the EIR at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures).
4. The energy input ratio (EIR) modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated EIR (inverse of the rated COP) and the EIR modifier curve (function of temperature) to give the EIR at the specific temperature and air flow conditions at which the coil is operating.
5. The part load fraction correlation (function of part load ratio) is a quadratic or a cubic curve with the independent variable being part load ratio (sensible cooling

load / steady-state sensible cooling capacity). The output of this curve is used in combination with the rated EIR and EIR modifier curves to give the “effective” EIR for a given simulation time step. The part load fraction (PLF) correlation accounts for efficiency losses due to compressor cycling. The curve should be normalized to a value of 1.0 when the part-load ratio equals 1.0 (i.e., the compressor(s) run continuously for the simulation time step).

The curves are simply specified by name. Curve inputs are described in the curve manager section of the input output reference document.

The next input item for this DX cooling coil object is the supply air fan operation mode. Either the supply air fan runs continuously while the DX coil cycles on/off (ContFanCycComp), or the fan and coil cycle on/off together (CycFanCycComp).

The next four input fields are optional and relate to the degradation of latent cooling capacity when the supply air fan operates continuously while the cooling coil/compressor cycle on and off to meet the cooling load. The field Supply Air Fan Operation Mode must be “ContFanCycComp” and these next four input fields must have positive values in order to model latent capacity degradation.

The next input describes the type of outdoor condenser coil used with the DX cooling coil (Air Cooled or Evap Cooled). The following three inputs are required when modeling an evaporative-cooled condenser: evaporative condenser effectiveness, evaporative condenser air volume flow rate, and the power consumed by the evaporative condenser pump. Crankcase heater capacity and cutout temperature are entered as the final two inputs for this object. See section “DX Cooling Coil Model” in the EnergyPlus Engineering Document for further details regarding this model.

Field: Coil Name

A unique user-assigned name for an instance of a DX cooling coil. Any reference to this DX coil by another object will use this name.

Field: Availability Schedule

The name of the schedule (ref: Schedule) that denotes whether the DX cooling coil can run during a given time period. A schedule value greater than 0 (usually 1 is used) indicates that the unit can be on during a given time period. A value less than or equal to 0 (usually 0 is used) denotes that the unit must be off.

Field: Rated Total Cooling Capacity (gross)

The total, full load cooling capacity (sensible plus latent) in watts of the DX coil unit at rated conditions (air entering the cooling coil at 26.7°C drybulb/19.4°C wetbulb, air entering the outdoor condenser coil at 35°C drybulb/23.9°C wetbulb¹, and a cooling coil air flow rate defined by field “rated air volume flow rate” below). Capacity should be “gross” (i.e., supply air fan heat is NOT included).

Field: Rated SHR

The sensible heat ratio (sensible capacity divided by total cooling capacity) of the DX cooling coil at rated conditions (air entering the cooling coil at 26.7°C drybulb/19.4°C wetbulb, air entering the outdoor condenser coil at 35°C drybulb/23.9°C wetbulb, and a cooling coil air flow rate defined by field “rated air volume flow rate” below). Both the sensible and total cooling capacities used to define the Rated SHR should be “gross” (i.e., supply air fan heat is NOT included).

Field: Rated COP

The coefficient of performance (cooling power output in watts divided by electrical power input in watts) of the DX cooling coil unit at rated conditions (air entering the

¹ The 23.9°C wet-bulb temperature condition is not applicable for air-cooled condensers which do not evaporate condensate.

cooling coil at 26.7°C drybulb/19.4°C wetbulb, air entering the outdoor condenser coil at 35°C drybulb/ 23.9°C wetbulb, and a cooling coil air flow rate defined by field “rated air volume flow rate” below). The input power includes electric power for the compressor(s) and condenser fan(s) but does not include the power consumption of the supply air fan. The cooling power output is the value entered above in the field “Rated Total Cooling Capacity (gross)”. If this input field is left blank, the default value is 3.0.

Field: Rated Air Volume Flow Rate

The air volume flow rate, in m^3 per second, across the DX cooling coil at rated conditions. The rated air volume flow rate should be between 0.00004699 m^3/s and 0.00006041 m^3/s per watt of rated total cooling capacity (350 to 450 cfm/ton). The rated total cooling capacity, rated SHR and rated COP should be performance information for the unit with air entering the cooling coil at 26.7°C drybulb/19.4°C wetbulb, air entering the outdoor condenser coil at 35°C drybulb/23.9°C wetbulb, and the rated air volume flow rate defined here.

Field: Coil Air Inlet Node

The name of the HVAC system node from which the DX cooling coil draws its inlet air.

Field: Coil Air Outlet Node

The name of the HVAC system node to which the DX cooling coil sends its outlet air.

Field: Total Cooling Capacity Modifier Curve (function of temperature)

The name of a biquadratic performance curve (ref: Performance Curves) that parameterizes the variation of the total cooling capacity as a function of the wet-bulb temperature of the air entering the cooling coil, and the dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The output of this curve is multiplied by the rated total cooling capacity to give the total cooling capacity at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures). The curve is normalized to have the value of 1.0 at the rating point.

Field: Total Cooling Capacity Modifier Curve (function of flow fraction)

The name of a quadratic performance curve (ref: Performance Curves) that parameterizes the variation of total cooling capacity as a function of the ratio of actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated total cooling capacity and the total cooling capacity modifier curve (function of temperature) to give the total cooling capacity at the specific temperature and air flow conditions at which the coil is operating. The curve is normalized to have the value of 1.0 when the actual air flow rate equals the rated air flow rate.

Field: Energy Input Ratio Modifier Curve (function of temperature)

The name of a biquadratic performance curve (ref: Performance Curves) that parameterizes the variation of the energy input ratio (EIR) as a function of the wet-bulb temperature of the air entering the cooling coil, and the dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The EIR is the inverse of the COP. The output of this curve is multiplied by the rated EIR (inverse of rated COP) to give the EIR at specific temperature operating conditions (i.e., at temperatures different from the rating point temperatures). The curve is normalized to a value of 1.0 at the rating point.

Field: Energy Input Ratio Modifier Curve (function of flow fraction)

The name of a quadratic performance curve (Ref: Performance Curves) that parameterizes the variation of the energy input ratio (EIR) as a function of the ratio of actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The EIR is the inverse of the COP. The output of this curve is multiplied by the rated EIR and the EIR modifier curve (function of temperature) to give the EIR at the specific temperature and air flow conditions at which the cooling coil is operating. This curve is normalized to a value of 1.0 when the actual air flow rate equals the rated air flow rate.

Field: Part Load Fraction Correlation (function of part load ratio)

This alpha field defines the name of a quadratic or cubic performance curve (Ref: Performance Curves) that parameterizes the variation of electrical power input to the DX unit as a function of the part load ratio (PLR, sensible cooling load/steady-state sensible cooling capacity). The product of the rated EIR and EIR modifier curves is divided by the output of this curve to give the “effective” EIR for a given simulation time step. The part load fraction (PLF) correlation accounts for efficiency losses due to compressor cycling.

The part load fraction correlation should be normalized to a value of 1.0 when the part load ratio equals 1.0 (i.e., no efficiency losses when the compressor(s) run continuously for the simulation time step). For PLR values between 0 and 1 ($0 \leq \text{PLR} < 1$), the following rules apply:

$$\text{PLF} \geq 0.7 \quad \text{and} \quad \text{PLF} \geq \text{PLR}$$

If $\text{PLF} < 0.7$ a warning message is issued, the program resets the PLF value to 0.7, and the simulation proceeds. The runtime fraction of the coil is defined as PLR/PLF . If $\text{PLF} < \text{PLR}$, then a warning message is issued and the runtime fraction of the coil is limited to 1.0.

A typical part load fraction correlation for a conventional, single-speed DX cooling coil (e.g., residential unit) would be:

$$\text{PLF} = 0.75 + 0.25(\text{PLR})$$

If the user wishes to model no efficiency degradation due to compressor cycling, the part load fraction correlation should be defined as follows:

$$\text{PLF} = 1.0 + 0.0(\text{PLR})$$

Field: Supply Air Fan Operation Mode

This input field has two choices: CycFanCycComp or ContFanCycComp. The first choice stands for “cycling fan cycling compressor”. This means that the unit unloads by cycling both the fan and compressor; that is, both the supply air fan and the DX coil unit compressor cycle on and off together to meet the load. The second choice stands for “continuous fan cycling compressor”. The supply air fan runs continuously while the DX coil unit compressor cycles.

Field: Nominal Time for Condensate Removal to Begin

The nominal time (in seconds) after startup for condensate to begin leaving the coil's condensate drain line at the coil's rated airflow and temperature conditions, starting with a dry coil. Nominal time is equal to the ratio of the energy of the coil's maximum condensate holding capacity (J) to the coil's steady-state latent capacity (W). Suggested value is 1000; zero value means the latent degradation model is disabled. The default value for this field is zero. The field Supply Air Fan Operation Mode must be “ContFanCycComp”, and this field as well as the next three input fields for this object must have positive values in order to model latent capacity degradation.

Field: Ratio of Initial Moisture Evaporation Rate and Steady-state Latent Capacity

Ratio of the initial moisture evaporation rate from the cooling coil (when the compressor first turns off, in Watts) and the coil's steady-state latent capacity (Watts) at rated airflow and temperature conditions. Suggested value is 1.5; zero value means the latent degradation model is disabled. The default value for this field is zero. The field Supply Air Fan Operation Mode must be "ContFanCycComp"; and this field, the previous field and the next two fields must have positive values in order to model latent capacity degradation.

Field: Maximum ON/OFF Cycling Rate

The maximum on-off cycling rate for the compressor (cycles per hour), which occurs at 50% run time fraction. Suggested value is 3; zero value means latent degradation model is disabled. The default value for this field is zero. The field Supply Air Fan Operation Mode must be "ContFanCycComp"; and this field, the previous two fields and the next field must have positive values in order to model latent capacity degradation.

Field: Latent Capacity Time Constant

Time constant (in seconds) for the cooling coil's latent capacity to reach steady state after startup. Suggested value is 45; zero value means latent degradation model is disabled. The default value for this field is zero. The field Supply Air Fan Operation Mode must be "ContFanCycComp", and this field as well as the previous three input fields for this object must have positive values in order to model latent capacity degradation.

Field: Condenser Type

The type of condenser used by the DX cooling coil. Valid choices for this input field are Air Cooled or Evap Cooled. The default for this field is Air Cooled.

Field: Evaporative Condenser Effectiveness

The effectiveness of the evaporative condenser, which is used to determine the temperature of the air entering the outdoor condenser coil as follows:

$$T_{condinlet} = (T_{wb,o}) + (1 - EvapCondEffectiveness)(T_{db,o} - T_{wb,o})$$

where

$T_{cond\ inlet}$ = the temperature of the air entering the condenser coil (C)

$T_{wb,o}$ = the wet-bulb temperature of the outdoor air (C)

$T_{db,o}$ = the dry-bulb temperature of the outdoor air (C)

The resulting condenser inlet air temperature is used by the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature). The default value for this field is 0.9, although valid entries can range from 0.0 to 1.0. This field is not used when Condenser Type = Air Cooled.

If the user wants to model an air-cooled condenser, they should simply specify AIR COOLED in the field Condenser Type. In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) input fields for this object should reference performance curves that are a function of outdoor dry-bulb temperature.

If the user wishes to model an evaporative-cooled condenser AND they have performance curves that are a function of the wet-bulb temperature of air entering the condenser coil, then the user should specify Condenser Type = Evap Cooled and the evaporative condenser effectiveness value should be entered as 1.0. In this case, the

Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) input fields for this object should reference performance curves that are a function of the wet-bulb temperature of air entering the condenser coil.

If the user wishes to model an air-cooled condenser that has evaporative media placed in front of it to cool the air entering the condenser coil, then the user should specify Condenser Type = Evap Cooled. The user must also enter the appropriate evaporative effectiveness for the media. In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) input fields for this object should reference performance curves that are a function of outdoor dry-bulb temperature. Be aware that the evaporative media will significantly reduce the dry-bulb temperature of the air entering the condenser coil, so the Total Cooling Capacity and EIR Modifier Curves must be valid for the expected range of dry-bulb temperatures that will be entering the condenser coil.

Field: Evaporative Condenser Air Volume Flow Rate

The air volume flow rate, in m^3 per second, entering the evaporative condenser. This value is used to calculate the amount of water used to evaporatively cool the condenser inlet air. The minimum value for this field must be greater than zero, and this input field is autosizable (equivalent to $0.000144 \text{ m}^3/\text{s}$ per watt of rated total cooling capacity [850 cfm/ton]). This field is not used when Condenser Type = Air Cooled.

Field: Evaporative Condenser Pump Rated Power Consumption

The rated power of the evaporative condenser water pump in Watts. This value is used to calculate the power required to pump the water used to evaporatively cool the condenser inlet air. The default value for this input field is zero, but it is autosizable (equivalent to 0.004266 W per watt [15 W/ton] of rated total cooling capacity). This field is not used when Condenser Type = Air Cooled.

Field: Crankcase Heater Capacity

This numeric field defines the crankcase heater capacity in Watts. When the outdoor air dry-bulb temperature is below the value specified in the input field "Maximum Outdoor Dry-bulb Temperature for Crankcase Heater Operation" (described below), the crankcase heater is enabled during the time that the compressor is not running. If this cooling coil is used as part of an air-to-air heat pump (Ref. UnitarySystem:HeatPump:AirToAir), the crankcase heater defined for this DX cooling coil is ignored and the crankcase heater power defined for the DX heating coil (Ref. Coil:DX:HeatingEmpirical) is enabled during the time that the compressor is not running for either heating or cooling. The value for this input field must be greater than or equal to 0, and the default value is 0. To simulate a DX cooling coil without a crankcase heater, enter a value of 0.

Field: Maximum Outdoor Dry-bulb Temperature for Crankcase Heater Operation

This numeric field defines the outdoor air dry-bulb temperature above which the compressor's crankcase heater is disabled. The value for this input field must be greater than or equal to 0.0°C , and the default value is 10°C .

Below is the input data dictionary description for the CoolingBypassFactorEmpirical DX coil.

```

COIL:DX:CoolingBypassFactorEmpirical,
  \min-fields 14
  A1 , \field Coil Name
        \required-field
        \type alpha
  A2 , \field Availability Schedule
        \required-field
        \type object-list
        \object-list ScheduleNames
  N1 , \field Rated Total Cooling Capacity (gross)
        \required-field
        \type real
        \units W
        \minimum> 0.0
        \autosizable
        \note gross capacity excluding supply air fan heat
        \note rating point: air entering the cooling coil at 26.7 C drybulb/19.4 C wetbulb, and
        \note air entering the outdoor condenser coil at 35 C drybulb/23.9 C wetbulb
  N2 , \field Rated SHR
        \required-field
        \type real
        \minimum 0.5
        \maximum 1.0
        \autosizable
        \note rated sensible heat ratio (gross sensible capacity/gross total capacity)
        \note sensible and total capacities do not include supply fan heat
  N3 , \field Rated COP
        \type real
        \minimum> 0.0
        \default 3.0
        \note does not include supply fan heat or supply fan electrical energy input
  N4 , \field Rated Air Volume Flow Rate
        \required-field
        \type real
        \units m3/s
        \minimum> 0.0
        \autosizable
        \note volume flow rate corresponding to Rated total cooling capacity, Rated SHR and Rated COP
        \note should be between 0.00004699 m3/s and .00006041 m3/s per watt of rated total cooling
capacity
  A3 , \field Coil Air Inlet Node
        \required-field
        \type alpha
  A4 , \field Coil Air Outlet Node
        \required-field
        \type alpha
  A5 , \field Total Cooling Capacity Modifier Curve (function of temperature)
        \required-field
        \type object-list
        \object-list BiquadraticCurves
        \note curve = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb
        \note wb = entering wetbulb temperature (C)
        \note edb = drybulb temperature seen by the condenser (C)
  A6 , \field Total Cooling Capacity Modifier Curve (function of flow fraction)
        \required-field
        \type object-list
        \object-list QuadraticCurves
        \note curve = a + b*ff + c*ff**2
        \note ff = fraction of the full load flow
  A7 , \field Energy Input Ratio Modifier Curve (function of temperature)
        \required-field
        \type object-list
        \object-list BiquadraticCurves
        \note curve = a + b*wb + c*wb**2 + d*edb + e*edb**2 + f*wb*edb
        \note wb = entering wetbulb temperature (C)
        \note edb = drybulb temperature seen by the condenser (C)
  A8 , \field Energy Input Ratio Modifier Curve (function of flow fraction)
        \required-field
        \type object-list
        \object-list QuadraticCurves
        \note curve = a + b*ff + c*ff**2

```

```

\ note ff = fraction of the full load flow
A9 , \field Part Load Fraction Correlation (function of part load ratio)
\required-field
\type object-list
\object-list Quadratic_CubicCurves
\ note quadratic curve =  $a + b \cdot \text{PLR} + c \cdot \text{PLR}^2$ 
\ note cubic curve =  $a + b \cdot \text{PLR} + c \cdot \text{PLR}^2 + d \cdot \text{PLR}^3$ 
\ note PLR = part load ratio (cooling load/steady-state capacity)
A10, \field Supply Air Fan Operation Mode
\required-field
\type choice
\key CycFanCycComp
\key ContFanCycComp
N5, \field Nominal Time for Condensate Removal to Begin
\type real
\units s
\minimum 0.0
\maximum 3000.0
\default 0.0
\ note The nominal time for condensate to begin leaving the coil's condensate
\ note drain line at the coil's rated airflow and temperature conditions.
\ note Nominal time is equal to the ratio of the energy of the coil's maximum
\ note condensate holding capacity (J) to the coil's steady-state latent capacity (W).
\ note Suggested value is 1000; zero value means latent degradation model is disabled.
N6, \field Ratio of Initial Moisture Evaporation Rate and Steady-state Latent Capacity
\type real
\units dimensionless
\minimum 0.0
\maximum 5.0
\default 0.0
\ note Ratio of the initial moisture evaporation rate from the cooling coil (when
\ note the compressor first turns off) and the coil's steady-state latent capacity
\ note at rated airflow and temperature conditions. Suggested value is 1.5; zero value
\ note means latent degradation model is disabled.
N7, \field Maximum ON/OFF Cycling Rate
\type real
\units cycles/hr
\minimum 0.0
\maximum 5.0
\default 0.0
\ note The maximum on-off cycling rate for the compressor, which occurs at 50% run time
\ note fraction. Suggested value is 3; zero value means latent degradation model is disabled.
N8, \field Latent Capacity Time Constant
\type real
\units s
\minimum 0.0
\maximum 500.0
\default 0.0
\ note Time constant for the cooling coil's latent capacity to reach steady state after
\ note startup. Suggested value is 45; zero value means latent degradation model is disabled.
A11, \field Condenser Type
\type choice
\key AIR COOLED
\key EVAP COOLED
\default AIR COOLED
N9, \field Evaporative Condenser Effectiveness
\type real
\units dimensionless
\minimum 0.0
\maximum 1.0
\default 0.9
N10, \field Evaporative Condenser Air Volume Flow Rate
\type real
\units m3/s
\minimum> 0.0
\autosizable
\ note Used to calculate evaporative condenser water use
N11, \field Evaporative Condenser Pump Rated Power Consumption
\type real
\units W
\minimum 0.0

```

```

\default 0.0
\autosizable
\note Rated power consumed by the evaporative condenser's water pump
N12, \field Crankcase Heater Capacity
\type real
\minimum 0.0
\default 0.0
\units W
\ip-units W
N13; \field Maximum Outdoor Dry-bulb Temperature for Crankcase Heater Operation
\type real
\minimum 0.0
\default 10.0
\units C

```

Following is an example input for a CoolingBypassFactorEmpirical DX coil.

```

COIL:DX:CoolingBypassFactorEmpirical,
Zone1WindACDXCoil,          ! Coil Name
FanAndCoilAvailSched,       ! Availability Schedule
10548,                       ! Rated Total Cooling Capacity (gross)
0.75,                        ! Rated SHR
3.0,                         ! Rated COP
0.637,                       ! Rated Air Volume Flow Rate (m3/s)
Zone1WindACFanOutletNode,    ! Coil Air Inlet Node
Zone1WindACAirOutletNode,    ! Coil Air Outlet Node
WindACCoolCapFT,             ! Total Cooling Capacity Modifier Curve (function of temperature)
WindACCoolCapFFF,            ! Total Cooling Capacity Modifier Curve (function of flow fraction)
WindACEIRFT,                 ! Energy Input Ratio Modifier Curve (function of temperature)
WindACEIRFFF,                ! Energy Input Ratio Modifier Curve (function of flow fraction)
WindACPLFFPLR,               ! Part Load Fraction Correlation (function of part load ratio)
ContFanCycComp,              ! Supply Air Fan Operation Mode
1000.,                       ! Nominal Time for Condensate Removal to Begin {s}
1.5,                          ! Ratio of Initial Moisture Evaporation Rate and Steady-state Latent Capacity
3.0,                          ! Maximum ON/OFF Cycling Rate {cycles/hr}
45.0,                         ! Latent Capacity Time Constant {s}
AIR COOLED,                  ! Condenser Type
,                             ! Evaporative Condenser Effectiveness
,                             ! Evaporative Condenser Air Volume Flow Rate {m3/s}
,                             ! Evaporative Condenser Pump Rated Power Consumption {W}
30.,                          ! Crankcase Heater Capacity {W}
10.;                          ! Maximum Outdoor Dry-bulb Temperature for Crankcase Heater Operation {C}

```

DX Cooling Coil Outputs

```

HVAC,Average,DX Coil Total Cooling Rate[W]
HVAC,Sum,DX Coil Total Cooling Energy[J]
HVAC,Average,DX Coil Sensible Cooling Rate[W]
HVAC,Sum,DX Coil Sensible Cooling Energy[J]
HVAC,Average,DX Coil Latent Cooling Rate[W]
HVAC,Sum,DX Coil Latent Cooling Energy[J]
HVAC,Average,DX Cooling Coil Electric Power[W]
HVAC,Sum,DX Cooling Coil Electric Consumption[J]
HVAC,Average,DX Cooling Coil Runtime Fraction

If not part of UnitarySystem:HeatPump:AirToAir:
HVAC,Average,DX Cooling Coil Crankcase Heater Power[W]
HVAC,Sum,DX Cooling Coil Crankcase Heater Consumption[J]

Evaporative-cooled condenser:
HVAC,Average,DX Cooling Coil Condenser Inlet Temp[C]
HVAC,Average,DX Cooling Coil Evap Condenser Water Consumption[m3]
HVAC,Average,DX Cooling Coil Evap Condenser Pump Electric Power[W]
HVAC,Sum,DX Cooling Coil Evap Condenser Pump Electric Consumption[J]

```

Field: DX Coil Total Cooling Rate [W]

This field is the total (sensible and latent) cooling rate output of the DX coil in Watts. This is determined by the coil inlet and outlet air conditions and the air mass flow rate through the coil.

Field: DX Coil Total Cooling Energy [J]

This is the total (sensible plus latent) cooling output of the DX coil in Joules over the time step being reported. This is determined by the coil inlet and outlet air conditions and the air mass flow rate through the coil. This output is also added to a report meter with Resource Type = EnergyTransfer, End Use Key = CoolingCoils, Group Key = System (Ref. Report Meter).

Field: DX Coil Sensible Cooling Rate [W]

This output is the moist air sensible cooling rate output of the DX coil in Watts. This is determined by the inlet and outlet air conditions and the air mass flow rate through the coil.

Field: DX Coil Sensible Cooling Energy [J]

This is the moist air sensible cooling output of the DX coil in Joules for the time step being reported. This is determined by the inlet and outlet air conditions and the air mass flow rate through the coil.

Field: DX Coil Latent Cooling Rate [W]

This is the latent cooling rate output of the DX coil in Watts. This is determined by the inlet and outlet air conditions and the air mass flow rate through the coil.

Field: DX Coil Latent Cooling Energy [J]

This is the latent cooling output of the DX coil in Joules for the time step being reported. This is determined by the inlet and outlet air conditions and the air mass flow rate through the coil.

Field: DX Cooling Coil Electric Power [W]

This output is the electricity consumption rate of the DX coil compressor and condenser fan(s) in Watts.

Field: DX Cooling Coil Electric Consumption [J]

This is the electricity consumption of the DX coil compressor and condenser fan(s) in Joules for the time step being reported. This output is also added to a report meter with Resource Type = Electricity, End Use Key = Cooling, Group Key = System (Ref. Report Meter).

Field: DX Cooling Coil Runtime Fraction

This is the runtime fraction of the DX coil compressor and condenser fan(s) for the time step being reported.

Field: DX Cooling Coil Crankcase Heater Power[W]

This is the average electricity consumption rate of the DX coil compressor's crankcase heater in Watts for the time step being reported.

Field: DX Cooling Coil Crankcase Heater Consumption[J]

This is the electricity consumption of the DX coil compressor's crankcase heater in Joules for the time step being reported. This output is also added to a report meter with Resource Type = Electricity, End Use Key = Cooling, Group Key = System (ref. Report Meter).

Field: Cooling Coil Condenser Inlet Temp [C]

This is the inlet air temperature to the condenser coil in degrees C. This value can represent the outdoor air dry-bulb temperature, wet-bulb temperature, or somewhere in between from the weather data being used, depending on the value used in the input field "Evaporative Condenser Effectiveness". The temperature reported here is used in the various modifier curves related to temperature (e.g., Total Cooling Capacity Modifier Curve [function of temperature]).

Field: DX Cooling Coil Evap Condenser Water Consumption [m3]

This output is the amount of water used to evaporatively cool the condenser coil inlet air, in cubic meters. This output is also added to a report meter with Resource Type = Water, End Use Key = Cooling, Group Key = System (ref. Report Meter).

Field: DX Cooling Coil Evap Condenser Pump Electric Power [W]

This is the average electricity consumption rate of the evaporative condenser water pump in Watts for the time step being reported.

Field: DX Cooling Coil Evap Condenser Pump Electric Consumption [J]

This is the electricity consumption rate of the evaporative condenser water pump in Joules for the time step being reported. This output is also added to a report meter with Resource Type = Electricity, End Use Key = Cooling, Group Key = System (ref. Report Meter).

Engineering Document for the Direct Expansion (DX) Cooling Coil Model

Overview

This model (object name Coil:DX:CoolingBypassFactorEmpirical) simulates the performance of an air-cooled or evaporative-cooled direct expansion (DX) air conditioner. The model uses performance information at rated conditions along with curve fits for variations in total capacity, energy input ratio and part-load fraction to determine the performance of the unit at part-load conditions (Henderson et al. 1992, ASHRAE 1993). Sensible/latent capacity splits are determined by the rated sensible heat ratio (SHR) and the apparatus dew point (ADP)/bypass factor (BF) approach. This approach is analogous to the NTU-effectiveness calculations used for sensible-only heat exchanger calculations, extended to a cooling and dehumidifying coil.

This model simulates the thermal performance of the DX cooling coil and the power consumption of the outdoor condensing unit (compressor, fan, crankcase heater and evap condenser water pump). The performance of the indoor supply air fan varies widely from system to system depending on control strategy (e.g., constant fan vs. AUTO fan, constant air volume vs. variable air volume, etc.), fan type, fan motor efficiency and pressure losses through the air distribution system. Therefore, this DX system model does not account for the thermal effects or electric power consumption of the indoor supply air fan. EnergyPlus contains separate models for simulating the performance of various indoor fan configurations, and these models can be easily linked with the DX system model described here to simulate the entire DX air conditioner being considered (e.g., see Furnace:HeatCool, Unitary System:HeatCool, Air Conditioner:Window:Cycling or UnitarySystem:HeatPump).

Model Description

The user must input the total cooling capacity, sensible heat ratio (SHR), coefficient of performance (COP) and the volumetric air flow rate across the cooling coil at rated conditions. The capacity, SHR and COP inputs should be “gross” values, excluding any thermal or energy impacts due to the indoor supply air fan. The rated conditions are considered to be air entering the cooling coil at 26.7°C drybulb/19.4°C wetbulb and air entering the outdoor condenser coil at 35°C drybulb/23.9°C wetbulb. The rated volumetric air flow should be between 0.00004699 m³/s and 0.00006041 m³/s per watt of rated total cooling capacity (350 – 450 cfm/ton).

The user must also input five performance curves that describe the change in total cooling capacity and efficiency at part-load conditions:

- 1) Total cooling capacity modifier curve (function of temperature)
 - 2) Total cooling capacity modifier curve (function of flow fraction)
 - 3) Energy input ratio (EIR) modifier curve (function of temperature)
 - 4) Energy input ratio (EIR) modifier curve (function of flow fraction)
 - 5) Part load fraction correlation (function of part load ratio)
- The total cooling capacity modifier curve (function of temperature) is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The output of this curve is multiplied by the rated total cooling capacity to give the total cooling capacity at the specific entering air temperatures at which the DX coil unit is operating (i.e., at temperatures different from the rating point temperatures).

$$TotCapTempModFac = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i}) \quad (0.5)$$

where

$T_{wb,i}$ = wet-bulb temperature of the air entering the cooling coil, °C

$T_{c,i}$ = dry-bulb temperature of the air entering an air-cooled condenser or wet-bulb temperature of the air entering an evaporative-cooled condenser, °C

- The total cooling capacity modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated total cooling capacity and the total cooling capacity modifier curve (function of temperature) to give the total cooling capacity at the specific temperature and air flow conditions at which the DX unit is operating.

$$TotCapFlowModFac = a + b(ff) + c(ff)^2 \quad (0.6)$$

where

$$ff = flow\ fraction = \left(\frac{Actual\ air\ mass\ flowrate}{Rated\ air\ mass\ flowrate} \right)$$

Note: The actual volumetric air flow rate through the cooling coil for any simulation time step where the DX unit is operating must be between 0.00003356 m³/s and

.00006713 m³/s per watt of rated total cooling capacity (250 - 500 cfm/ton). The simulation will issue a warning message if this air flow range is exceeded.

- The energy input ratio (EIR) modifier curve (function of temperature) is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil (wet-bulb temperature if modeling an evaporative-cooled condenser). The output of this curve is multiplied by the rated EIR (inverse of the rated COP) to give the EIR at the specific entering air temperatures at which the DX coil unit is operating (i.e., at temperatures different from the rating point temperatures).

$$EIRTempModFac = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{wb,i})(T_{c,i}) \quad (0.7)$$

where

$T_{wb,i}$ = wet-bulb temperature of the air entering the cooling coil, °C

$T_{c,i}$ = dry-bulb temperature of the air entering an air-cooled condenser or wet-bulb temperature of the air entering an evaporative-cooled condenser, °C

- The energy input ratio (EIR) modifier curve (function of flow fraction) is a quadratic curve with the independent variable being the ratio of the actual air flow rate across the cooling coil to the rated air flow rate (i.e., fraction of full load flow). The output of this curve is multiplied by the rated EIR (inverse of the rated COP) and the EIR modifier curve (function of temperature) to give the EIR at the specific temperature and air flow conditions at which the DX unit is operating.

$$EIRFlowModFac = a + b(ff) + c(ff)^2 \quad (0.8)$$

where

$$ff = \text{flow fraction} = \left(\frac{\text{Actualairmass flowrate}}{\text{Ratedairmassflowrate}} \right)$$

- The part load fraction correlation (function of part load ratio) is a quadratic or a cubic curve with the independent variable being part load ratio (sensible cooling load / steady-state sensible cooling capacity). The output of this curve is used in combination with the rated EIR and EIR modifier curves to give the “effective” EIR for a given simulation time step. The part load fraction (PLF) correlation accounts for efficiency losses due to compressor cycling.

$$PartLoadFrac = PLF = a + b(PLR) + c(PLR)^2 \quad (0.9)$$

or

$$PartLoadFrac = a + b(PLR) + c(PLR)^2 + d(PLR)^3 \quad (0.10)$$

where

$$PLR = \text{part-load ratio} = \left(\frac{\text{sensible cooling load}}{\text{steady-state sensible cooling capacity}} \right)$$

The part-load fraction correlation should be normalized to a value of 1.0 when the part load ratio equals 1.0 (i.e., no efficiency losses when the compressor(s) run continuously for the simulation time step). For PLR values between 0 and 1 ($0 \leq PLR < 1$), the following rules apply:

$$PLF \geq 0.7 \quad \text{and} \quad PLF \geq PLR$$

If $PLF < 0.7$ a warning message is issued, the program resets the PLF value to 0.7, and the simulation proceeds. The runtime fraction of the coil is defined as PLR/PLF . If $PLF < PLR$, then a warning message is issued and the runtime fraction of the coil is limited to 1.0.

A typical part load fraction correlation for a conventional, single-speed DX cooling coil (e.g., residential or small commercial unit) would be:

$$PLF = 0.75 + 0.25(PLR)$$

All five part-load curves are accessed through EnergyPlus' built-in performance curve equation manager (curve: quadratic, curve:cubic and curve:biquadratic). It is not imperative that the user utilize all coefficients shown in equations (0.5) through (0.9) if their performance equation has fewer terms (e.g., if the user's PartLoadFrac performance curve is linear instead of quadratic, simply enter the values for a and b, and set coefficient c equal to zero).

For any simulation time step, the total (gross) cooling capacity of the DX unit is calculated as follows:

$$\dot{Q}_{total} = \dot{Q}_{total, rated} (TotCapTempModFac) (TotCapFlowModFac) \quad (0.11)$$

In a similar fashion, the electrical power consumed by the DX unit (compressors plus outdoor condenser fans) for any simulation time step is calculated using the following equation:

$$Power = \left(\dot{Q}_{total} \right) (EIR) (RTF) \quad (0.12)$$

where

$$\dot{Q}_{total} = \text{Total cooling capacity, W -- ref. equation (0.11)}$$

$$EIR = \text{Energy input ratio} = \left(\frac{1}{COP_{rated}} \right) (EIRTempModFac) (EIRFlowModFac)$$

$$COP_{rated} = \text{Coefficient of performance at rated conditions (user input)}$$

$$RTF = \left(\frac{PLR}{PartLoadFrac} \right) = \text{runtime fraction of the cooling coil}$$

The crankcase heater is assumed to operate when the cooling coil's compressor is OFF and the outdoor dry-bulb temperature is below the maximum outdoor temperature for crankcase heater operation. The average crankcase heater power for the simulation time step is calculated as follows:

$$P_{crankcase} = \dot{Q}_{capcrankcase} (1 - RTF) \quad (0.13)$$

where

$P_{crankcase}$ = DX cooling coil crankcase heater power, W

$\dot{Q}_{capcrankcase}$ = crankcase heater capacity, W

If this cooling coil is used as part of an air-to-air heat pump (Ref. UnitarySystem:HeatPump:AirToAir), the crankcase heater defined for this DX cooling coil is disregarded and the associated output variable is omitted. Instead, the crankcase heater defined for the DX heating coil (Coil:DX:HeatingEmpirical) is enabled during the time that the compressor is not running for either heating or cooling. In this instance, RTF in the above equations would be the runtime fraction of the heat pump's heating coil or cooling coil, whichever is greater.

In addition to calculating the total cooling capacity provided by the DX air conditioner, it is important to properly determine the break down of total cooling capacity into its sensible (temperature) and latent (dehumidification) components. The model computes the sensible/ latent split using the rated SHR and the ADP/BF approach (Carrier et al. 1959). When the DX coil model is initially called during an EnergyPlus simulation, the rated total capacity and rated SHR are used to calculate the coil bypass factor (BF) at rated conditions. The rated total capacity and rated SHR are first used to determine the ratio of change in air humidity ratio to air dry-bulb temperature:

$$SlopeRated = \left(\frac{w_{in} - w_{out}}{T_{db,in} - T_{db,out}} \right)_{rated} \quad (0.14)$$

where

w_{in} = humidity ratio of the air entering the cooling coil at rated conditions, kg/kg

w_{out} = humidity ratio of the air leaving the cooling coil at rated conditions, kg/kg

$T_{db,in}$ = dry-bulb temperature of the air entering the cooling coil at rated conditions, °C

$T_{db,out}$ = dry-bulb temperature of the air leaving the cooling coil at rated conditions, °C

Along with the rated entering air conditions, the algorithm then searches along the saturation curve of the psychrometric chart until the slope of the line between the point on the saturation curve and the inlet air conditions matches *SlopeRated*. Once this point, the apparatus dew point, is found on the saturation curve the coil bypass factor at rated conditions is calculated as follows:

$$BF_{rated} = \frac{h_{out,rated} - h_{ADP}}{h_{in,rated} - h_{ADP}} \quad (0.15)$$

where

$h_{out,rated}$ = enthalpy of the air leaving the cooling coil at rated conditions, J/kg

$h_{in,rated}$ = enthalpy of the air entering the cooling coil at rated conditions, J/kg

h_{ADP} = enthalpy of saturated air at the coil apparatus dew point, J/kg

The coil bypass factor is analogous to the “ineffectiveness” (1-e) of a heat exchanger, and can be described in terms of the number of transfer of unit (NTU).

$$BF = e^{-NTU} = e^{-\left(\frac{UA}{c_p}\right) / \dot{m}} = e^{-A \phi \dot{m}} \quad (0.16)$$

For a given coil geometry, the bypass factor is only a function of air mass flow rate. The model calculates the parameter A_0 in equation (0.16) based on BF_{rated} and the rated air mass flow rate. With A_0 known, the coil BF can be determined for non-rated air flow rates.

For each simulation time step when the DX air conditioner operates to meet a cooling load, the total cooling capacity at the actual operating conditions is calculated using equation (0.11) and the coil bypass factor is calculated based on equation (0.16). The coil bypass factor is used to calculate the operating sensible heat ratio (SHR) of the cooling coil using equations (0.17) and (0.18).

$$h_{ADP} = h_{in} - \frac{(\dot{Q}_{total} / \dot{m})}{1 - BF} \quad (0.17)$$

$$SHR = Minimum \left(\left(\frac{h_{TinwADP} - h_{ADP}}{h_{in} - h_{ADP}} \right), 1 \right) \quad (0.18)$$

where

h_{in} = enthalpy of the air entering the cooling coil, J/kg

h_{ADP} = enthalpy of air at the apparatus dew point condition, J/kg

$h_{TinwADP}$ = enthalpy of air at the entering coil dry-bulb temperature and humidity ratio at ADP, J/kg

$\dot{m}$ = air mass flow rate, kg/s

With the SHR for the coil at the current operating conditions, the properties of the air leaving the cooling coil are calculated using the following equations:

$$h_{out} = h_{in} - \frac{\dot{Q}_{total}}{\dot{m}} \quad (0.19)$$

$$h_{Tin,wout} = h_{in} - (1 - SHR)(h_{in} - h_{out}) \quad (0.20)$$

$$w_{out} = PsyWFnTdbH(T_{in}, h_{Tin,wout}) \quad (0.21)$$

$$T_{db,out} = PsyTdbFnHW(h_{out}, w_{out}) \quad (0.22)$$

where

h_{out} = enthalpy of the air leaving the cooling coil, J/kg

$h_{Tin,wout}$ = enthalpy of air at the entering coil dry-bulb temperature and leaving air humidity ratio, J/kg

W_{out} = leaving air humidity ratio, kg/kg

T_{dbout} = leaving air dry-bulb temperature, °C

$PsyWFnTdbH$ = EnergyPlus psychrometric function, returns humidity ratio given dry-bulb temperature and enthalpy

$PsyTdbFnHW$ = EnergyPlus psychrometric function, returns dry-bulb temperature given enthalpy and humidity ratio

Dry Coil Conditions

If the model determines that the cooling coil is dry ($\eta_{in} < \eta_{ADP}$), then equations (0.11) and (0.12) are invalid since they are functions of entering wet-bulb temperature. Under dry-coil conditions, coil performance is a function of dry-bulb temperature rather than wet-bulb temperature. In this case, the model recalculates the performance of the DX cooling unit using the calculation procedure described above but with $\eta_{in} = \eta_{dry}$, where η_{dry} is the inlet air humidity ratio at the coil dry-out point (SHR = 1.0).

Condenser Options: Air Cooled vs. Evaporative Cooled

As described previously, this model can simulate the performance of air-cooled or evaporative-cooled DX air conditioners. The following paragraphs describe three modeling options.

If the user wants to model an air-cooled condenser, they should simply specify AIR COOLED in the field Condenser Type. In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) (equations (0.5) and (0.7) above) will utilize the outdoor dry-bulb temperature.

If the user wishes to model an evaporative-cooled condenser AND they have performance curves that are a function of the wet-bulb temperature of air entering the condenser coil, then the user should specify Condenser Type = Evap Cooled and the evaporative condenser effectiveness value should be entered as 1.0. In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) (equations (0.5) and (0.7) above) will utilize the outdoor wet-bulb temperature.

If the user wishes to model an air-cooled condenser that has evaporative media placed in front of it to cool the air entering the condenser coil, then the user should specify Condenser Type = Evap Cooled. The user must also enter the appropriate evaporative effectiveness for the media. In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) will utilize the condenser inlet air temperature as calculated below:

$$T_{c,i} = (T_{wb,o}) + (1 - EvapCondEffectiveness)(T_{db,o} - T_{wb,o})$$

where

$T_{c,i}$ = the temperature of the air entering the condenser coil, °C

$T_{wb,o}$ = the wet-bulb temperature of the outdoor air, °C

$T_{db,o}$ = the dry-bulb temperature of the outdoor air, °C

In this case, the Total Cooling Capacity Modifier Curve (function of temperature) and the Energy Input Ratio Modifier Curve (function of temperature) input fields for this

object should reference performance curves that are a function of outdoor dry-bulb temperature. Be aware that the evaporative media will significantly reduce the dry-bulb temperature of the air entering the condenser coil, so the Total Cooling Capacity and EIR Modifier Curves must be valid for the expected range of dry-bulb temperatures that will be entering the condenser coil.

If an evaporative-cooled condenser is modeled, the power requirements for the water pump are calculated as follows:

$$P_{\text{evapcondpump}} = \dot{Q}_{\text{capevapcondpump}} (RTF)$$

where

$P_{\text{evapcondpump}}$ = DX cooling coil evap condenser pump electric power, W

$\dot{Q}_{\text{capevapcondpump}}$ = evaporative condenser pump rated power consumption, W

Water consumption for the evaporative-cooled condenser is calculated using the difference in air humidity level across the evaporative media and the condenser air mass flow rate:

$$V_{\text{water}} = \frac{\dot{m}_{\text{air}} (w_{\text{evapcondout}} - w_{\text{evapcondin}})}{r_{\text{water}}} (RTF) (TimeStepSys) (3600.)$$

where

V_{water} = DX cooling coil evap condenser water consumption, m³

$\dot{m}_{\text{air}}$ = evaporative condenser air mass flow rate, kg/s

$w_{\text{evapcondin}}$ = humidity ratio of outdoor air entering the evap condenser, kg/kg

$w_{\text{evapcondout}}$ = humidity ratio of air leaving the evap condenser, kg/kg

r_{water} = density of water at the outdoor dry-bulb temperature, kg/m³

$TimeStepSys$ = HVAC system simulation time step, hr

Supply Air Fan Control: Cycling vs. Continuous

One of the inputs to the DX cooling coil model is the supply air fan operation mode: cycling fan, cycling compressor (CycFanCycComp) or continuous fan, cycling compressor (ContFanCycComp). The first operation mode is frequently referred to as "AUTO fan", where the compressor(s) and supply air fan operate in unison to meet the zone cooling load, and cycle off together when the cooling load has been met. The second operation mode is often referred to as "fan ON", where the compressor(s) cycle on and off to meet the zone cooling load but the supply air fan operates continuously regardless of compressor operation.

The EnergyPlus methodology for determining the impact that HVAC equipment has on an air stream is to calculate the mass flow rate and air properties (e.g., enthalpy, dry-bulb temperature, humidity ratio) exiting the equipment. These exiting conditions are passed along as inlet conditions to the next component model in the air stream.

Eventually the flow rate and properties of the air being supplied to the conditioned zone are used in the zone energy balance to determine the resulting zone air temperature and humidity ratio.

With this methodology, the determination of the air mass flow rate and air properties for the two different supply air fan operation modes is slightly different. For the case of cycling fan/cycling compressor, the conditions of the air leaving the cooling coil are the steady-state values calculated using equations (0.19), (0.21) and (0.22) above. However the air mass flow rate passed along to the next component (and eventually to the conditioned zone) is the average air mass flow rate for the system simulation time step (determined by the cooling system; see Air Conditioner:Window, Furnace:HeatCool, Unitary System:HeatCool or UnitarySystem:HeatPump).

For the case of continuous fan/cycling compressor, the air mass flow rate is constant. However, the air properties leaving the cooling coil are calculated as the average conditions during the system simulation time step. The model assumes that the exiting air conditions are the steady-state values calculated using equations (0.19), (0.21) and (0.22) above when the compressor(s) operate. For the remainder of the system simulation time step, it is assumed that the air exiting the DX coil has the same properties as the air entering the coil. For this supply air fan operating strategy, the leaving air properties are calculated as follows:

$$h_{outContFanCycComp} = h_{out}(PLR) + h_{in}(1 - PLR) \quad (0.23)$$

$$w_{outContFanCycComp} = w_{out}(PLR) + w_{in}(1 - PLR) \quad (0.24)$$

$$T_{dboutContFanCycComp} = PsyTdbFnHW(h_{outContFanCycComp}, w_{outContFanCycComp}) \quad (0.25)$$

Latent Capacity Degradation with Continuous Supply Air Fan Operation

The latent (dehumidification) capacity of a direct-expansion (DX) cooling coil is strongly affected by part-load, or cyclic, operation. This is especially true in applications where the supply air fan operates continuously while the cooling coil cycles on and off to meet the cooling load. During constant fan operation, moisture condenses on the cooling coil when the compressor operates, but part or all of the moisture that is held by the coil evaporates back into the airstream when the cooling coil is deactivated (Figure 8). The net effect is that the amount of moisture removed from the air is degraded at part-load conditions as compared to steady-state conditions when the compressor operates continuously (Figure 9).

EnergyPlus is able to model latent capacity degradation based on algorithms developed by Henderson and Rengarajan (1996). The model is applicable to single-stage cooling units, like residential and small commercial air conditioners or heat pumps with less than 19 kW of nominal cooling capacity. The model inputs are described in the EnergyPlus Input/Output Reference for the object Coil:DX:CoolingBypassFactorEmpirical. The model is enabled only if the four numerical inputs are defined (values greater than zero, see IO Reference) and the field "Supply Air Fan Operation Mode" must be "ContFanCycComp".

Figure 8. Transient Sensible and Latent Capacity of a Cooling Coil Over an Operating Cycle

Figure 9. Field Data Showing the Net Impact of Part-Load Operation on Sensible Heat Ratio

Figure 10. Concepts of Moisture Buildup and Evaporation

Figure 10 graphically depicts the latent degradation concepts and defines several key model parameters. After the cooling coil starts to operate, the coil temperature is eventually reduced below the dewpoint temperature of the entering air. Moisture from the air then builds on the surface of the coil until time t_o has elapsed and the total moisture mass on the coil is M_o . After this time (t_o), moisture begins to fall from the coil and all of the latent capacity provided by the coil is “useful” since this condensate is collected and removed from the unit. When the coil cycles off and the supply air fan continues to operate, the initial moisture mass buildup on the coil (M_o) evaporates back into the supply air stream. If the cooling coil cycles back on before all of the moisture has evaporated, then the time until the first condensate removal (t_o) is shorter for this cooling cycle since the coil is already partially wetted.

Figure 10 also shows several parameters that are used in the latent degradation model. The ratio of the coil’s moisture holding capacity (M_o) and the steady-state latent capacity ($\dot{Q}_L$) is defined as t_{wet} : the nominal time for moisture to fall from the coil (ignoring transient effects at startup and starting with a dry coil). The ratio of the initial moisture evaporation rate ($\dot{Q}_e$) and the steady-state latent capacity ($\dot{Q}_L$) is defined as γ . Both t_{wet} and γ at the rated air volume flow rate and temperature conditions are required model inputs. Two other model inputs are the Maximum ON/OFF Cycling Rate (cycles per hour, N_{max}) and the time constant (τ , in seconds) for the cooling coil’s latent capacity to reach steady state after startup. The

development of the latent degradation model is fully described by Henderson and Rengarajan (1996). The model implemented in EnergyPlus is for their “linear decay” evaporation model.

During the simulation, all of the steady-state calculations described previously in equations (0.5) through (0.18) are completed. The latent degradation model then modifies the steady-state sensible heat ratio for the coil as shown below. The value of t_{wet} at the current air volume flow rate and entering air conditions is first calculated based on the rated value of t_{wet} entered by the user:

$$t_{wet} = \text{Minimum} \left(t_{wet,rated} \left(\frac{\dot{Q}_{latent,rated}}{\dot{Q}_{latent}} \right), t_{wet,max} \right)$$

where

t_{wet} = nominal time for condensate removal to begin at the current airflow and entering air conditions, starting with a dry coil (sec)

$t_{wet,rated}$ = nominal time for condensate removal to begin at the coil's rated airflow and entering air conditions, starting with a dry coil (sec)

$\dot{Q}_{latent,rated}$ = cooling coil latent capacity at the rated airflow and temperature conditions, W

$\dot{Q}_{latent}$ = cooling coil latent capacity at the current airflow and temperature conditions, W

$t_{wet,max}$ = maximum allowed value for t_{wet} (9999.0 sec)

Likewise, the value of g at the current air volume flow rate and entering air conditions is calculated based on the rated value of g entered by the user:

$$g = g_{rated} \left(\frac{\dot{Q}_{latent,rated}}{\dot{Q}_{latent}} \right) \left(\frac{T_{db,i} - T_{wb,i}}{T_{db,rated} - T_{wb,rated}} \right)$$

where:

g = ratio of the initial moisture evaporation rate from the cooling coil (when the compressor first turns off, in Watts) and the coil's steady-state latent capacity (Watts) at the current air volume flow rate and entering air conditions

g_{rated} = g at rated air flow and entering air conditions

$T_{db,i}$ = dry-bulb temperature of the air entering the cooling coil, °C

$T_{wb,i}$ = wet-bulb temperature of the air entering the cooling coil, °C

$T_{db,rated}$ = dry-bulb temperature of air entering the cooling coil at rated conditions (26.7°C)

$T_{wb,rated}$ = wet-bulb temperature of air entering the cooling coil at rated conditions (19.4°C)

The cooling coil on and off times are then calculated based on the maximum number of cycles per hour and the calculated run-time fraction for the coil.

$$t_{on} = \frac{3600}{4N_{max}(1-X)}$$

$$t_{off} = \frac{3600}{4N_{max}X}$$

where

t_{on} = duration of cooling coil on-cycle (sec)

N_{max} = maximum on/off cycles per hour (cph)

X = cooling coil runtime fraction (-)

t_{off} = duration of cooling coil off-cycle (sec)

The equation for calculating the time t_o when moisture first begins to fall from the cooling coil is shown below, and is solved iteratively by EnergyPlus:

$$t_o^{j+1} = g t_{off} - \left(\frac{g^2}{4t_{wet}} \right) t_{off}^2 - t \left(e^{\frac{t_o^j}{t}} - 1 \right), \quad t_{off} \leq \left(\frac{2t_{wet}}{g} \right)$$

where

t_o = time where condensate removal begins (sec)

t = latent capacity time constant at start-up (sec)

j = iteration number

The part-load latent heat ratio of the cooling coil is then calculated with t_o , t_{on} and t , which is in turn used to calculate the “effective” sensible heat ratio of the cooling including part-load latent degradation effects.

$$\frac{LHR}{LHR_{ss}} = \text{Maximum} \left(\left(\frac{t_{on} - t_o}{t_{on} + t \left(e^{\left(\frac{-t_{on}}{t} \right)} - 1 \right)} \right), 0.0 \right)$$

$$SHR_{eff} = 1 - (1 - SHR_{ss}) \left(\frac{LHR}{LHR_{ss}} \right)$$

where

LHR = part-load latent heat ratio

LHR_{ss} = latent heat ratio at steady-state conditions ($1 - SHR_{ss}$ with SHR_{ss} from eqn. (0.18))

SHR_{eff} = part-load sensible heat ratio ($SHR_{ss} = SHR_{eff} = 1.0$)

SHR_{ss} = steady-state sensible heat ratio (from eqn. (0.18))

With the “effective” SHR for the coil at the current operating conditions, including the impacts of latent degradation, equations (0.19) through (0.22) are then used to calculate the properties of the air leaving the cooling coil when it operates. Finally, equations (0.23) through (0.25) are used to calculate the average leaving air conditions (average when the coil is on and off) for the simulation time step.

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Appendix D

EnergyPlus Documentation for Cooling Coils with Air-to-Air Heat Exchangers for Improved Dehumidification

This appendix contains the EnergyPlus documentation (Input/Output Reference and Engineering Manual) that describes using air-to-air heat exchangers to improve the dehumidification performance of cooling coils.

Input Output Reference for Coil:DX:CoolingHeatExchangerAssisted

The heat exchanger-assisted DX cooling coil is a “virtual” component consisting of a direct expansion (DX) cooling coil and an air-to-air heat exchanger as shown in Figure 11 below. The air-to-air heat exchanger precools the air entering the cooling coil, and reuses this energy to reheat the supply air leaving the cooling coil. This heat exchange process improves the latent removal performance of the cooling coil by allowing it to dedicate more of its cooling capacity toward dehumidification (lower sensible heat ratio).

This compound object models the basic operation of an air-to-air heat exchanger in conjunction with a cooling coil. The heat exchanger-assisted DX cooling coil does not have an operating schedule of its own; its operating schedule is governed by the availability schedules for the DX cooling coil and the air-to-air heat exchanger. This compound object is used in place of where a DX cooling coil object would normally be used by itself.

To model a heat exchanger-assisted DX cooling coil, the input data file should include the following objects:

- Coil:DX:CoolingHeatExchangerAssisted compound object
- Air-to-air heat exchanger object (Heat Exchanger:Air to Air:Flat Plate or Heat Exchanger: Air to Air:Generic)
- DX cooling coil object (COIL:DX:CoolingBypassFactorEmpirical)

Links to the cooling coil and air-to-air heat exchanger specifications are provided in the input data syntax for the Coil:DX:CoolingHeatExchangerAssisted compound object. A description of each input field for this compound object is provided below.

Figure 11. Schematic of the Coil:DX:CoolingHeatExchangerAssisted compound object

Field: Name of the heat exchanger assisted cooling coil

A unique user-assigned name for the heat exchanger-assisted DX cooling coil. Any reference to this compound component by another object (e.g., Furnace:BlowThru:HeatCool, UnitarySystem:BlowThru:HeatCool, UnitarySystem:HeatPump:AirToAir, DXSystem:AirLoop, Air Conditioner:Window:Cycling) will use this name.

Field: Inlet node name

The name of the HVAC system node from which this compound object draws its inlet air. This node name must also match the supply air inlet node name specified in the air-to-air heat exchanger object.

Field: Outlet node name

The name of the HVAC system node to which the compound object sends its outlet (supply) air. This node name must also match the exhaust (secondary) air outlet node name specified in the air-to-air heat exchanger object.

Field: Heat exchanger type

This alpha field denotes the type of heat exchanger being modeled. Valid choices are Heat Exchanger:Air to Air:Flat Plate or Heat Exchanger:Air to Air:Generic.

Field: Heat exchanger name

This alpha field denotes the name of the air-to-air heat exchanger being modeled.

Field: Cooling coil type

This alpha field denotes the type of DX cooling coil being modeled. The only valid choice is Coil:DX:CoolingBypassFactorEmpirical.

Field: Cooling coil name

This alpha field denotes the name of the DX cooling coil being modeled.

Field: Cooling coil inlet node name

The name of the HVAC system air node at the inlet to the cooling coil. This node name must match the inlet air node name specified in the cooling coil object and also match the supply air outlet node name specified in the air-to-air heat exchanger object.

Field: Heat exchanger exhaust air inlet node name

The name of the HVAC system air node entering the heat exchanger's exhaust air inlet. This node name must match the exhaust (secondary) air inlet node name specified in the air-to-air heat exchanger object and also match the outlet node name specified in the cooling coil object.

The full IDD specification follows:

```
COIL:DX:CoolingHeatExchangerAssisted,  
  \min-fields 9  
A1 , \field Name of the heat exchanger assisted cooling coil  
  \required-field  
A2 , \field Inlet node name  
  \required-field  
  \note Name of the inlet node for this compound object  
  \note Must match the supply air inlet node name in the air-to-air heat exchanger object  
A3 , \field Outlet node name  
  \required-field  
  \note Name of the outlet node for this compound object  
  \note Must match the exhaust (secondary) air outlet node name in the  
  \note air-to-air heat exchanger object  
A4 , \field Heat exchanger type  
  \required-field  
  \choice  
  \key Heat Exchanger:Air to Air:Flat Plate  
  \key Heat Exchanger:Air to Air:Generic  
A5 , \field Heat exchanger name  
  \required-field  
A6 , \field Cooling coil type  
  \required-field  
  \choice  
  \key COIL:DX:CoolingBypassFactorEmpirical  
A7 , \field Cooling coil name  
  \required-field  
A8 , \field Cooling coil inlet node name  
  \required-field  
  \note Must match the supply air outlet node name in the air-to-air heat exchanger object  
  \note and also match the inlet air node name in the cooling coil object  
A9 ; \field Heat exchanger exhaust air inlet node name  
  \required-field  
  \note Must match the exhaust (secondary) air inlet node name in the air-to-air  
  \note heat exchanger object and also match the outlet node name in the cooling coil object
```

Following is an example input for this compound object:

```

COIL:DX:CoolingHeatExchangerAssisted,
HeatExchangerAssistedCoolingCoil,      ! Name of the heat exchanger assisted cooling coil
HeatExchangerSupplyAirInletNode,        ! Inlet node name
HeatExchangerExhaustAirOutletNode,      ! Outlet node name
Heat Exchanger:Air to Air:Generic,       ! Heat exchanger type
Air to Air Heat Exchanger 1,            ! Heat exchanger name
COIL:DX:CoolingBypassFactorEmpirical,   ! Cooling coil type
DX Cooling Coil 1,                      ! Cooling coil name
DX Cooling Coil Air Inlet Node,          ! Cooling coil inlet node name
HeatExchangerExhaustAirInletNode;        ! Heat exchanger exhaust air inlet node name

HEAT EXCHANGER:AIR TO AIR:GENERIC,
Air to Air Heat Exchanger 1,            !- Heat exchanger name
FanAndCoilAvailSched,                  !- Availability schedule name
1.3,                                    !- Nominal supply air flow rate {m3/s}
.2,                                     !- Sensible effectiveness at 100% airflow heating condition
.0,                                     !- Latent effectiveness at 100% airflow heating condition
.23,                                    !- Sensible effectiveness at 75% airflow heating condition
.0,                                     !- Latent effectiveness at 75% airflow heating condition
.2,                                     !- Sensible effectiveness at 100% airflow cooling condition
.0,                                     !- Latent effectiveness at 100% airflow cooling condition
.23,                                    !- Sensible effectiveness at 75% airflow cooling condition
.0,                                     !- Latent effectiveness at 75% airflow cooling condition
HeatExchangerSupplyAirInletNode,        !- Supply air inlet node name
DX Cooling Coil Air Inlet Node,          !- Supply air outlet node name
HeatExchangerExhaustAirInletNode,       !- Exhaust air inlet node name
HeatExchangerExhaustAirOutletNode,     !- Exhaust air outlet node name
50.0,                                   !- Nominal electric power {W}
No,                                     !- Supply air outlet temperature control
Rotary,                                 !- Heat exchanger type
None;                                   !- Frost control type

COIL:DX:CoolingBypassFactorEmpirical,
DX Cooling Coil 1,                      !- Coil Name
FanAndCoilAvailSched,                  !- Availability Schedule
25000,                                 !- Rated Total Cooling Capacity (gross) {W}
0.75,                                  !- Rated SHR
3.0,                                   !- Rated COP
1.3,                                   !- Rated Air Volume Flow Rate {m3/s}
DX Cooling Coil Air Inlet Node,         !- Coil Air Inlet Node
HeatExchangerExhaustAirInletNode,      !- Coil Air Outlet Node
ACCoolCapFT,                           !- Total Cooling Capacity Modifier Curve (function of temperature)
ACCoolCapFFF,                          !- Total Cooling Capacity Modifier Curve (function of flow fraction)
ACEIRFT,                               !- Energy Input Ratio Modifier Curve (function of temperature)
ACEIRFFF,                              !- Energy Input Ratio Modifier Curve (function of flow fraction)
ACPLFFPLR,                             !- Part Load Fraction Correlation (function of part load ratio)
CycFanCycComp;                         !- Supply Air Fan Operation Mode

```

Engineering Document for Heat Exchanger-Assisted Cooling Coils

An air-to-air heat exchanger can be used to enhance the dehumidification performance of a conventional cooling coil. EnergyPlus has two compound objects to model this scenario: Coil:DX:CoolingHeatExchangerAssisted and Coil:Water:CoolingHeatExchangerAssisted. The input syntax for these compound objects can be found in the EnergyPlus Input/Output Reference.

As shown in Figure 12, the air-to-air heat exchanger precools the air entering the cooling coil, and reuses this energy to reheat the supply air leaving the cooling coil. This heat exchange process improves the latent removal performance of the cooling coil by allowing it to dedicate more of its cooling capacity toward dehumidification (lower sensible heat ratio).

Figure 12. Schematic of a heat exchanger assisted cooling coil

Modeling of the heat exchanger assisted cooling coil is performed by consecutively modeling the air-to-air heat exchanger and the cooling coil until convergence on a solution is achieved. The detailed modeling calculations for the individual components (air-to-air heat exchangers and cooling coils) are described elsewhere in this document.

Modeling of the heat exchanger assisted cooling coil begins by initializing the air mass flow rate (based on the air mass flow rate placed on the compound object's inlet air node) and passing this value to the exhaust air inlet node of the air-to-air heat exchanger. The heat exchanger and cooling coil are then successively modeled using the calculation routines specific to the type of heat exchanger and cooling coil selected. The air temperature exiting the cooling coil is compared with the air temperature exiting the cooling coil on the previous modeling iteration for this simulation time step. When modeling the air-to-air heat exchanger during the first modeling iteration, the cooling coil exiting air temperature from the previous simulation time step is used as the heat exchanger's exhaust air inlet condition. Convergence is reached when the change in this air temperature for successive iterations is within a specified tolerance (0.001°C). Consecutive modeling of the heat exchanger and cooling coil is terminated and a warning message is issued if the number of modeling iterations exceeds 15.

Input Output Reference for Coil:Water:CoolingHeatExchangerAssisted

The heat exchanger-assisted water cooling coil is a “virtual” component consisting of a chilled-water cooling coil and an air-to-air heat exchanger as shown in Figure 13 below. The air-to-air heat exchanger precools the air entering the cooling coil, and reuses this energy to reheat the supply air leaving the cooling coil. This heat exchange process improves the latent removal performance of the cooling coil by allowing it to dedicate more of its cooling capacity toward dehumidification (lower sensible heat ratio).

Figure 13. Schematic of the Coil:Water:CoolingHeatExchangerAssisted compound object

This compound object models the basic operation of an air-to-air heat exchanger in conjunction with a chilled-water cooling coil. The heat exchanger-assisted water cooling coil does not have an operating schedule of its own; its operating schedule is governed by the availability schedules for the chilled-water cooling coil and the air-to-air heat exchanger. This compound object is used in place of where a chilled-water cooling coil object would normally be used by itself.

To model a heat exchanger-assisted water cooling coil, the input data file should include the following objects:

- Coil:Water:CoolingHeatExchangerAssisted compound object
- Air-to-air heat exchanger object (Heat Exchanger:Air to Air:Flat Plate or Heat Exchanger: Air to Air:Generic)
- Chilled-water cooling coil object (COIL:Water:SimpleCooling or COIL:Water:DetailedFlatCooling)

Links to the cooling coil and air-to-air heat exchanger specifications are provided in the input data syntax for the Coil:Water:CoolingHeatExchangerAssisted compound object. A description of each input field for this compound object is provided below.

Field: Name of the heat exchanger assisted cooling coil

A unique user-assigned name for the heat exchanger-assisted water cooling coil. Any reference to this compound component by another object (e.g., Unit Ventilator, Fan Coil Unit:4 Pipe, component in an air loop BRANCH object) will use this name.

Field: Inlet node name

The name of the HVAC system node from which this compound object draws its inlet air. This node name must also match the supply air inlet node name specified in the air-to-air heat exchanger object.

Field: Outlet node name

The name of the HVAC system node to which the compound object sends its outlet (supply) air. This node name must also match the exhaust (secondary) air outlet node name specified in the air-to-air heat exchanger object.

Field: Heat exchanger type

This alpha field denotes the type of heat exchanger being modeled. Valid choices are Heat Exchanger:Air to Air:Flat Plate or Heat Exchanger:Air to Air:Generic.

Field: Heat exchanger name

This alpha field denotes the name of the air-to-air heat exchanger being modeled.

Field: Cooling coil type

This alpha field denotes the type of chilled-water cooling coil being modeled. Valid choices are Coil:Water:SimpleCooling and Coil:Water:DetailedFlatCooling.

Field: Cooling coil name

This alpha field denotes the name of the chilled-water cooling coil being modeled.

Field: Cooling coil inlet node name

The name of the HVAC system air node at the inlet to the cooling coil. This node name must match the inlet air node name specified in the cooling coil object and also match the supply air outlet node name specified in the air-to-air heat exchanger object.

Field: Heat exchanger exhaust air inlet node name

The name of the HVAC system air node entering the heat exchanger's exhaust air inlet. This node name must match the exhaust (secondary) air inlet node name specified in the air-to-air heat exchanger object and also match the outlet air node name specified in the cooling coil object.

The full IDD specification follows:

```

COIL:Water:CoolingHeatExchangerAssisted,
  \min-fields 9
A1 , \field Name of the heat exchanger assisted cooling coil
    \required-field
A2 , \field Inlet node name
    \required-field
    \note Name of the inlet node for this compound object
    \note Must match the supply air inlet node name in the air-to-air heat exchanger object
A3 , \field Outlet node name
    \required-field
    \note Name of the outlet node for this compound object
    \note Must match the exhaust (secondary) air outlet node name in the
    \note air-to-air heat exchanger object
A4 , \field Heat exchanger type
    \required-field
    \choice
    \key Heat Exchanger:Air to Air:Flat Plate
    \key Heat Exchanger:Air to Air:Generic
A5 , \field Heat exchanger name
    \required-field
A6 , \field Cooling coil type
    \required-field
    \choice
    \key COIL:Water:SimpleCooling
    \key COIL:Water:DetailedFlatCooling
A7 , \field Cooling coil name
    \required-field
A8 , \field Cooling coil inlet node name
    \required-field
    \note Must match the supply air outlet node name in the air-to-air heat exchanger object
    \note and also match the inlet air node name in the cooling coil object
A9 ; \field Heat exchanger exhaust air inlet node name
    \required-field
    \note Must match the exhaust (secondary) air inlet node name in the air-to-air
    \note heat exchanger object and also match the outlet node name in the cooling coil object

```

Following is an example input for this compound object:

```

COIL:Water:CoolingHeatExchangerAssisted,
  HeatExchangerAssistedCoolingCoil,      ! Name of the heat exchanger assisted cooling coil
  HeatExchangerSupplyAirInletNode,        ! Inlet node name
  HeatExchangerExhaustAirOutletNode,      ! Outlet node name
  Heat Exchanger:Air to Air:Generic,       ! Heat exchanger type
  Heat Exchanger Assisting Cooling Coil,  ! Heat exchanger name
  COIL:Water:SimpleCooling,               ! Cooling coil type
  ZoneCoolingCoil,                       ! Cooling coil name
  CoolingCoilInletNode,                   ! Cooling coil inlet node name
  HeatExchangerExhaustAirInletNode;       ! Heat exchanger exhaust air inlet node name

HEAT EXCHANGER:AIR TO AIR:GENERIC,
  HeatExchangerAssistedCoolingCoil,      !- Heat exchanger name
  FanAndCoilAvailSched,                  !- Availability schedule name
  0.84,                                  !- Nominal supply air flow rate {m3/s}
  .2,                                    !- Sensible effectiveness at 100% airflow heating condition
  .0,                                    !- Latent effectiveness at 100% airflow heating condition
  .23,                                  !- Sensible effectiveness at 75% airflow heating condition
  .0,                                    !- Latent effectiveness at 75% airflow heating condition
  .2,                                    !- Sensible effectiveness at 100% airflow cooling condition
  .0,                                    !- Latent effectiveness at 100% airflow cooling condition
  .23,                                  !- Sensible effectiveness at 75% airflow cooling condition
  .0,                                    !- Latent effectiveness at 75% airflow cooling condition
  HeatExchangerSupplyAirInletNode,        !- Supply air inlet node name
  CoolingCoilInletNode,                   !- Supply air outlet node name
  HeatExchangerExhaustAirInletNode,       !- Exhaust air inlet node name
  HeatExchangerExhaustAirOutletNode,     !- Exhaust air outlet node name
  50.0,                                   !- Nominal electric power {W}
  No,                                     !- Supply air outlet temperature control
  Rotary,                                 !- Heat exchanger type
  None;                                   !- Frost control type

```

```

COIL:Water:SimpleCooling,
  ZoneCoolingCoil,           !- Coil Name
  FanAndCoilAvailSched,      !- Available Schedule
  600.,                      !- UA of the Coil {W/K}
  0.0010,                    !- Max Water Flow Rate of Coil {m3/s}
  0.9,                      !- Leaving Relative Humidity of Coil
  ChWInletNode,              !- Coil_Water_Inlet_Node
  ChWOutletNode,             !- Coil_Water_Outlet_Node
  CoolingCoilInletNode,      !- Coil_Air_Inlet_Node
  HeatExchangerExhaustAirInletNode; !- Coil_Air_Outlet_Node

```


Appendix E

EnergyPlus Documentation for a Heat Transfer Coefficient Calculator and Autosizing for the Cooling Tower Model

This appendix contains the EnergyPlus documentation (Input/Output Reference and Engineering Manual) that describes using cooling tower models and the improvements added as part of this project.

Input Output Reference for Cooling Tower:Single Speed

Cooling towers are components that may be assigned to condenser loops. The closed-circuit cooling tower is modeled as a counterflow heat exchanger with a single-speed fan (induced draft configuration) based on Merkel's theory. The user must define tower performance via one of two methods: design heat transfer coefficient-area product (UA) and design water flow rate, or nominal tower capacity at a specific rating point. Regardless of which method is chosen, the design airflow rate and corresponding fan power must be specified. The model will also account for tower performance in the "free convection" regime, when the tower fan is off but the water pump remains on and heat transfer still occurs (albeit at a low level). If the user wants the model to account for "free convection", they must specify the corresponding airflow rate and heat transfer coefficient-area product (UA), or the nominal tower capacity during this mode of operation.

The cooling tower seeks to maintain the temperature of the water exiting the cooling tower at (or below) a set point. The set point schedule is defined by the field "Condenser Loop Temperature Setpoint schedule or reference" for the CONDENSER LOOP object. The model first checks to determine the impact of "free convection", if specified by the user, on the tower exiting water temperature. If the exiting water temperature based on "free convection" is at or below the set point, then the tower fan is not turned on. If the exiting water temperature remains above the set point after "free convection" is modeled, then the tower fan is turned on to reduce the exiting water temperature to the set point. The model assumes that part-load operation is represented by a simple linear interpolation between two steady-state regimes (i.e., tower fan on for the entire simulation time step and tower fan off for the entire simulation time step). Cyclic losses are not taken into account.

The IDD specification for the single-speed cooling tower is given below.

```
COOLING TOWER:SINGLE SPEED,
  \min-fields 9
  \memo This tower model is based on Merkel's theory, which is also the basis
  \memo for the tower model in ASHRAE's HVAC1 Toolkit. The closed-circuit cooling tower
  \memo is modeled as a counterflow heat exchanger with a single-speed fan drawing air
  \memo through the tower (induced-draft configuration).
A1 , \field Tower Name
    \required-field
    \type alpha
    \note Tower name
A2 , \field Water Inlet Node Name
    \required-field
    \type alpha
    \note Name of tower water inlet node
A3 , \field Water Outlet Node Name
    \required-field
    \type alpha
    \note Name of tower water outlet node
N1 , \field Design Water Flow Rate
    \type real
    \units m3/s
    \minimum> 0.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
    \ip-units gal/min
```

```

N2 , \field Design Air Flow Rate
    \required-field
    \type real
    \units m3/s
    \minimum> 0.0
    \autosizable
N3 , \field Fan Power at Design Air Flow Rate
    \required-field
    \type real
    \units W
    \minimum> 0.0
    \autosizable
    \ip-units W
N4 , \field Tower UA Value at Design Air Flow Rate
    \type real
    \units W/K
    \minimum> 0.0
    \maximum 300000.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
N5 , \field Air Flow Rate in Free Convection Regime
    \type real
    \units m3/s
    \minimum 0.0
    \default 0.0
    \autosizable
N6 , \field Tower UA Value at Free Convection Air Flow Rate
    \type real
    \units W/K
    \minimum 0.0
    \maximum 300000.0
    \default 0.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
A4 , \field Tower Performance Input Method
    \type Choice
    \key UA and Design Water Flow Rate
    \key Nominal Capacity
    \default Nominal Capacity
    \note User can define tower thermal performance by specifying the tower UA
    \note and the Design Air Flow Rate, or by specifying the tower nominal capacity
N7 , \field Tower Nominal Capacity
    \type real
    \units W
    \minimum> 0.0
    \note Nominal tower capacity with entering water at 35C (95F), leaving water at
    \note 29.44C (85F), entering air at 25.56C (78F) wet-bulb temperature and 35C (95F)
    \note dry-bulb temperature. Design water flow rate assumed to be 5.382E-8 m3/s per watt
    \note (3 gpm/ton). Nominal tower capacity times (1.25) gives the actual tower
    \note heat rejection at these operating conditions.
N8 ; \field Tower Free Convection Capacity
    \type real
    \units W
    \minimum 0.0
    \note Tower capacity in free convection regime with entering water at 35C (95F),
    \note leaving water at 29.44C (85F), entering air at 25.56C (78F) wet-bulb temperature
    \note and 35C (95F) dry-bulb temperature. Design water flow rate assumed to be
    \note 5.382E-8 m3/s per watt of nominal tower capacity (3 gpm/ton). Tower free
    \note convection capacity times (1.25) gives the actual tower heat rejection at these
    \note operating conditions.

```

Field: Tower Name

This alpha field contains the identifying name for the cooling tower.

Field: Water Inlet Node Name

This alpha field contains the identifying name for the cooling tower's water inlet node.

Field: Water Outlet Node Name

This alpha field contains the identifying name for the cooling tower's water outlet node.

Field: Design Water Flow Rate

This numeric field contains the design water flow rate through the tower in m³/s. This value is the flow rate of the condenser loop water being cooled by the tower (not the flow rate of water being sprayed on the outside of the heat exchange coil). If the input field "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then a water flow rate greater than zero must be defined or the field can be autosized. If autosized, a Plant Sizing object must be defined and the design water flow rate is derived from the design load to be rejected by the condenser loop and the design loop delta T. If "Tower Performance Input Method" is specified as "Nominal Capacity", then this field must be left blank since the model automatically assumes a water flow rate of 5.382E-8 m³/s per watt (3 gpm/ton) of tower capacity specified in the field "Tower Nominal Capacity".

Field: Design Air Flow Rate

This numeric field contains the design air flow rate induced by the tower fan in m³/s. A value greater than zero must be defined regardless of the tower performance input method. Alternately, this field can be autosized. If autosized, the design air flow rate is calculated as follows:

$$\text{Design Air FlowRate} = \frac{0.5 \mathbf{r}_{air} (\text{Fan power at Design Air Flow Rate})}{190.}$$

where a fan pressure rise of 190 Pascals and total fan efficiency of 0.5 are assumed.

Field: Fan Power at Design Air Flow Rate

This numeric field contains the fan power (in watts) at the design air flow rate specified in the previous field. A value greater than zero must be specified regardless of the tower performance input method, or this field can be autosized. If autosized, the fan power is calculated as follows:

If "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then

$$\text{Fan power} = 0.0105 \cdot \mathbf{r}_{water} \cdot C_{p,water} \cdot \text{DesignWater Flow Rate} \cdot \text{Design Loop} \Delta T$$

is used.

If "Tower Performance Input Method" is specified as "Nominal Capacity", then

$$\text{Fan power} = 0.0105 \cdot \text{Tower NominalCapacity}$$

is used.

Field: Tower UA Value at Design Air Flow Rate

This numeric field contains the heat transfer coefficient-area product (UA) in watts per degree Celsius corresponding to the design air and water flow rates specified above. If the input field "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then a UA value greater than zero but less than or equal to 300,000 must be defined, or the field can be autosized. If autosized, a Plant Sizing object must be defined and the design tower UA value is derived from the design load to be rejected by the condenser loop and the design loop delta T, assuming a tower water inlet temperature of 35C and tower inlet air at 35C drybulb/25.6C wetbulb. If "Tower Performance Input Method" is specified as "Nominal Capacity", then this field must be left blank since the model automatically calculates the tower UA based on the tower capacity specified in the field "Tower Nominal Capacity".

Field: Air Flow Rate in Free Convection Regime

This numeric field contains the air flow rate (m³/s) when the tower is in the "free convection" regime (water flow exists but tower fan is turned off). This value must be less than the value specified for the field "Design Air Flow Rate". This field may be autosized, in which case it is

set to 10% of the “Design Air Flow Rate”. If the user does not wish to model “free convection” and is using the Tower Performance Input Method “UA and Design Water Flow”, then this field should be set to 0.0. If the user specifies the Tower UA Value at Free Convection Air Flow Rate or Tower Free Convection Capacity as a value greater than zero, then the free convection air flow rate must be specified greater than 0.0.

Field: Tower UA Value at Free Convection Air Flow Rate

This numeric field contains the heat transfer coefficient-area product (W/°C) when the tower is in the “free convection” regime (water flow exists but tower fan is turned off). This value must be less than the value specified for the field “Tower UA Value at Design Air Flow Rate”. This field may be autosized, in which case it is set to 10% of the “Tower UA Value at Design Air Flow Rate”. If the user does not wish to model “free convection” and is using the Tower Performance Input Method “UA and Design Water Flow”, then this field should be set to 0.0. If “Tower Performance Input Method” is specified as “Nominal Capacity”, then this field must be left blank since the model automatically calculates the tower UA based on the tower capacity specified in the field “Tower Free Convection Capacity”.

Field: Tower Performance Input Method

This alpha field contains the method by which the user will specify tower performance: “UA and Design Water Flow Rate” or “Nominal Capacity”. If this field is left blank in the input data file, the default input method is assumed to be “Nominal Capacity”. If the method “UA and Design Water Flow Rate” is selected, then the user must enter design UA values, design water flow rates and air flow rates as described for the previous input fields. If the method “Nominal Capacity” is selected then the fields “Design Water Flow Rate”, “Tower UA Value at Design Air Flow Rate” and “Tower UA Value at Free Convection Air Flow Rate” must be left blank, but the fields “Nominal Tower Capacity” and “Tower Free Convection Capacity” must be entered as described below.

Field: Tower Nominal Capacity

This numeric input field contains the “nominal” heat rejection capacity of the cooling tower in watts, with entering water at 35C (95F), leaving water at 29.4C (85F), entering air at 25.6C (78F) wetbulb and 35C (95F) drybulb temperatures. The design water flow rate is assumed to be 5.382E-8 m³/s per watt of nominal capacity (3 gpm/ton). 125% of this nominal tower capacity gives the actual tower heat rejection at these operating conditions (based on historical assumption that the tower must dissipate 0.25W of compressor heat for every watt of heat removed by the evaporator).

Field: Tower Free Convection Capacity

This numeric input field contains the “nominal” heat rejection capacity of the cooling tower in watts when the tower is in the “free convection” regime (water flow exists but tower fan is turned off), with entering water at 35C (95F), leaving water at 29.4C (85F), entering air at 25.6C (78F) wetbulb and 35C (95F) drybulb temperatures. The design water flow rate is assumed to be 5.382E-8 m³/s per watt of nominal tower capacity (input field above). 125% of this free convection tower capacity gives the actual tower heat rejection at these operating conditions (based on historical assumption that the tower must dissipate 0.25W of compressor heat for every watt of heat removed by the evaporator). The value specified for this field must be less than the value specified for the field “Tower Nominal Capacity”. If the user does not wish to model “free convection”, then this field should be set to 0.0. If the user specifies a value greater than zero, then the “Air Flow Rate in Free Convection Regime” field must contain a value greater than zero.

Two examples of an IDF specification for this object are shown below:

```

COOLING TOWER:SINGLE SPEED,
My Tower,                ! Tower name
Condenser Tower Inlet Node, ! Tower inlet water node name
Condenser Tower Outlet Node, ! Tower outlet water node name
.0011,                   ! Design water flow rate, m3/s
16.0,                    ! Design air flow rate, m3/s
10000.,                  ! Fan power at design air flow, W
3500.,                   ! Tower UA at design flow rates, W/C
0.0,                     ! Air flow rate for free convection, m3/s
0.0,                     ! Tower UA at free convection air flow, W/C
UA AND DESIGN WATER FLOW RATE;! Tower Performance Input Method

```

```

COOLING TOWER:SINGLE SPEED,
My Tower,                ! Tower name
Condenser Tower Inlet Node, ! Tower inlet water node name
Condenser Tower Outlet Node,! Tower outlet water node name
,                        ! Design water flow rate, m3/s
autosize,                ! Design air flow rate, m3/s
1000.,                   ! Fan power at design air flow, W
,                        ! Tower UA at design flow rates, W/C
autosize,                ! Air flow rate for free convection, m3/s
,                        ! Tower UA at free convection air flow, W/C
NOMINAL CAPACITY,       ! Tower Performance Input Method
95250.,                  ! Tower Nominal Capacity
9525.;                   ! Tower Free Convection Capacity

```

Cooling Tower:Single Speed Outputs

```

HVAC,Average,Tower Fan Electric Power [W]
HVAC,Sum,Tower Fan Electric Consumption [J]
Zone,Meter,HeatRejection:Electricity [J]

HVAC,Average,Tower Heat Transfer [W]

HVAC,Average,Tower Water Inlet Temp [C]
HVAC,Average,Tower Water Outlet Temp [C]
HVAC,Average,Tower Water Mass Flow Rate [kg/s]

```

Tower Fan Electric Power [W]

Tower Fan Electric Consumption [J]

These outputs are the electric power input to the tower fans. Consumption is metered on HeatRejection:Electricity, Electricity:Plant, and Electricity:Facility.

Tower Heat Transfer [W]

This is the rate at which heat is removed from the condenser water loop by the tower.

Tower Water Inlet Temp [C]

Tower Water Outlet Temp [C]

Tower Water Mass Flow Rate [kg/s]

These outputs are the tower water inlet and outlet temperatures, and mass flow rate.

Engineering Document for Cooling Towers

Overview

The EnergyPlus cooling tower model is based on Merkel's theory (Merkel 1925), which is also the basis for the tower model included in ASHRAE's HVAC1 Toolkit for primary HVAC system energy calculations (ASHRAE 1999, Bourdouxhe et al. 1994). Cooling tower performance is modeled using effectiveness-NTU relationships for counterflow heat exchangers. The model can be used to simulate the performance of both single speed and two speed mechanical-draft cooling towers. The model will also account for tower performance in the "free convection" regime, when the tower fan is off but the water pump

remains on. For part-load operation, the model assumes a simple linear interpolation between two steady-state regimes without accounting for any cycling losses.

Model Description

Based on Merkel's theory, the steady-state total heat transfer between the air and water entering the tower can be defined by the following equation:

$$d\dot{Q}_{total} = \frac{UdA}{c_p} (h_s - h_a) \quad (0.26)$$

where

h_s = enthalpy of saturated air at the wetted-surface temperature, J/kg

h_a = enthalpy of air in the free stream, J/kg

c_p = specific heat of moist air, J/kg-°C

U = cooling tower overall heat transfer coefficient, W/m²-°C

A = heat transfer surface area, m²

Equation (0.26) is based on several assumptions:

- air and water vapor behave as ideal gases
- the effect of water evaporation is neglected
- fan heat is neglected
- the interfacial air film is assumed to be saturated
- the Lewis number is equal to 1

In this model, it is also assumed that the moist air enthalpy is solely a function of the wet-bulb temperature and that the moist air can be treated as an equivalent ideal gas with its mean specific heat defined by the following equation:

$$\bar{c}_{pe} = \frac{\Delta h}{\Delta T_{wb}} \quad (0.27)$$

where

Δh = enthalpy difference between the air entering and leaving the tower, J/kg

ΔT_{wb} = wet-bulb temperature difference between the air entering and leaving the tower, °C

Since the liquid side conductance is much greater than the gas side conductance, the wetted-surface temperature is assumed to be equal to the water temperature. Based on this assumption and equations (0.26) and (0.27), the expression for total heat transfer becomes:

$$d\dot{Q}_{total} = U_e dA (T_w - T_{wb}) \quad (0.28)$$

where

$$U_e = \frac{U \bar{c}_{pe}}{c_p}$$

T_{wb} = wet-bulb temperature of the air, °C

T_w = temperature of the water, °C

An energy balance on the water and air sides of the air/water interface yields the following equations:

$$d\dot{Q}_{total} = \dot{m}_w c_{pw} dT_w \quad (0.29)$$

$$d\dot{Q}_{total} = \dot{m}_a \bar{c}_{pe} dT_{wb} \quad (0.30)$$

where

$\dot{m}_w$ = mass flow rate of water, kg/s

$\dot{m}_a$ = mass flow rate of air, kg/s

Assuming that the heat capacity rate ($\dot{m}c_p$) for the cooling tower water is less than that for the air, the effectiveness of the cooling tower can be defined by analogy to the effectiveness of a simple heat exchanger:

$$e = \frac{T_{win} - T_{wout}}{T_{win} - T_{wbin}} \quad (0.31)$$

where

e = heat exchanger effectiveness

T_{win} = inlet water temperature, °C

T_{wout} = outlet water temperature, °C

T_{wbin} = wet-bulb temperature of the inlet air, °C

Combining equations (0.28), (0.29), and (0.30) and integrating over the entire heat transfer surface area, and combining the result with equation (0.31) provides the following expression for cooling tower effectiveness:

$$e = \frac{1 - \exp \left\{ -NTU \left[1 - \left(\dot{C}_w / \dot{C}_a \right) \right] \right\}}{1 - \left(\dot{C}_w / \dot{C}_a \right) \exp \left\{ -NTU \left[1 - \left(\dot{C}_w / \dot{C}_a \right) \right] \right\}} \quad (0.32)$$

where

$\dot{C}_w = \dot{m}_w c_{pw}$ and $\dot{C}_a = \dot{m}_a \bar{c}_{pe}$

$NTU = \text{Number of Transfer Units} = \frac{UA_e}{\dot{C}_w}$

This equation is identical to the expression for effectiveness of an indirect contact (i.e., fluids separated by a solid wall) counterflow heat exchanger (Incropera and DeWitt 1981). Therefore, the cooling tower can be modeled, in the steady-state regime, by an equivalent counterflow heat exchanger as shown in the following figure.

Figure 14. Cooling Tower Schematic

The first fluid is water and the second fluid is an equivalent fluid entering the heat exchanger at temperature $T_{wb in}$ and specific heat $\bar{c}_{pe}$. The heat exchanger is characterized by a single parameter, its overall heat transfer coefficient-area product UA_e . The actual cooling tower heat transfer coefficient-area product is related to UA_e by the following expression:

$$UA = UA_e \frac{c_p}{\bar{c}_{pe}} \quad (0.33)$$

This heat transfer coefficient-area product is assumed to be a function of the air mass flow rate only and can be estimated from laboratory test results or manufacturers' catalog data.

Method for Calculating Steady-State Exiting Water Temperature

The objective of the cooling tower model is to predict the exiting water temperature and the fan power required to meet the exiting water set point temperature. Since only the inlet air and inlet water temperatures are known at any simulation time step, an iterative procedure is required to determine the exiting fluid temperatures using the equations defined in the previous section. In the case of the EnergyPlus model, the iterations are performed to determine the exiting wet-bulb temperature of the air. The exiting water temperature is then calculated based on an energy balance that assumes that the energy absorbed by the air is equivalent to the energy removed from the water. The procedure for calculating the steady-state, exiting air wet-bulb temperature is outlined below.

As explained previously, it is assumed that the moist air enthalpy can be defined by the wet-bulb temperature alone. Therefore, the first step in the procedure is to calculate the enthalpy of moist air entering the cooling tower based on the ambient wet-bulb temperature from the weather file. Since an iterative solution is required, a first guess of the outlet air wet-bulb temperature is then made and the enthalpy of this estimated outlet air wet-bulb temperature is calculated. Based on these inlet and outlet air conditions, the mean specific heat of the air is calculated based on equation (0.27), repeated here:

$$\bar{c}_{pe} = \frac{\Delta h}{\Delta T_{wb}}$$

With the overall heat transfer coefficient-area product for the cooling tower entered by the user, the effective heat transfer coefficient-area product is calculated by rearranging equation (0.33):

$$UA_e = UA \frac{\bar{c}_{pe}}{c_p}$$

With $\bar{C}_{pe}$ and UA_e known, the effectiveness of the heat exchanger is then calculated:

$$e = \frac{1 - \exp \left\{ -NTU \left[1 - \left(\dot{C}_{\min} / \dot{C}_{\max} \right) \right] \right\}}{1 - \left(\dot{C}_{\min} / \dot{C}_{\max} \right) \exp \left\{ -NTU \left[1 - \left(\dot{C}_{\min} / \dot{C}_{\max} \right) \right] \right\}}$$

where

$$\dot{C}_{\min} = \text{Minimum}(\dot{C}_w, \dot{C}_a) \text{ and } \dot{C}_{\max} = \text{Maximum}(\dot{C}_w, \dot{C}_a)$$

$$\dot{C}_w = \dot{m}_w C_{pw} \text{ and } \dot{C}_a = \dot{m}_a \bar{C}_{pe}$$

$$NTU = \text{Number of Transfer Units} = \frac{UA_e}{\dot{C}_{\min}}$$

The heat transfer rate is then calculated as follows:

$$\dot{Q}_{total} = e \dot{C}_{\min} (T_{win} - T_{wbin})$$

The outlet air wet-bulb temperature is then recalculated:

$$T_{wbout} = T_{wbin} + \frac{\dot{Q}_{total}}{\dot{C}_a}$$

The iterative process of calculating T_{wbout} continues until convergence is reached.

Finally, the outlet water temperature is calculated as follows:

$$T_{wout} = T_{win} + \frac{\dot{Q}_{total}}{\dot{C}_w}$$

Calculating the Actual Exiting Water Temperature and Fan Power

The previous section describes the methodology used for calculating the steady-state temperature of the water leaving the cooling tower. This methodology is used to calculate the exiting water temperature in the free convection regime (water pump on, tower fan off) and with the tower fan operating (including low and high fan speed for the two-speed tower). The exiting water temperature calculations use the fluid flow rates (water and air) and the UA-values entered by the user for each regime.

The cooling tower model seeks to maintain the temperature of the water exiting the cooling tower at (or below) a set point. The set point schedule is defined by the field “Loop Temperature Setpoint Schedule Name” for the CONDENSER LOOP object. The model first checks to determine the impact of “free convection”, if specified by the user, on the tower exiting water temperature. If free convection is not specified by the user, then the exiting water temperature is initially set equal to the entering tower water temperature. If the user specifies “free convection” and the steady-state exiting water temperature based on “free convection” is at or below the set point, then the tower fan is not turned on.

If the exiting water temperature remains above the set point after “free convection” is modeled, then the tower fan is turned on to reduce the exiting water temperature to the set point. The model assumes that part-load operation is represented by a simple linear interpolation between two steady-state regimes (e.g., tower fan on for the entire simulation

time step and tower fan off for the entire simulation time step). Cyclic losses are not taken into account.

The fraction of time that the tower fan must operate is calculated based on the following equation:

$$w = \frac{T_{set} - T_{wout, off}}{T_{wout, on} - T_{wout, off}} \quad (0.34)$$

where

T_{set} = exiting water set point temperature, °C

$T_{wout, off}$ = exiting water temperature with tower fan off, °C

$T_{wout, on}$ = exiting water temperature with tower fan on, °C

The average fan power for the simulation time step is calculated by multiplying w by the steady-state fan power specified by the user.

The calculation method for the two-speed tower is similar to that for the single-speed tower example described above. The model first checks to see if “free convection” is specified and if the resulting exiting water temperature is below the set point temperature. If not, then the model calculates the steady-state exiting water temperature with the tower fan at low speed. If the exiting water temperature at low fan speed is below the set point temperature, then the average fan power is calculated based on the result of equation (0.34) and the steady-state, low speed fan power specified by the user. If low-speed fan operation is unable to reduce the exiting water temperature below the set point, then the tower fan is increased to its high speed and the steady-state exiting water temperature is calculated. If this temperature is below the set point, then a modified version of equation (0.34) is used to calculate runtime at high fan speed:

$$w = \frac{T_{set} - T_{wout, low}}{T_{wout, high} - T_{wout, low}} \quad (0.35)$$

where

T_{set} = exiting water set point temperature, °C

$T_{wout, low}$ = exiting water temperature with tower fan at low speed, °C

$T_{wout, high}$ = exiting water temperature with tower fan at high speed, °C

The average fan power for the simulation time step is calculated for the two-speed cooling tower as follows:

$$Power_{fan, avg} = w(Power_{fan, high}) + (1 - w)(Power_{fan, low}) \quad (0.36)$$

References

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- Clark, D.R., HVACSIM+ Building Systems and Equipment Simulation Program Reference Manual, Pub. No. NBSIR 84-2996, National Bureau of Standards, U.S. Department of Commerce, January, 1985

Elmahdy, A.H., Analytical and Experimental Multi-Row Finned-Tube Heat Exchanger Performance During Cooling and Dehumidifying Processes , Ph.D. Thesis, Carleton University, Ottawa, Canada, December, 1975.

Elmahdy, A.H., and Mitalas, G.P., "A Simple Model for Cooling and Dehumidifying Coils for Use in Calculating Energy Requirements for Buildings," ASHRAE Transactions , 1977 , Vol. 83, Part 2, pp. 103-117.

Incropera, F.P. and D.P. DeWitt. 1981. Fundamentals of Heat Transfer. New York: John Wiley & Sons.

Merkel, F. 1925. Verduftungskuhlung. VDI Forschungarbeiten, No 275, Berlin.

Input Output Reference for Cooling Tower:Two Speed

The two-speed cooling tower is modeled in a similar fashion to the single-speed tower. The closed-circuit cooling tower is modeled as a counterflow heat exchanger with a two-speed fan (induced draft configuration) based on Merkel's theory. The user must define tower performance via one of two methods: heat transfer coefficient-area product (UA) and design water flow rate, or nominal tower capacity at a specific rating point. Regardless of which method is chosen, the airflow rate and corresponding fan power at both high and low fan speed must be specified. The model will also account for tower performance in the "free convection" regime, when the tower fan is off but the water pump remains on and heat transfer still occurs (albeit at a low level). If the user wants the model to account for "free convection", they must specify the corresponding air flow rate and heat transfer coefficient-area product (UA), or the nominal tower capacity during this mode of operation.

The cooling tower seeks to maintain the temperature of the water exiting the cooling tower at (or below) a set point. The set point schedule is defined by the field "Condenser Loop Temperature Setpoint schedule or reference" for the CONDENSER LOOP object. The model first checks to determine the impact of "free convection", if specified by the user, on the tower exiting water temperature. If the exiting water temperature based on "free convection" is at or below the set point, then the tower fan is not turned on. If the exiting water temperature remains above the set point after "free convection" is modeled, then the tower fan is turned on at low speed to reduce the exiting water temperature. If operating the tower fan at low speed does not reduce the exiting water temperature to the set point, then the tower fan is increased to its high speed.

The model assumes that part-load operation is represented by a simple linear interpolation between two steady-state regimes (i.e., tower fan at high speed for the entire simulation time step and tower fan at low speed for the entire simulation time step, or tower fan at low speed for the entire simulation time step and tower fan off for the entire simulation time step). Cyclic losses are not taken into account.

The IDD specification for the two-speed cooling tower is given below.

```
COOLING TOWER:TWO SPEED,
  \min-fields 12
    \memo This tower model is based on Merkel's theory, which is also the basis
    \memo for the tower model in ASHRAE's HVAC1 Toolkit. The closed-circuit cooling tower
    \memo is modeled as a counterflow heat exchanger with a two-speed fan drawing air
    \memo through the tower (induced-draft configuration).
  A1 , \field Tower Name
    \required-field
    \type alpha
    \note Tower name
  A2 , \field Water Inlet Node Name
    \required-field
    \type alpha
    \note Name of tower water inlet node
  A3 , \field Water Outlet Node Name
    \required-field
    \type alpha
    \note Name of tower water outlet node
  N1 , \field Design Water Flow Rate
    \type real
    \units m3/s
    \minimum> 0.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
    \ip-units gal/min
```

```

N2 , \field Air Flow Rate at High Fan Speed
    \required-field
    \type real
    \units m3/s
    \minimum> 0.0
    \autosizable
N3 , \field Fan Power at High Fan Speed
    \required-field
    \type real
    \units W
    \minimum> 0.0
    \autosizable
    \ip-units W
N4 , \field Tower UA Value at High Fan Speed
    \type real
    \units W/K
    \minimum> 0.0
    \maximum 300000.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
N5 , \field Air Flow Rate at Low Fan Speed
    \required-field
    \type real
    \units m3/s
    \minimum> 0.0
    \autosizable
    \note Low speed air flow rate must be less than high speed air flow rate
    \note Low speed air flow rate must be greater than free convection air flow rate
N6 , \field Fan Power at Low Fan Speed
    \required-field
    \type real
    \units W
    \minimum> 0.0
    \autosizable
    \ip-units W
N7 , \field Tower UA Value at Low Fan Speed
    \type real
    \units W/K
    \minimum> 0.0
    \maximum 300000.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
    \note Low speed tower UA must be less than high speed tower UA
    \note Low speed tower UA must be greater than free convection tower UA
N8 , \field Air Flow Rate in Free Convection Regime
    \type real
    \units m3/s
    \minimum 0.0
    \default 0.0
    \autosizable
N9 , \field Tower UA Value at Free Convection Air Flow Rate
    \type real
    \units W/K
    \minimum 0.0
    \maximum 300000.0
    \default 0.0
    \autosizable
    \note Leave field blank if Tower Performance Input Method is NOMINAL CAPACITY
A4 , \field Tower Performance Input Method
    \type Choice
    \key UA and Design Water Flow Rate
    \key Nominal Capacity
    \default Nominal Capacity
    \note User can define tower thermal performance by specifying the tower UA
    \note and the Design Air Flow Rate, or by specifying the tower nominal capacity
N10, \field Tower High-Speed Nominal Capacity
    \type real
    \units W
    \minimum> 0.0
    \note Nominal tower capacity with entering water at 35C (95F), leaving water at
    \note 29.44C (85F), entering air at 25.56C (78F) wet-bulb temperature and 35C (95F)
    \note dry-bulb temperature, with the tower fan operating at high speed. Design water
    \note flow rate assumed to be 5.382E-8 m3/s per watt(3 gpm/ton). Nominal tower capacity
    \note times (1.25) gives the actual tower heat rejection at these operating conditions.
N11, \field Tower Low-Speed Nominal Capacity

```

```

\type real
\units W
\minimum> 0.0
\note Nominal tower capacity with entering water at 35C (95F), leaving water at
\note 29.44C (85F), entering air at 25.56C (78F) wet-bulb temperature and 35C (95F)
\note dry-bulb temperature, with the tower fan operating at low speed. Design water flow
\note rate assumed to be 5.382E-8 m3/s per watt of tower high-speed nominal capacity
\note (3 gpm/ton). Nominal tower capacity times (1.25) gives the actual tower heat
\note rejection at these operating conditions.
N12: \field Tower Free Convection Capacity
\type real
\units W
\minimum 0.0
\note Tower capacity in free convection regime with entering water at 35C (95F),
\note leaving water at 29.44C (85F), entering air at 25.56C (78F) wet-bulb temperature
\note and 35C (95F) dry-bulb temperature. Design water flow rate assumed to be
\note 5.382E-8 m3/s per watt of tower high-speed nominal capacity (3 gpm/ton). Tower
\note free convection capacity times (1.25) gives the actual tower heat rejection at
\note these operating conditions.

```

Field: Tower Name

This alpha field contains the identifying name for the cooling tower.

Field: Water Inlet Node Name

This alpha field contains the identifying name for the cooling tower's water inlet node.

Field: Water Outlet Node Name

This alpha field contains the identifying name for the cooling tower's water outlet node.

Field: Design Water Flow Rate

This numeric field contains the design water flow rate through the tower in m³/s. This value is the flow rate of the condenser loop water being cooled by the tower (not the flow rate of water being sprayed on the outside of the heat exchange coil). If the input field "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then a water flow rate greater than zero must be defined or the field can be autosized. If autosized, a Plant Sizing object must be defined and the design water flow rate is derived from the design load to be rejected by the condenser loop and the design loop delta T. If "Tower Performance Input Method" is specified as "Nominal Capacity", then this field must be left blank since the model automatically assumes a design water flow rate of 5.382E-8 m³/s per watt (3 gpm/ton) of tower capacity specified in the field "Tower High-Speed Nominal Capacity".

Field: Air Flow Rate at High Fan Speed

This numeric field contains the tower air flow rate at high fan speed in m³/s. A value greater than zero must be defined regardless of the tower performance input method. Alternately, this field can be autosized. If autosized, the design air flow rate is calculated as follows:

$$AirFlowRateatHighFanSpeed = \frac{0.5 \mathbf{r}_{air} (FanPoweratHighFanSpeed)}{190.}$$

where a fan pressure rise of 190 Pascals and total fan efficiency of 0.5 are assumed.

Field: Fan Power at High Fan Speed

This numeric field contains the fan power (in Watts) at the high-speed air flow rate specified in the previous field. A value greater than zero must be specified regardless of the tower performance input method, or this field can be autosized. If autosized, the fan power is calculated as follows:

If "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then

$$Fan\ power_{HighFanSpeed} = 0.0105 \cdot \mathbf{r}_{water} \cdot C_{pwater} \cdot DesignWater\ FlowRate \cdot DesignLoop\Delta T$$

is used.

If "Tower Performance Input Method" is specified as "Nominal Capacity", then

$$Fan\ power_{HighFanSpeed} = 0.0105 \cdot Tower\ High-Speed\ NominalCapacity$$

is used.

Field: Tower UA Value at High Fan Speed

This numeric field contains the heat transfer coefficient-area product (UA) in watts per degree Celsius corresponding to the high-speed air flow rate and design water flow rate specified above. If the input field "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", then a UA value greater than zero but less than or equal to 300,000 must be defined, or the field can be autosized. If autosized, a Plant Sizing object must be defined and the tower UA value at high fan speed is derived from the design load to be rejected by the condenser loop and the design loop delta T, assuming a tower water inlet temperature of 35C and tower inlet air at 35C drybulb/25.6C wetbulb. If "Tower Performance Input Method" is specified as "Nominal Capacity", then this field must be left blank since the model automatically calculates the tower UA based on the capacity specified in the field "Tower High-Speed Nominal Capacity".

Field: Air Flow Rate at Low Fan Speed

This numeric field contains the tower air flow rate at low fan speed in m³/s. This value must be greater than zero, less than the value specified for the field "Air Flow Rate at High Fan Speed", and greater than the value specified for the field "Air Flow Rate in Free Convection Regime". This field may be autosized, in which case it is set to 50% of the "Air Flow Rate at High Fan Speed".

Field: Fan Power at Low Fan Speed

This numeric field contains the fan power (in Watts) at the low-speed air flow rate specified in the previous field. This value must be specified greater than zero or the field may be autosized, in which case it is set to 16% of the "Fan Power at High Fan Speed".

Field: Tower UA Value at Low Fan Speed

This numeric field contains the heat transfer coefficient-area product (UA) in watts per degree Celsius corresponding to the design water flow rate and low-speed air flow rate specified above. If the input field "Tower Performance Input Method" is specified as "UA and Design Water Flow Rate", this value must be greater than zero but less than or equal to 300,000, less than the value specified for the field "Tower UA Value at High Fan Speed", and greater than the value specified for the field "Tower UA Value at Free Convection Flow Rate". This field may be autosized, in which case it is set to 60% of the "Tower UA Value at High Fan Speed". If "Tower Performance Input Method" is specified as "Nominal Capacity", then this field must be left blank since the model automatically calculates the tower UA based on the tower capacity specified in the field "Tower Low-Speed Nominal Capacity".

Field: Air Flow Rate in Free Convection Regime

This numeric field contains the air flow rate (m³/s) when the tower is in the "free convection" regime (water flow exists but tower fan is turned off). This value must be less than the value specified for the field "Air Flow Rate at Low Fan Speed". This field may be autosized, in which case it is set to 10% of the "Air Flow Rate at High Fan Speed". If the user does not wish to model "free convection" and is using the Tower Performance Input Method "UA and Design Water Flow", then this field should be set to 0.0. If the user specifies the Tower UA Value at Free Convection Air Flow Rate or Tower Free Convection Capacity as a value greater than zero, then the free convection air flow rate must be specified greater than 0.0.

Field: Tower UA Value at Free Convection Air Flow Rate

This numeric field contains the heat transfer coefficient-area product (W/°C) when the tower is in the "free convection" regime (water flow exists but tower fan is turned off). This value must be less than the value specified for the field "Tower UA Value at Low Fan Speed". This field may be autosized, in which case it is set to 10% of the "Tower UA Value at High Fan Speed". If the user does not wish to model "free convection" and is using the Tower Performance Input Method "UA and Design Water Flow", then this field should be set to 0.0.

If “Tower Performance Input Method” is specified as “Nominal Capacity”, then this field must be left blank since the model automatically calculates the tower UA based on the tower capacity specified in the field “Tower Free Convection Capacity”.

Field: Tower Performance Input Method

This alpha field contains the method by which the user will specify tower performance: “UA and Design Water Flow Rate” or “Nominal Capacity”. If this field is left blank in the input data file, the default input method is assumed to be “Nominal Capacity”. If the method “UA and Design Water Flow Rate” is selected, then the user must enter UA values, design water flow rate and air flow rates as described for the previous input fields. If the method “Nominal Capacity” is selected then the fields “Design Water Flow Rate”, “Tower UA Value at High Fan Speed”, “Tower UA Value at Low Fan Speed” and “Tower UA Value at Free Convection Air Flow Rate” must be left blank, but the fields “Tower High-Speed Nominal Capacity”, “Tower Low-Speed Nominal Capacity” and “Tower Free Convection Capacity” must be entered as described below.

Field: Tower High-Speed Nominal Capacity

This numeric input field contains the “nominal” heat rejection capacity of the cooling tower in watts under high-speed fan operation, with entering water at 35C (95F), leaving water at 29.4C (85F), entering air at 25.6C (78F) wetbulb and 35C (95F) drybulb temperatures. The design water flow rate is assumed to be $5.382\text{E-}8 \text{ m}^3/\text{s}$ per watt of high-speed nominal capacity (3 gpm/ton). 125% of this nominal tower capacity gives the actual tower heat rejection at these operating conditions (based on historical assumption that the tower must dissipate 0.25W of compressor heat for every watt of heat removed by the evaporator).

Field: Tower Low-Speed Nominal Capacity

This numeric input field contains the “nominal” heat rejection capacity of the cooling tower in watts under low-speed fan operation, with entering water at 35C (95F), leaving water at 29.4C (85F), entering air at 25.6C (78F) wetbulb and 35C (95F) drybulb temperatures. The design water flow rate is assumed to be $5.382\text{E-}8 \text{ m}^3/\text{s}$ per watt of high-speed nominal tower capacity (input field above). 125% of this nominal tower capacity gives the actual tower heat rejection at these operating conditions (based on historical assumption that the tower must dissipate 0.25W of compressor heat for every watt of heat removed by the evaporator). The value specified for this field must be greater than zero but less than the value specified for the field “Tower High-Speed Nominal Capacity”.

Field: Tower Free Convection Capacity

This numeric input field contains the “nominal” heat rejection capacity of the cooling tower in watts when the tower is in the “free convection” regime (water flow exists but tower fan is turned off), with entering water at 35C (95F), leaving water at 29.4C (85F), entering air at 25.6C (78F) wetbulb and 35C (95F) drybulb temperatures. The design water flow rate is assumed to be $5.382\text{E-}8 \text{ m}^3/\text{s}$ per watt of high-speed nominal tower capacity (input field above). 125% of this free convection tower capacity gives the actual tower heat rejection at these operating conditions (based on historical assumption that the tower must dissipate 0.25W of compressor heat for every watt of heat removed by the evaporator). The value specified for this field must be less than the value specified for the field “Tower Low-Speed Nominal Capacity”. If the user does not wish to model “free convection”, then this field should be set to 0.0. If the user specifies a value greater than zero, then the “Air Flow Rate in Free Convection Regime” field must contain a value greater than zero.

Two examples of an IDF specification for this object are shown below:

```

COOLING TOWER:TWO SPEED,
  My Tower,                ! Tower name
  Condenser Tower Inlet Node, ! Water inlet node name
  Condenser Tower Outlet Node, ! Water outlet node name
  .0011,                   ! Design water flow rate, m3/s
  16.0,                    ! Air flow rate at high fan speed, m3/s
  10000,                   ! Fan power at high fan speed, W
  3500.,                   ! Tower UA at high fan speed, W/C
  8.0,                     ! Air flow rate at low fan speed, m3/s
  1600,                    ! Fan power at low fan speed, W
  2100.,                   ! Tower UA at low fan speed, W/C
  1.6,                     ! Air flow rate for free convection, m3/s
  350,                     ! Tower UA at free convection air flow, W/C
  UA AND DESIGN WATER FLOW RATE; ! Tower performance input method

```

```

COOLING TOWER:TWO SPEED,
  My Tower,                ! Tower name
  Condenser Tower Inlet Node, ! Water inlet node name
  Condenser Tower Outlet Node, ! Water outlet node name
  ,                         ! Design water flow rate, m3/s
  autosize,                ! Air flow rate at high fan speed, m3/s
  1000,                    ! Fan power at high fan speed, W
  ,                         ! Tower UA at high fan speed, W/C
  autosize,                ! Air flow rate at low fan speed, m3/s
  160,                     ! Fan power at low fan speed, W
  ,                         ! Tower UA at low fan speed, W/C
  autosize,                ! Air flow rate for free convection, m3/s
  ,                         ! Tower UA at free convection air flow, W/C
  NOMINAL CAPACITY,        ! Tower performance input method
  95250.,                  ! Tower high-speed nominal capacity, W
  57150.,                  ! Tower low-speed nominal capacity, W
  9525.;                   ! Tower free convection capacity, W

```

Cooling Tower:Two Speed Outputs

```

HVAC,Average,Tower Fan Electric Power [W]
HVAC,Sum,Tower Fan Electric Consumption [J]
Zone,Meter,HeatRejection:Electricity [J]

HVAC,Average,Tower Heat Transfer [W]

HVAC,Average,Tower Water Inlet Temp [C]
HVAC,Average,Tower Water Outlet Temp [C]
HVAC,Average,Tower Water Mass Flow Rate [kg/s]

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Tower Fan Electric Power [W]

Tower Fan Electric Consumption [J]

These outputs are the electric power input to the tower fans. Consumption is metered on HeatRejection:Electricity, Electricity:Plant, and Electricity:Facility.

Tower Heat Transfer [W]

This is the rate at which heat is removed from the condenser water loop by the tower.

Tower Water Inlet Temp [C]

Tower Water Outlet Temp [C]

Tower Water Mass Flow Rate [kg/s]

These outputs are the tower water inlet and outlet temperatures, and mass flow rate.