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ABSTRACT

Thermal management is a cross-cutting technology that directly or indirectly affects engine performance, fuel economy, safety and reliability, aerodynamics, driver/passenger comfort, materials selection, emissions, maintenance, and component life. This review paper provides an assessment of thermal management for large trucks, particularly as it impacts these features. Observations arrived at from a review of the state of the art for thermal management for over-the-road trucks are highlighted and commented on. Trends in the large truck industry, pertinent engine/truck design and performance objectives, and the implications of these relative to thermal management, are presented. Finally, new thermal management concepts for high efficiency vehicles are described.

INTRODUCTION

Goals of the U.S. Department of Energy's Office of Heavy Vehicle Technologies (OHVT) are to improve the fuel economy and reduce emissions of over-the-road, Class 7-8 trucks. To accomplish these goals, DOE/OHVT and industry have been focusing research and development efforts on the diesel engine and related fuels technology. There are also opportunities for improvements in truck thermal management, which will, directly or indirectly, lead to improved fuel economy and reduced emissions. However, the development of the thermal management system has, in general, not kept pace with engine development.

The function of a truck thermal management system is to provide cooling and temperature control of the engine, engine and transmission oils, charge air, electronics, fuel, and recirculated exhaust gas for emissions control, and control of underhood temperatures and cab climate. A truck thermal management system comprises an assembly of components and heat transfer fluids. The components include heat exchangers, fan, coolant pump, compressor, sensors, actuators, and assorted piping and hoses. The heat transfer fluids include ambient air, coolant (water/ethylene-glycol solution), engine and transmission oils, intake air, exhaust gas, fuel, and refrigerants. A flow circuit can be associated with each of the heat transfer fluids; either a fan, pump, or compressor is involved to circulate or move the fluid in that circuit. These components and fluids must work together to satisfy the vehicle's heat rejection and temperature control requirements.

Vehicle thermal management is a crosscutting technology, in that it directly or indirectly affects engine performance, fuel economy, safety and reliability, aerodynamics,

driver/passenger comfort, materials selection, emissions, maintenance, and component life. It follows that an effective and responsive thermal management system is critical to the design and operation of over-the-road trucks that are fuel-efficient, and satisfy increasingly stringent emissions standards.

The purpose of this paper is to focus attention on thermal management for large trucks, particularly as it impacts fuel economy, emissions, and safety. In the following, observations arrived at from a review of the state of the art in over-the-road truck thermal management are highlighted, and commented on. Trends in the large truck industry, pertinent engine/truck design and performance objectives, and the implications of these relative to thermal management, are presented. Finally, new thermal management concepts/needs for high efficiency vehicles are described.

CURRENT STATUS OF CLASS 7-8 TRUCK THERMAL MANAGEMENT

The basic architecture of a truck thermal management system has changed little over the last 50 years. And, for the most part, the changes and improvements that have been made have been incremental. The designs of some of the system components, for example, the coolant pump, are essentially unchanged. A review of the state of the art of truck thermal management is important as it allows for establishment of a baseline, and the identification of technical barriers to system improvements, as well as opportunities for system improvements. Pertinent observations are highlighted and briefly commented on below, as they may influence the development and implementation of thermal management concepts, and lead to the identification of research needed to improve the thermal management system.

Large trucks are custom designed. Successive trucks coming off an assembly line will typically have different engines and different cooling system. The engine manufacturer typically specifies the water pump and thermostat, while the truck manufacturer specifies the fan and radiator. In general, custom designs are not compatible with design optimization.

Designed to operate under extreme conditions.. Truck thermal management systems must currently be designed to operate in extreme conditions; these are conditions that the majority of the trucks will never experience. As a consequence, there is much conservatism in the designs, resulting in excess capacity.

Reliability/durability is a priority. Reliability is a primary consideration of engine and truck manufacturers. The emphasis on reliability contributes to increased conservatism, which is reflected in the increased size, weight, and capacity of thermal management system components.

Weight and space. Thermal management system components contribute to the overall gross vehicle weight (GVW) of the truck, and take up valuable space under the hood. While this might be considered a trivial observation, it does provide a focus for research, viz., the reduction of component weight and size.

Ultimate heat sink is ambient air. The ultimate heat sink for all of the heat that must be rejected is the ambient air. This is a difficult heat sink in the sense that the heat sink is a gas (ambient air, with an inherently low heat transfer coefficient) and the heat sink temperature can vary widely (in the U.S., in the approximate range of - 40 °F to 115 °F).

Fan. The fan represents a major energy draw as much as 10 % of the engine horsepower. This large power requirement precludes the use of an electric drive. The fan is an engine-driven axial fan, typically operated in an on/off mode, automatically controlled by sensors, but capable of being over-ridden and manually operated by the driver. The axial fan type establishes the location of the radiator to be in front of the truck. The on/off mode of operation does not allow for optimal control of airflow through the heat exchangers and underhood compartment.

Coolant pump. The coolant pump is engine-driven. As a result, the pump speed, and therefore coolant flow rate, is directly proportional to engine speed. Coolant flow to the engine is controlled by a by-pass and thermostat. This does not allow for accurate control of engine temperature. Combustion can occur at less than optimal temperatures producing higher emissions, reduced fuel economy, and reduced performance. The pump also generates more flow and pressure than is required for most operating conditions, representing an excessive energy draw.

Fluids are inherently poor heat transfer fluids. Heat transfer fluids found in truck thermal management systems include ambient air, coolant, oils, exhaust gas, fuel, and charge-air. All are inherently poor heat transfer fluids. As a result heat transfer enhancement takes on added importance, and there is a need for improving the heat transfer properties of the fluids.

Heat transfer mechanism is forced convection. Coolant systems are designed assuming the dominant heat transfer mechanism to be forced convection. Nucleate boiling is a significantly more efficient heat transfer mechanism.

Size/location of radiator influences aerodynamics. The radiator has a pronounced effect on the aerodynamic styling of a truck, and hence on the ability to reduce aerodynamic drag coefficient and realize improved fuel economy.

Engine cooling jacket. The engine cooling jacket accommodates the engine coolant flow passages. The cooling jacket contributes significantly to the size and weight of the engine.

Refrigerated trailers. A large number of over-the-road trucks pull refrigerated trailers. The refrigeration unit can be considered part of the truck-trailer thermal management system. The size and weight of a unit are important relative to fuel economy and cargo hauled. The units are typically located on the front of the trailer, between the trailer and the truck. In that location, it has the potential to negatively influence aerodynamic drag.

Considerable quantity of waste heat available. The physical size of a truck radiator attests to the large amount of heat that is being dissipated to the ambient. Dependent on operating conditions, torque and load, as much as 30 % of the energy available in the fuel is dissipated as heat. This is waste heat that is available for recovery and use.

TRENDS/PERFORMANCE OBJECTIVES AND THEIR IMPLICATIONS

Trends in the large truck industry, and design and performance objectives of the industry, brought on, as examples, by need to satisfy more stringent emissions requirements, and the desire to improve fuel economy and to maximize cargo-carrying capacity, have important implications for the thermal management system. In many cases, added demands are made on the existing thermal management system. In other cases, new thermal management system concepts are required to accommodate the changes in heat rejection associated with a given trend, or to realize a specific design/performance objectives. These trends and objectives are highlighted below and their implications relative to thermal management are discussed.

Improve fuel economy. A goal of the DOE Office of Heavy Vehicle Technologies is to increase the average over-the-road fuel economy of the class 6-8 truck fleet from 5-7 miles-per-gallon to 10. Reducing the aerodynamic drag will have a major impact, as discussed below. However, it will also be necessary to obtain the maximum efficiency from the engine. This requires that the engine be operated at its optimal temperature. Currently used cooling strategies do not allow for accurate and optimal control of engine temperature. Non-optimal cooling will also adversely affect emissions.

The energy draws of the fan, coolant pump, and compressor also become important when evaluating overall fuel economy. In particular, the large engine-driven axial fan represents a major energy draw.

Reducing the weight of the thermal management system (heat exchangers, fan, pumps, and fluid inventories) will contribute to an overall reduction in the weight of a truck and will thereby contribute to improved fuel economy. Many truck-trailer rigs operate at maximum allowable weight. In such cases, the weight reduction of the thermal management system will be compensated for by an increase in cargo carried. Nevertheless, a fuel savings, as well as a emissions reduction may be realized if improving the cargo carrying capacity of a truck-trailer rig serves to take a number of trucks off of the road.

Reduce emissions. EPA's new diesel engine exhaust gas emissions standard will taken effect in 2002. A thermal management that will minimize emissions by accurately controlling the engine temperature to obtain optimal engine performance is required. Exhaust gas recirculation (EGR) is an emissions control strategy that is being planned for implementation. EGR involves recirculating combustion gases back into the cylinder intake. Combustion temperature is reduced by the exhaust gas, lowering NOx and particulate emission levels without significantly affecting fuel consumption. Exhaust gas temperatures can reach 700°C (1260°F), and must be cooled to a temperature in the

range of 150 to 200°C (272 to 362°F). EGR will significantly increase heat rejection requirements up to 50 per cent.

Increase horsepower. There is a trend toward more powerful engines, among other things, to facilitate acceleration and hill climbing. Higher horsepower means additional heat rejection. This directly translates into larger size heat exchangers, in particular, the radiator, and increased flow rates.

Reduce aerodynamic drag. Reducing aerodynamic drag has a significant and positive impact on fuel economy, as a significant fraction of a vehicle's total available horsepower is used to overcome it; for every reduction of 0.01 in overall drag coefficient of the large trucks in the Nation's fleet of trucks, approximately 100,000,000 gallons of fuel will be saved annually [1]. Motivated by the potential for significant energy savings nationally, the DOE Office of Heavy Vehicle Technologies is conducting a program to reduce aerodynamic drag [2]. The program is focused primarily on external air flow over and around the tractor-trailer combination and its affect on drag coefficient.

Thermal management interacts with aerodynamic drag reduction in three ways:

(a) The flow fields to which a moving vehicle is subjected to includes the underhood airflow, passing through the engine compartment and through the various air-cooled heat exchangers, as well as external airflow. It follows that the truck's vehicle thermal management system directly contributes to the aerodynamic drag experienced by the vehicle. With current tractor-trailer designs, the contribution to overall vehicle drag from underhood flow is small relative to the contribution from external flow (Olson 1998). However, as the external flow contribution to overall drag coefficient is reduced, the contribution from underhood airflow as a fraction of the total aerodynamic drag will increase. As a consequence, reducing the contribution from underhood airflow has the potential for making a meaningful contribution to overall drag reduction, with concurrent fuel savings.

(b) Aerodynamic drag is determined by the styling of the truck, which, in turn, is dictated in large part by the size and location of the radiator. The trend toward higher horsepower engines, accompanied by added heat rejection requirements, suggest larger-size radiators that put severe restrictions on the degree of aerodynamic styling that can be accomplished. Aerodynamic styling also puts restrictions on underhood space occupied by thermal management system components, and can lead to increases in underhood air temperatures.

(c) As vehicle aerodynamics are improved, and drag forces are reduced, demands on the braking systems increase with concurrent increases in braking heat dissipation requirements. To supplement downhill braking, engine braking is often used, and operators will also manually engage the fan to get retarding. Both of these strategies increase the heat rejection requirements, putting an additional load on the radiator.

Increase cargo-carrying capacity. A fleet operator's goal is to maximize the cargo-carrying capacity of a truck-trailer rig. Any reduction in the overall weight of a truck's thermal management can be translated into added cargo-carrying capacity. As discussed above, this can contribute to fuel savings if it effectively takes trucks off of the road.

Increase use of electronics. The use of on-board electronics for engine control, climate control, signal processing and a wide variety of other applications is increasing and can be expected to continue to increase. The electronic computer chips used in such devices must be temperature-controlled to less than 120°C. In cases in which electronic circuit chips are integrated onto injection pumps, the fuel is used as a coolant. This is a cooling load that can be expected to increase in the future.

Increase use of oil cooling. The engine oil is being increasingly used as an engine cooling fluid. It is currently being sprayed on the pistons to facilitate heat rejection. Oil cooling of the cylinder heads is being used, and consideration is being given to totally oil-cooled engines. The application of this cooling concept is hindered by the inherently poor heat transfer characteristics of oil.

Improve driver comfort. Driver comfort is receiving more attention by truck manufacturers. It is important to fleet operators for driver retention as well as for reasons of safety. Sleeper cabs are larger with more amenities; this translates to added demands for controlled heating and cooling of the cab. Additionally more electronic devices in the cab add to the cooling load. Fan noise and vibration are also factors affecting driver comfort and safety.

Improve reliability and reduce maintenance. Reliability is of highest importance. If the cooling system fails, the truck can not operate. Engine manufacturers are planning to offer longer warranties, and it is important that the thermal management system match these extended warranty periods. Full life oils and lubricants, which would reduce maintenance, are under development. To preclude premature deterioration of such fluids, it is important that cooling be provided to control fluid temperatures within a specified range. Leaks and structural failures are unacceptable. As a consequence, truck thermal-management-system components are conservatively designed for durability and robustness. This is not generally compatible with the goals to minimize component weight, for example, using plastics, and to introduce new concepts. Therefore, requirements for high reliability can be considered a barrier to the implementation of certain new thermal management system concepts. Any new concepts/designs must first be proven reliable.

Improve safety and environment. To minimize damage and injury resulting from accidents, the U.S. Department of Transportation would like to see energy- or shock-absorbing materials/devices incorporated in the front-ends of trucks. Current up-front positioning of the radiator, which is dictated by the engine-driven axial fan, precludes designing an energy absorbing system into the front end.

There are environmental and health concerns with ethylene-glycol, as ingestion of ethylene-glycol by humans or animals can be harmful or fatal. Propylene-glycol is being considered as a replacement; it is less toxic and possesses very similar heat transfer characteristics. Also as a result of environmental concerns, the ability to recycle/reprocess used heat transfer fluids must be considered.

THERMAL MANAGEMENT CONCEPTS FOR HIGHER PERFORMANCE

Thermal management concepts and research areas that might be developed to meet the requirements for additional heat rejection, to meet the goal to improve fuel economy, and to contribute to the adherence to new and more stringent emission standards, are described below. Application of these concepts and technologies such as these will contribute to the overall goal of developing an advanced thermal management for large trucks.

Computer controlled thermal management system. A computer-controlled thermal management system, designed and developed to take advantage of recent advancements that have been made in microprocessors, sensors, and electronics, is a concept that will lead to optimal engine performance and an associated reduction in fuel consumption and pollutant emissions [4, 5]. Such a system, which requires a controllable, electrically-driven engine-coolant pump, will provide optimal, and accurate, control of engine temperature, and thereby improve fuel economy and reduce emissions. The system will also have the potential to contribute to a reduction in engine and component size and weight, and fluid inventory. Additional benefits that may be possible include enabling the use of nucleate boiling cooling and facilitating precision cooling; eliminating the thermostat and coolant bypass circuit; reducing engine size and weight by reducing the required size and number of coolant passages in the engine; reducing the amount of time the fan is required to run; reducing radiator size; providing for gradual cool down; mitigating thermal shock and increased engine wear; reducing engine warm-up time, thereby shortening the time period of maximum production of emissions; decreasing energy horsepower draw; and providing heat to the cab without the need to run the engine.

Hybrid forced convection/nucleate boiling cooling. Virtually all internal combustion engines are designed to be cooled by forced convection. Nevertheless, nucleate boiling remains the most efficient form of heat transfer. The onset of nucleate boiling dramatically increases the amount of heat transferred to the fluid, resulting in a lower wall temperature. In nucleate-boiling cooling, the coolant is vaporized in the engine, absorbing the engine heat, and condensed in the radiator. There are numerous advantages associated with this mode of heat transfer. However, film boiling and dry-out must be controlled and prevented to avoid dangerous hotspots and overheating as a result of the poor film-boiling heat transfer coefficient. Film boiling can be controlled by controlling the coolant flow.

A hybrid forced-convection/nucleate-boiling system [e.g., 6-8] is a concept in which convective heat transfer would handle perhaps 95% of the cooling requirements and nucleate boiling would handle the remaining 5% associated with thermally severe

conditions, would remove much of the conservatism built in to current truck thermal management systems. Its application can be expected to lead to smaller heat exchangers, fans, and pumps, with a concurrent reduction in energy draw to power the fan and pump drives. The geometry, size, and surface of the coolant flow passages in the cylinder head will be important design parameters governing the critical heat flux.

Advanced heat transfer fluids. An emerging technology that shows promise for improving the heat transfer characteristics of engine coolants and is the concept of nanofluids [9,10]. Nanofluids are a class of engineered heat transfer fluids formed by dispersing nanometer-sized metallic particles in traditional heat transfer fluids such as water/ethylene glycol mixtures and oils to improve thermal conductivity. Test results [10] have shown that increases of up to 40% in thermal conductivity are possible for water/ethylene-glycol solutions; the results are a function of the nanoparticle material and the volume percent of nanoparticle loading. A recent paper [11] illustrates how nanoparticles introduced into oils can improve their lubricity and load-carrying capacity. Thus it may be possible to achieve multiple benefits from application of this technology. The concept of *ifill for life*, when applied to engine coolants and oils, makes the application of nanofluid technology more feasible.

Heat transfer enhancements. Heat transfer surface enhancement is of general importance. For air cooled heat exchangers, such as the radiator, the airside represents the controlling heat transfer resistance and determines in large part the heat exchanger size. Passive heat transfer methods (e.g., louvered fins) have been extensively studied and developed, and it is not likely that more than incremental improvements can be realized. An active heat transfer enhancement would involve the application of smart materials. Smart materials are special materials that respond to external stimuli such as temperature and pressure. It may be possible to incorporate such materials in the design of enhancement devices to optimize for flow regime and pressure drop.

Light-weight, high conductivity materials for heat exchangers. Light-weight materials with higher thermal conductivity have the potential for reducing the weight and size of heat exchangers. For example, the concept of a carbon/carbon-composite heat exchanger is being developed for military aircraft applications [12]. Weight savings up to 40 per cent for aluminum replacement, and up to 60 per cent for stainless steel replacements, with a concurrent reduction in size can be expected [13].

Underhood airflow management. Improved management of underhood airflow will allow one to maximize heat transfer and minimize contribution to overall aerodynamic drag.

Heat storage for *ipeak shaving*. The ultimate heat sink is the ambient air whose temperature can vary greatly. There is a need for a concept to store heat when operating in hot climates, during hill climbs, or during downhill braking, and dissipate it later (when ambient temperatures cool, which is the case in desert areas at night, or when the truck is operating *ion-the-flat*). This is analogous to the electric power industry's use of energy storage and/or auxiliary power units for *ipeak shaving*, during hot summer days.

Heat exchanger/fan design/positioning. The concepts of repositioning and redesign of the heat exchangers (as examples, designing a radiator with a circular frontal shape rather than rectangular to match with fan, or a curved- rather than flat-radiator to facilitate aerodynamic styling of the truck) has the potential to influence aerodynamic drag, heat exchanger efficiency, and safety. For example, the orientation of a radiator relative to the vertical plane, and the downstream ducting of the airflow, can significantly affect aerodynamic drag.

A new cooling system concept, termed the compact cooling system (CCS), has been proposed [14]. In contrast to a conventional cooling system, which is an "axial system," the CCS is a "radial system." It is based on a radial fan, with the heat exchangers (radiator, CAC, and condenser) positioned around the fan. While there are several advantages with this type of system, an inherent disadvantage of the CCS is that "packaging" may be a problem because of limited "fore-to-aft" space in the engine compartment.

Waste heat recovery and utilization. Significant waste heat is available to be recovered to drive an electric generator or to provide power to the crankshaft. This waste heat is also available to be stored, for example, in a heat battery. Recovery and use of waste heat can reduce fuel consumption and emissions. Various concepts for waste heat recovery and utilization have been proposed [15-20]. These methods and technologies must be evaluated, further developed, adapted to large trucks, and implemented.

Heat recovery can also be used for endothermic fuel reforming reactions in which exhaust gas thermal energy is transformed into reformed fuel chemical energy, implying improvements in overall engine efficiency; Jones and Wyszynski [21], present the design, construction, and testing of a reforming reactor. Heat recovery might also be used in thermal-electric converters to power fuel reforming devices such as the plasmatron [22, 23].

SUMMARY AND CONCLUDING REMARKS

Thermal management is an important, but largely neglected, technology area affecting engine performance, fuel economy, and emissions. Trends and performance objectives in the large truck industry include higher horsepower engines, improved aerodynamics, improved fuel economy, reduced emissions, improved safety, increased electronics, improved driver comfort, increased cargo-carrying capacity, higher reliability, and reduced maintenance. All of these have important implications relative to thermal management.

Several thermal management concepts leading to higher efficiency heavy vehicles were identified and discussed. With one or two exceptions (for example, nanofluids and carbon-carbon composite heat exchangers), these concepts are not new, in the sense that they have previously been discussed and reported in the open literature. For the most part, and for a variety of reasons, they have not been implemented on large trucks. However, with the trucking industry facing increasing heat rejection requirements,

coupled with a desire to improve fuel economy and a need to reduce emissions, the time is right for developing and applying many of these concepts.

If it is to be successful, implementation of a new concept will require research and component development, and will necessitate close cooperation among equipment suppliers, engine manufacturers, truck manufacturers, and researchers,. Cost for implementing a new concept may not be as big a barrier for trucks as it would be for automobiles, if the payoff in terms of fuel economy, emissions reduction, and cargo-carrying capacity can be demonstrated. However, a very real barrier to any new technology, is the trucking industry's demand for high reliability and durability, which accounts for the conservatism in the thermal management component design, and results in a resistance to implement any new technologies unless they can be proven reliable.

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