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**BPM: A Tool to Predict Boiler Performance
on a PC**

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BPM: A Tool to Predict Boiler Performance on a PC

ABSTRACT

The Department of Energy has developed and made available to the public a PC-based software package (BPM 3.0) to help engineers predict the performance of utility boilers in non-standard modes of operation for power generation systems. This package is especially useful for analyzing changes in boiler performance resulting from fuel switching, changes in operating modes (e.g., constant versus variable pressure), and physical changes to the boiler. The report discusses the use of the program.

INTRODUCTION

Predicting the performance of utility boilers is often difficult under scenarios in which boiler operations differ from their normal mode because of their complexity, controls, and the heat transfer equations that govern their performance. A personal-computer-based software package is available from the U.S. Department of Energy (DOE) that can help engineers deal with this complexity. Burns and Roe, under sponsorship of the Pittsburgh Energy Technology Center of DOE, has developed the package to provide the public with a nonproprietary code for application to power generation systems. It is commonly used to analyze changes in performance due to fuel switching, changes in operating mode (e.g., constant versus variable pressure), and physical changes to the boiler.

Numerous new capabilities have been added to the first version of the Boiler Performance Model (BPM), which was developed in the mid-1980s. The latest release, version 3.0, was made available to the public in the spring of 1992. The programs have been streamlined to allow predictions to be made by scientists and engineers who are not

necessarily boiler design experts. This was accomplished by creating four sample boiler models that are representative of a large number of utility boilers. Although the models require and contain detailed data, any user can easily perform parametric studies of fuel and other operational changes by simply revising the existing data files. The programs then compute the new performance characteristics--boiler efficiency, steam temperatures, gas velocities, gas temperatures, etc. The package includes "expert" modules that scan the results and flag any parameters that exceed commonly established guidelines. The results are presented in either textual or graphical form.

The software is available through the Energy Science and Technology Center in Oak Ridge, Tennessee (P.O. Box 1020, Oak Ridge, TN 37831; Phone: 615-576-2606), and is currently being used by several academic, industry, and government organizations.

The objective of this paper is to familiarize the potential user with the use of BPM for predicting boiler performance under different scenarios.

SYSTEM REQUIREMENTS

BPM 3.0 requires an IBM PC-compatible computer with at least 640 kB of memory, a hard disk drive, a graphic video card (CGA, EGA or VGA,) and either a dot matrix or laser printer. Calculation speed is computer dependent. For example, a typical boiler model requires about two to five minutes for convergence on a machine with a 20 MHz 80386 processor and no math coprocessor, although time to convergence varies significantly from one boiler model to another.

USING BPM 3.0

BPM 3.0 is a menu-driven program. Each module is linked to a Central Manager module that allows the user to move through the various program modules (see Figure 1). The modules are grouped under three broad types:

Data Manager modules allow the user to create new boiler models, and edit physical, operating, and fuel data for existing models.

Calculation modules take input data from the models and calculate the performance measures of interest. The output of these programs can be routed to the screen, a printer, or an output file. The results of these calculations are also stored in the operating data (OPD) file of the model so they can be used by other modules.

Reporting modules sift through the model's operating and physical (PHY) data files to extract key values. These results are then printed in a useful, concise format. Figure 2 is an example output from the TPROFILE module showing the steam temperature at the inlet and outlet of each superheater section.

CAPABILITIES AND LIMITATIONS

The software supports most utility fossil-fuel-fired boiler configurations, including the following:

- Subcritical and supercritical pressures
- Tilting tangential burners
- Split backpass steam temperature control
- Multiple reheat circuits
- Multiple attemperators
- Plain, straight fin, and spiral fin economizers
- Regenerative and tubular air heaters
- Divided furnace

The current version of the software does not support stokers, fluidized beds, and cyclones.

CALCULATION PROCEDURE

To run the calculations for a given boiler model, the user must first specify a main steam flow rate and outlet pressure; feedwater flow rate, temperature, and pressure; and cold reheat flow rate, temperature, and pressure. The user also specifies target main and hot reheat steam temperatures. The software then executes the five calculation programs in order:

HTTOSTM (heat-to-steam) calculates the amount of heat that the main steam, reheat steam, and economizer circuits must absorb to achieve the target conditions.

BLREFFIC (boiler efficiency) calculates boiler efficiency by the heat loss method. At this point, the air heater exit temperature is not known, so an estimated value (or the value calculated in the previous iteration) is used. By dividing the heat-to-steam value by the boiler efficiency, the total required heat input, and therefore the fuel flow rate, can be calculated.

LOWFURN (lower furnace) calculates the heat absorption in the lower furnace based on fuel flow rate, other operating conditions, and furnace geometry. The furnace exit gas temperature and direct radiative heat leaving the lower furnace are calculated.

CONVPASS (convective pass) calculates the heat absorbed by the steam in each tube bank section from the upper furnace to the air heater inlet. Heat transfer coefficients are calculated, based on flue gas velocity, temperature, and composition, as well as tube bank geometry (the calculation of tube bank heat transfer is described in more detail below). Since most boilers have a combination of parallel- and counter-flowing circuits, CONVPASS generally must make several iterations before coming to convergence. CONVPASS does an upper furnace

calculation to distribute direct radiative heat leaving the lower furnace. CONVPASS has a controller mechanism that changes steam temperature control parameters (burner tilt, spray flow, etc.) to try to match target steam conditions.

AIRHTR (air heater) calculates the heat transferred in the air heater.

This cycle of five modules must be repeated several times to achieve convergence, since the output of some modules is used as input to earlier modules in the cycle. BLREFFIC, for example, needs the air heater exit gas temperature to calculate boiler efficiency, yet this value is not calculated until AIRHTR is run. The software has an AutoRun feature that cycles through the modules automatically until convergence is reached.

Also shown in Figure 1 are two additional calculation procedures: Industrial Boiler and DOEADV (advanced combustion boilers being developed for DOE). These two procedures are not discussed in the present report, which focuses on present day utility boilers.

CALCULATION OF HEAT TRANSFER IN A TUBE BANK

The key calculations performed by CONVPASS are the calculation of heat transfer coefficients, steam temperature rise, and gas temperature drop in a tube bank section of a boiler model. A simplified description of a tube bank heat transfer calculation is presented here.

Figure 3 shows a schematic of a typical boiler superheater bank. The pertinent physical characteristics of this section include tube outside diameter, cross pitch, longitudinal pitch, tube length, and duct width, among others. It is assumed that conditions of the steam and flue gas entering the section are known (sometimes the steam inlet temperature is not known, which means that CONVPASS will have to use a previously calculated value

as an estimate and iterate the calculation until convergence). The temperature of the steam leaving the section and the temperature of the gas leaving the section are to be calculated. Heat transferred to the steam is calculated in three parts: convective heat transfer, nonluminous radiant heat transfer, and direct radiant heat transfer. For convective and nonluminous heat transfer, a heat transfer coefficient is calculated and the result is used in the heat transfer equation:

$$H_g = U_t A L$$

where

H_g = heat transferred to steam from gas, Btu/hr.

U_t = total heat transfer coefficient, convective plus nonluminous ($U_c + U_n$), Btu/(hr, sq ft, °F).

A = heat transfer area, sq ft.

L = Log mean temperature difference, °F.

For counterflow tube banks (that is, steam flowing in the opposite direction as gas), log mean temperature difference is defined, as referenced in Figure 3, as

$$L = (\Delta T_1 - \Delta T_2) / \log_e(\Delta T_1 / \Delta T_2)$$

where

$$\Delta T_1 = T_{g1} - T_{s2}$$

$$\Delta T_2 = T_{g2} - T_{s1}$$

The convective heat transfer coefficient, U_c , is calculated according to *Steam - Its Generation and Use* by the Babcock and Wilcox Company (1):

$$U_c = 0.287 [V^{0.61} / (OD/12)^{0.39}] F_{pp} F_a F_d$$

where

V = mean gas mass velocity, lb/(hr, sq ft).

OD = tube outside diameter, in.

F_{pp} = physical properties factor.

F_a = arrangement factor.

F_d = depth factor.

The depth and arrangement factors are empirical and depend on the number of tubes and other physical factors. The physical properties factor is calculated from the transport properties (specific heat, conductivity, and viscosity) of the gas at the given gas composition and temperature. BPM has an internal module that calculates transport properties for flue gas.

The nonluminous heat transfer coefficient, U_n , is calculated according to Volume 2 of the *Modern Power Station Practice* (2):

$$U_n = P_n K_t K_e$$

where

P_n = a fifth-order polynomial curve fit based on the tube bank radiant beam length (RBL) and the volumetric fractions of CO_2 and H_2O in the flue gas.

K_t = tube surface temperature adjustment factor.

K_e = tube emissivity adjustment factor.

Having calculated the quantity of heat transferred to the steam from the gas, the next step is to determine the quantity of heat transferred from direct radiation. The amount of direct radiation entering the convective pass is calculated by an upper furnace subroutine of CONVPASS. Each successive tube bank in the convective pass intercepts a portion of the direct radiation while the remainder passes through to the next bank. CONVPASS performs a shape factor calculation to determine the fraction of radiation that is absorbed in each tube bank.

The total heat absorbed by a tube bank is

$$H_t = H_g + H_r$$

where

H_t = total heat absorbed by tube bank, Btu/hr.

H_g = heat transferred to steam from gas (defined above), Btu/hr.

H_r = heat absorbed from direct radiation, Btu/hr.

To calculate the steam temperature rise across the tube bank, CONVPASS makes use of internal steam tables to calculate enthalpies. To calculate the gas temperature drop across the tube bank, CONVPASS uses its gas properties subroutine to calculate flue gas specific heat.

CREATING BOILER MODELS

Due to the level of detail required for accurate calculations, the creation of boiler models is a fairly involved and time-consuming process. A complete boiler model consists of four input files, which the software identifies with three-letter filename extensions:

The **physical data file** (distinguished by a PHY extension) contains all of the dimensions for each of the tube bank sections in the convective pass: tube diameters, cross and longitudinal pitches, circuit descriptions, etc.

The **furnace data file** (FRN) contains the dimensions of the lower furnace.

The **fuel data file** (FUL) contains the ultimate analysis for the fuel. For solid fuels, the FUL file can also contain an ash analysis.

The **operating data file** (OPD) contains the gas and steam temperatures, pressures, and flow rates for each tube bank section in the convective pass. During the execution of the calculation modules, certain values in the OPD file are

changed as a result of the calculations (outgoing steam and gas temperatures, for example). Thus the OPD file contains the computed results of the calculations.

To create a PHY file, a user generally works with drawings and system descriptions. The user first must describe the physical layout of the sections and how they are connected to each other. Figure 4 shows an example of a sketch that modelers typically produce to depict the physical layout. After the layout has been described, the modeler must enter all of the relevant data for each section. The software prints out data sheets to make the data collection process more manageable. The creation of FRN and FUL files is comparatively simple, as each requires only a few input items. Like the PHY file, the OPD file has data for each section in the model. Many of these are calculated by the calculation modules so many of the data items can be left blank. However, it is often more efficient to input "initial guesses" for the steam and gas temperatures; otherwise, initial convergence can take a long time.

Once the data files have been created, the model is complete. The next step in the modeling process is calibration. This step is extremely important, as the calculated results from an uncalibrated model cannot be relied upon for accuracy. Calibration of a model requires that a user have boiler test data available (in the absence of test data, design data can be substituted). The user sets up the data files to match the conditions of the test (same fuel analysis, ambient conditions, etc.), then runs the software and compares the output to the test data. If there are significant differences, the user can adjust the model by applying effectiveness factors to certain tube banks, changing assumptions regarding gas distribution, and so forth. This process also finds data entry errors in the OPD and PHY files.

REPORTING MODULES

The five reporting modules are designed to perform tasks that the user would normally do as part of the modeling process. These modules do not do any significant calculating;

rather, they sift through the data files and present the information in a concise format. The five reporting modules perform the following functions:

TPROFIL (temperature profile) extracts the steam and water temperatures from the OPD file and prints the data for each main steam, reheat steam, and economizer circuit from inlet to outlet.

CONSIST (data consistency checker) assists in the model development phase of a study and is usually run after the data files have been created but before calibration. CONSIST checks the data files for obvious errors in geometry (e.g., tube OD greater than cross pitch), "short circuits" in the physical layout, and other common problems that will cause errors during the execution of the calculation programs.

RESAN (results analyzer) helps the user interpret the calculated output. The calculated results are compared to common boiler design limits, such as flue gas velocity and heat release rates in the furnace. Exceeding the limits generally means that derating of the boiler is required.

CLRSPCGR (tube clear space requirements grapher) and **FGVELGR** (flue gas velocity grapher) present the tube clear space and calculated flue gas velocity, respectively, for each section in the model in a graphical format.

SAMPLE MODELS

The software package includes the data files for four sample boiler models. A Sample Boiler Models Manual, which contains all printouts and input data sheets for each model, is also included. The sample models serve two purposes. When creating models, the samples can be used as references for good modeling technique, or, if a user does not want to go through the effort of creating a model, the sample "generic boilers" can be

used. The four models were chosen to be representative of typical U.S. boiler designs. They include: (a) tangential-fired coal-burning, (b) tangential-fired oil-burning (with a divided furnace), (c) wall-fired coal-burning (with a split backpass and designed for a high-slugging coal), and (d) wall-fired oil-burning units.

APPLICATIONS

A fully calibrated boiler model can be used to predict performance under a variety of operating and physical modifications. BPM can be used to answer such questions as:

- How will the boiler perform if we switch from high-sulfur to low-sulfur coal?
- Is this oil-fired boiler capable of burning coal-water fuel? Orimulsion? What kind of derating can we expect?
- If the gas recirculation fan hasn't worked right for years, is it worthwhile to fix it? What kind of performance improvements can be expected from the boiler? Does it justify the cost?
- Can the boiler run at sliding pressure rather than the present constant pressure? What happens to boiler performance?
- When experimenting with ammonia injection in the boiler for NO_x control, the boiler has a pretty narrow temperature window. Where in the convective pass should the injection point be? Does it move when the load is changed?
- Adding a scrubber will require a boost in air heater exit temperature. Can this be done while maintaining steam temperature control and minimizing efficiency impact?

To perform any such study, the necessary changes are made to the data files for the boiler model. The program is then run, and the calculated results show the software's performance predictions. An example of a typical application, the effect of firing coal-water fuel (CWF) in an oil-fired boiler, is presented below.

SAMPLE APPLICATION: CONVERTING AN OIL-FIRED BOILER TO COAL-WATER FUEL (CWF)

CWF is a liquid fuel that can be fired in boilers designed exclusively for oil-firing without major modifications to the plant fuel-handling and storage equipment. BPM can predict performance changes by addressing the major areas of concern that arise when switching to this coal-based fuel. Areas of concern would include:

- Derating
- Boiler efficiency
- Main and reheat steam temperatures
- Spray flow rates
- Furnace heat release rates
- Gas and air flow rates
- Gas velocities through tube sections

The "conversion" to CWF firing is made by creating a CWF fuel file and changing the OPD file to read from the appropriate fuel file. The calculation cycle is then run to convergence.

For this example, one of the sample boiler models, TANGOIL, was used. The boiler, sized for a 550 MWe power plant, is designed to produce 4,200,000 lb/hr (1,900,000 kg/hr) of main steam at a throttle pressure of 2615 psia (18 MPa) and temperature of 1005 °F (540 °C). It is a single reheat unit with a design reheat flow of 3,780,000 lb/hr (1,784,000 kg/hr), temperature of 1005 °F (540 °C) and pressure of 600 psia (4.1 MPa). The furnace is tangentially-fired with controlled circulation. Figure 5 shows a side view of the boiler labeled with all of the numbered sections in the model.

Apart from changing the FUL file from oil to CWF, little was done to the TANGOIL.OPD file to accomplish the conversion to CWF firing. The CWF was assumed to be 30% water,

1.8% ash, and 0.2% sulfur by weight. Excess air to the furnace was increased by 8%; from 12% in the oil case to 20% in the CWF case. Unburned fuel under oil firing was assumed to be zero. Under CWF firing, unburned carbon was assumed to be 0.5% of the fuel by weight. All other assumptions and input data remained the same.

Table 1 shows a comparison of results of the calibrated oil-fired case and the CWF-fired case. Due to the increased excess air and the high moisture content in the CWF, the gas flow rate under CWF firing increased substantially (by 30%). As a result, heat absorption in tube banks that are primarily convective (reheater sections) rose while heat absorption in tube banks that are primarily radiant (superheater sections) fell. To avoid overheating of the reheater, the burners tilted down to -23 degree (from +29 degree), forcing main steam temperature 47 °F (25 °C) below design, even with zero main steam spray flow. Thus, generator output will be reduced. Boiler efficiency is reduced due to high fuel moisture losses and increased air heater exit temperature. Economizer outlet water temperature is higher but still well below saturation.

The results analyzer module, RESAN, indicated that flue gas velocities in the back pass were above normal limits for ash-laden fuels. These flue gas velocity limits, which vary from one boiler manufacturer to another, are likely to require derating of the unit.

EXPERIENCE WITH BPM

The BPM has been applied to a wide variety of study applications for a number of utility and government clients. The following are a few examples of these studies:

- Study of coal-water slurry retrofit to oil-fired boilers.
- Evaluation of reheat steam temperature control problems at a utility station.
- Target heat-rate study for two utility stations.
- Study of conversion of a utility station to Orimulsion firing.
- Study of deeply beneficiated alternative fuels.

- Determination of coal quality impact at an Italian utility station.
- Performance predictions for conversion of a utility station to variable pressure operation.
- Study of conversion of units at two utility stations in China (PRC) from oil to coal firing.
- Study of repowering options at North Bangkok (Thailand) Station.

DISCLAIMER

Reference herein to any specific commercial product by tradename, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof.

REFERENCES

1. *Steam: its generation and use*, S.C. Stultz and J.B. Kitto, Editors, Babcock & Wilcox Company, p:4-14, 1992.
2. *Modern Power Station Practice - Volume 2, Mechanical Boilers, Fuel and Ash-handling Plant*, Central Electricity Generating Board, 1971.

Table 1

Comparison of BPM results: oil firing vs. CWF firing in an oil-burning boiler

	Oil Case	CWF Case
Main steam temperature	1005 °F (540 °C)	958 °F (515 °C)
Hot reheat steam temperature	1005 °F (540 °C)	1005 °F (540 °C)
Main steam spray flow rate	148,000 lb/hr (67,000 kg/hr)	0 lb/hr
Burner tilt	+ 29°	-23°
Wet gas flow rate	4,464,000 lb/hr (2,024,000 kg/hr)	5,793,000 lb/hr (2,627,000 kg/hr)
Boiler efficiency	89.6%	86.8%
Furnace exit gas temperature	2573 °F (1412 °C)	2203 °F (1206 °C)
Air heater exit gas temperature	325 °F (162 °C)	340 °F (171 °C)
Economizer outlet water temperature	555 °F (290 °C)	563 °F (295 °C)
Back pass gas velocities	Normal	Higher

FIGURE 1
HIERARCHY OF MODULE MENUS IN BPM 3.0

UTILITY: Oil Fuel (Tangential Firing)
 PLANT AND UNIT: Example Run For DOE
 FILE NAME: TANGI200.OPD FILE LAST UPDATED: 06-28-91
 FILE NAME: TANGOIL.PHY FILE LAST UPDATED: 06-28-91

TIME: 06-28-1991 09:35:38 RUN # _____ ENGINEER _____
 Tangent. Firing (Oil)

MAIN STEAM CIRCUIT

GAS TEMPERATURE	STEAM TEMPERATURE
	1005.0(F)

BANK NO. 7 Main Steam Outlet	Outlet
STEAM FLOW = 4,200,000. (lbs/hr)	

	1005.0(F)
1598.0(F)	1005.0(F) (CALCULATED)

BANK NO. 6 Secondary SH	Superheater
STEAM FLOW = 4,200,000. (lbs/hr)	

2085.6(F)	807.1(F)
	807.1(F) (CALCULATED)

BANK NO. 5 Main Steam Attenuator	Attenuator
FLOW = 157,224.7 (lbs/hr)	

	848.8(F)
2098.3(F)	848.8(F) (CALCULATED)

BANK NO. 3 Primary SH Above Rad	Superheater
STEAM FLOW = 4,042,775. (lbs/hr)	

2407.8(F)	747.7(F)
2407.8(F)	747.7(F) (CALCULATED)

BANK NO. 2 Primary SH Rad.	Superheater
STEAM FLOW = 4,042,775. (lbs/hr)	

2565.0(F)	702.2(F)
1358.4(F)	702.2(F) (CALCULATED)

BANK NO. 11 Primary SH Sling Tub	Superheater
STEAM FLOW = 4,042,775. (lbs/hr)	

1319.6(F)	700.0(F)
	700.0(F) (CALCULATED)

BANK NO. 12 Steam Temp. Rise	Steam Temp. Riser

	690.0(F)

FIGURE 2
 SAMPLE OUTPUT FROM TROFILE MODULE

Figure 3
Boiler superheater bank

FIGURE 4
SCHMATIC OF TANGOIL.PHY MODEL

FIGURE 5
SIDE VIEW OF TANGOIL.PHY SHOWING MODEL SECTIONS

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