A STUDY ON THE PERFORMANCE OF RESIDENTIAL BOILERS FOR SPACE AND DOMESTIC HOT WATER HEATING

Cheol Park
George E. Kelly

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Building Technology
Building Environment Division
Gaithersburg, MD 20899

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, Acting Director
A STUDY ON THE PERFORMANCE OF RESIDENTIAL BOILERS FOR SPACE AND DOMESTIC HOT WATER HEATING

Cheol Park
George E. Kelly

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Building Technology
Building Environment Division
Gaithersburg, MD 20899

Sponsored by:
U.S. Department of Energy
Office of Buildings and Community Systems
Washington, DC 20585

June 1989
A STUDY ON THE PERFORMANCE OF RESIDENTIAL BOILERS FOR SPACE AND DOMESTIC HOT WATER HEATING

ABSTRACT
A residential boiler for space heating and domestic hot water heating was studied by conducting laboratory tests and computer simulations. A clam-shell, wet-base, oil-fired, residential boiler with a tankless coil for heating domestic water was selected for this research project.

The purpose of this study was to develop a method for evaluating the performance of an integrated space and water heating appliance. Based upon laboratory tests, a computer model was developed and used with the HVACSIM building system simulation program to simulate the operation of the integrated appliance.

The model was verified for heat-up, cool-down, cyclic, and standby modes of operation, along with various domestic hot water draw cycles. Using the verified model, computer simulations were carried out for both summer and winter operations of the appliance. As a result of these simulation studies, a simple method for determining the combined, seasonal efficiency of Type I appliance, whose primary design function is space heating and secondary function is domestic water heating, is presented.
ACKNOWLEDGMENTS

The authors are indebted to U.S. Department of Energy for funding this project and gratefully acknowledge Mr. Donald B. Ward and Mr. Charles P. Terlizzi for performing laboratory tests used in this report.
TABLE OF CONTENT

ABSTRACT ii
ACKNOWLEDGMENTS iii
TABLE OF CONTENTS iv
LIST OF FIGURES v
LIST OF TABLES vi
NOMENCLATURE vii
CONVERSION FACTORS FROM ENGLISH TO METRIC(SI) UNITS xi

1. INTRODUCTION 1

2. LABORATORY TESTINGS 2

2.1. Test Setup 2
2.2. Test Procedures 7

3. COMPUTER SIMULATIONS 12

3.1. Computer Model 14
3.1.1. Water Boiler Component Model 14
3.1.1.1. Gas-side Heat Transfer 16
3.1.1.2. Fire-box Wall Heat Transfer 16
3.1.1.3. Heat Exchanger Heat Transfer 20
3.1.1.4. Boiler Water Heat Transfer 21
3.1.1.5. Boiler Jacket Heat Transfer 22
3.1.1.6. Stack Gas Temperature 23
3.1.2. Domestic Water Heating Coil Model 24
3.1.3. Boiler Control 25

3.2. Computer Simulation Procedures 26
3.2.1. Source Program 26
3.2.2. Input Data Preparation 28
3.2.3. Execution of the Simulation 30
3.2.4. Analysis of Simulation Outputs 31

4. RESULTS AND DISCUSSION 31

4.1. Computer Model Verification 32
4.2. Simulations of Summer Operating Mode 37
4.3. Simulations of Winter Operating Mode 39

5. A METHOD FOR DETERMINING THE COMBINED SEASONAL EFFICIENCY 41

6. CONCLUSION 46

7. REFERENCES 49

APPENDICES 51
LIST OF FIGURES

Figure 1  External view of the wet-base hot water oil-fired boiler
Figure 2  Heat-exchange arrangement of the boiler
Figure 3  Test set-up of the boiler with a tankless coil
Figure 4  Sample screen dump of the displayed plots on a monitor
Figure 5  The burner and pump on/off status and the stack gas temperature of a typical space load simulation test
Figure 6  The status of the burner and circulating pump and the stack gas temperature of a combined load test
Figure 7  The cross-sectional view of the boiler
Figure 8  A schematic diagram of the modelled boiler sections
Figure 9  The routines called by the subroutines, TYPE62 and TYPE63
Figure 10 Block diagram of the boiler model for use with HVACSIM+
Figure 11 The stack gas and boiler water temperatures during the heat-up and cool-down periods
Figure 12 Part-load operation in space heating only
Figure 13 The stack gas and boiler water temperatures of a domestic hot water draw simulation
Figure 14 The boiler water temperature changes during a part of the standby period
Figure 15 The tankless coil outlet temperatures during a part of the draw period
Figure 16 Energy factor for different domestic hot water use levels
Figure 17 The energy consumption during the standby period showing the room temperature effect
Figure 18 The jacket loss during the standby period showing the room temperature effect
Figure 19 Fuel utilization efficiency with respect to the space load factor for space heating only
Figure 20 Fuel utilization efficiency for combined loads
Figure 21     Efficiency curves from computer simulation and the equation at 
              \( U = 60 \) gal

Figure 22     Efficiency curves from computer simulation and the equation at 
              \( U = 120 \) gal

Figure 23     Illustration of Steps 1 through 3 of the NIST's recommended 
              procedure

LIST OF TABLES

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 24-hour Draw Test</td>
<td>Bin Data Analysis</td>
</tr>
</tbody>
</table>
NOMENCLATURE

$A_{tf}$  surface area where convective heat transfer takes place

$A_{cross}$  cross sectional area through which a fluid passes

$A_{j}$  boiler jacket surface area

$A_{rc}$  effective emissivity

$A_{rf}$  surface area where radiative heat transfer takes place

$C_{p,product}$  specific heat of combustion products

$C_{p_{a}}$  specific heat of air

$C_{p_{g}}$  specific heat of gas

$C_{p_{w}}$  specific heat of boiler water

$C_{s}$  ratio of the boiler fire-box effective radiation heat transfer area to the total boiler fire-box area

$d_{c}$  domestic water heating coil diameter

$d_{h}$  hydraulic diameter

$EF$  energy factor

$HHV$  higher heating value of fuel

$h_{c}$  convective heat transfer coefficient

$h_{cw}$  convective heat transfer coefficient between the coil wall and the coil water

$I_{cf_{g},off}$  integration constant for gas during off-period

$I_{cf_{g},on}$  integration constant for gas during on-period

$I_{cfw}$  integration constant for boiler water

$k$  thermal conductivity

$l_{c}$  domestic water heating coil length

$L_{gpf}$  gas path length in the boiler fire-box

$m_{cw}$  mass flow rate of coil water

$m_{fuel}$  mass flow rate of fuel
mass flow rate of the draft air during off-period
mass flow rate of combustion products during on-period
mass of boiler water
circulating water flow rate
number of heat transfer units
deg number of heat transfer units during off-period
deg number of heat transfer units during on-period
number of heat transfer units during on-period
number of heat transfer units between gas and boiler water at full load
Nusselt number
Prandtl number
heat flow rate from boiler water to coil water
heat flow rate from combustion gas/draft air to boiler water through the fire-box wall
radiative and convection heat transfer from combustion gas to sink surface during off-period
radiative and convection heat transfer from combustion gas to sink surface during on-period
heat transfer rate between gas and boiler water through the heat-exchanger
heat flow rate during off-period between combustion gas products and boiler water
heat flow rate during on-period between combustion gas products and boiler water
fuel input energy
fuel input energy during stand-by period
fuel input rate
jacket heat loss rate
latent heat loss rate
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}_{s,\text{out}}$</td>
<td>average delivered heat flow rate to the space during a simulation period</td>
</tr>
<tr>
<td>$\dot{Q}_s$</td>
<td>heat gain rate of boiler water</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{stk}}$</td>
<td>heat loss rate through the stack</td>
</tr>
<tr>
<td>$\dot{Q}_{w,\text{out}}$</td>
<td>average heat flow rate for domestic water heating</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$R_{\text{ptf}}$</td>
<td>ratio of the mass of combustion products to the mass of fuel</td>
</tr>
<tr>
<td>$R_{\text{wtf}}$</td>
<td>ratio of the mass of water in fuel to the mass of fuel</td>
</tr>
<tr>
<td>$T_{\text{af}}$</td>
<td>adiabatic flame temperature</td>
</tr>
<tr>
<td>$T_{\text{bw}}$</td>
<td>boiler water temperature</td>
</tr>
<tr>
<td>$T_{\text{bw,ref}}$</td>
<td>reference boiler water temperature at an equilibrium state</td>
</tr>
<tr>
<td>$T_{\text{ex,gt}}$</td>
<td>exit gas temperature of the fire-box during on-period</td>
</tr>
<tr>
<td>$T_{\theta,\text{ave}}$</td>
<td>average of the fire-box exit gas temperature and adiabatic flame temperature</td>
</tr>
<tr>
<td>$T_{\text{in,cw}}$</td>
<td>inlet temperature of the domestic water heating coil</td>
</tr>
<tr>
<td>$T_{\text{in,hx}}$</td>
<td>gas temperature at the inlet of heat exchanger</td>
</tr>
<tr>
<td>$T_{k_s}$</td>
<td>absolute temperature of the sink surface</td>
</tr>
<tr>
<td>$T_{\text{out,cw}}$</td>
<td>outlet temperature of coil water</td>
</tr>
<tr>
<td>$T_{\text{ra}}$</td>
<td>boiler room air temperature</td>
</tr>
<tr>
<td>$T_{\text{rw}}$</td>
<td>boiler return water temperature</td>
</tr>
<tr>
<td>$T_{\text{stk,ss}}$</td>
<td>stack gas temperature at steady state</td>
</tr>
<tr>
<td>$T_{\text{surf,c}}$</td>
<td>surface temperature of the coil wall</td>
</tr>
<tr>
<td>$T_{\text{sw}}$</td>
<td>boiler supply water temperature</td>
</tr>
<tr>
<td>$U_j$</td>
<td>overall heat transfer coefficient</td>
</tr>
<tr>
<td>$V_{gf}$</td>
<td>volume of gas in the fire-box</td>
</tr>
<tr>
<td>w</td>
<td>weighting factor</td>
</tr>
<tr>
<td>$x_{\text{space}}$</td>
<td>space load factor</td>
</tr>
</tbody>
</table>
\( x_{\text{water}} \) \hspace{1cm} \text{water load factor}

\( \Delta T \) \hspace{1cm} \text{temperature difference}

\( \epsilon_{\text{gas}} \) \hspace{1cm} \text{gas emissivity}

\( \epsilon_{\text{sink}} \) \hspace{1cm} \text{sink surface emissivity of the boiler fire-box}

\( \eta_{225} \) \hspace{1cm} \text{part-load efficiency at 22.5\% of design space heating load}

\( \eta^* \) \hspace{1cm} \text{efficiency at the load } 0.225 + x_{\text{water}}

\( \eta_{ss} \) \hspace{1cm} \text{steady-state efficiency}

\( \eta_u \) \hspace{1cm} \text{fuel utilization efficiency}

\( \mu \) \hspace{1cm} \text{dynamic viscosity}

\( \sigma \) \hspace{1cm} \text{Stefan-Boltzmann constant}

\( r_g \) \hspace{1cm} \text{nominal gas time constant}

\( r_w \) \hspace{1cm} \text{nominal boiler water time constant}
<table>
<thead>
<tr>
<th>Physical Characteristic</th>
<th>From</th>
<th>To</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>ft</td>
<td>m</td>
<td>0.3048</td>
</tr>
<tr>
<td></td>
<td>in</td>
<td>m</td>
<td>0.0254</td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>ft(^2)</td>
<td>m(^2)</td>
<td>0.0929</td>
</tr>
<tr>
<td></td>
<td>in(^2)</td>
<td>m(^2)</td>
<td>6.4516 E-4</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>ft(^3)</td>
<td>m(^3)</td>
<td>2.8317 E-2</td>
</tr>
<tr>
<td></td>
<td>gal</td>
<td>L</td>
<td>3.7854</td>
</tr>
<tr>
<td><strong>Flow rate</strong></td>
<td>gpm</td>
<td>m(^3)/s</td>
<td>6.30902 E-5</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>lb(_m)</td>
<td>kg</td>
<td>0.4536</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>lb(_m)/ft(^3)</td>
<td>kg/m(^3)</td>
<td>1.60185</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>in Hg</td>
<td>kPa</td>
<td>3.37685</td>
</tr>
<tr>
<td></td>
<td>psi</td>
<td>kPa</td>
<td>6.89476</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>°F</td>
<td>°C</td>
<td>(T_c=(T_f-32)/1.8)</td>
</tr>
<tr>
<td><strong>Temperature Difference</strong></td>
<td>°F</td>
<td>°C</td>
<td>0.55555</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Btu/h</td>
<td>W</td>
<td>0.29307</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>Btu</td>
<td>kJ</td>
<td>1.055056</td>
</tr>
<tr>
<td><strong>U-value</strong></td>
<td>Btu/h-ft(^2)-F</td>
<td>W/m(^2)-K</td>
<td>5.678264</td>
</tr>
<tr>
<td><strong>Specific heat</strong></td>
<td>Btu/lb(_m)-F</td>
<td>kJ/kg-K</td>
<td>4.1868</td>
</tr>
</tbody>
</table>
1. **INTRODUCTION**

Although boilers with tankless coils have been around for a long time, other types of residential integrated appliances designed for both space and domestic hot water heating have recently emerged in the market place. Because of the newness of these combined appliances, a new method for rating their performance has become necessary. Responding to this need, the ASHRAE SPC-124P committee has developed a draft standard [1] entitled "A Method of Testing for Rating Combination Space Heating/Water Heating Appliances" and submitted it for public review.

Previously, Subherwal [2], Pietsch [3], and Nordstrom and Fuller [4] discussed the performance rating of combination space heating/water heating appliances in several papers. In an effort to review the ASHRAE's proposed test method, laboratory tests and computer simulations were performed at the National Institute of Standards and Technology (formerly National Bureau of Standards) on a clam-shell, wet-base, oil-fired, residential boiler with a tankless domestic water heating coil. Based upon the commercial steam boiler model by Chi [5], a residential boiler computer model was developed and is discussed in this report. Some of the information from a commercial boiler model, which was developed by Chi, Chern, and Didion [6], was also incorporated in this boiler model.

The computer model was then used to simulate the operation of the selected appliance by incorporating it in the HVACSIM* program, which is a dynamic building system simulation program created at NIST [7,8]. The computer model was verified with laboratory test data for heat-up, cool-down, cyclic,
and standby modes of operation, along with various domestic hot water draw cycles.

A series of computer simulations were performed for domestic water heating only (summer operation) and for combined space and domestic water heating (winter operation). A family of combined efficiency curves was obtained as a function of the space load factor for different domestic water loads. An analysis of the behavior of the selected boiler with a tankless coil leads to a new method for determining the combined, seasonal efficiency of appliances whose primary and secondary functions are space and domestic water heating, respectively.

2. LABORATORY TESTINGS

2.1. Test Setup

The integrated appliance under study was a residential wet-base hot water boiler with five sectional clam-shell, cast-iron heat exchangers. One of the heat exchanger sections contained a finned, copper coil for domestic hot water heating. The boiler’s DOE rated heating capacity was 158 kBtu/h and the firing rate of the oil burner was 1.35 gal/h. The boiler used a No.2 fuel oil. The external view and the heat exchanger arrangement of the boiler are shown in Figures 1 and 2, respectively.

Figure 3 shows the overall sketch of test setup, excluding some of the data acquisition instruments. A six-inch diameter stack was directly connected to the boiler top, and an 1/125 HP circulating water pump for space heating
Figure 1  External view of the wet-base hot water oil-fired boiler
Figure 2  Heat-exchange arrangement of the boiler
Test Set-up of a Boiler with a Tankless Coil

Figure 3 Test set-up of the boiler with a tankless coil
loop was located near the return port to the boiler. Two one-inch pipes were also connected to the inlet and the outlet ports of the domestic water heating coil. The majority of water piping was insulated with 1/2-inch insulation. A barometric damper for draft control was located in the stack.

Two load tanks were used to simulate the building load. Cold water from the tap cooled down the circulating boiler water in the main load tank. An auxiliary load tank served to increase the heat removal capacity of the cooling water. A pump circulated the cooling water through both load tanks. Only the main load tank contained a heat exchanger for cooling the circulating boiler water.

A controller, supplied by the manufacturer, controlled the operation of the oil burner. The input signal to the controller was provided by the thermocouple located in the clam-shell section of the heat exchanger which contained the tankless coil. The controller also controlled the water circulating pump depending upon the on/off condition of a thermostat that, in this case, sensed the load tank water temperature. An override switch was installed to bypass this thermostat and permit manual control of the pump.

A number of thermocouples were installed at various locations in the test apparatus. These thermocouples were connected to a data acquisition/control instrument that was connected to a personal computer. The test was automated using off-the-shelf data acquisition and control application software. A gas analyzer was used to measure the CO₂ concentration in the flue gas of the boiler.
The water flow rate for the space heating function was set by a manually operated valve, while the flow rate for domestic hot water remained constant during all water draws. Two water flow meters with electric pulse generators were used for measuring the amount of water flow through the boiler and the tankless coil. An in-line solenoid valve, controlled by the computer based data acquisition/control system, controlled the flow of domestic hot water.

2.2. Test Procedures

Laboratory testings were performed to provide input data for the computer model and to verify the model. Experimental work involved heat-up and cool-down tests, a steady-state test, and tests to determine the effects on efficiency of various space loads, water loads, and combined space and domestic water loads.

Prior to a test, the data acquisition sequence and control sequence were programmed into the computer. Measured data was automatically stored on the hard disk in the personal computer. Measurements of oil consumption and electric energy use were, however, performed manually. Oil consumption was determined by recording the weight of the oil container before, during, and after a test. Electric energy consumption was measured manually reading a watt-hour meter.

The data sampling period was limited by the size of data file that could be stored on the hard disk. In order to keep the data file manageable, two periods were used. A small sampling period was used for fast changing situations, while a large one was used for slow changes.
During a test, a color monitor displayed plots of selected variables with respect to time. The displayed plots revealed very valuable information on the status of the test. Figure 4 is a sample screen dump to a printer. The numeric value appearing inside a rectangular box is the totalized value of water flow in gallons for this particular test.

Heat-up and cool-down tests were made without any external water flow, i.e. no space heating load or domestic hot water load was imposed. The oil burner of the boiler stayed on until the boiler water temperature reached its cutoff point. Since no external water flow was allowed, the boiler water cooled down very slowly.

During steady-state tests, the space heating water circulated continuously through the boiler and the heat exchanger of the main load tank. The water flow rate was adjusted to make the burner run continuously without causing significant variation of the boiler water temperature. It was found, however, that it was very difficult to make such an adjustment due to variations in boiler and load tank temperatures. Because of this, steady-state experiments usually lasted less than 30 minutes. No domestic hot water was drawn during these tests.

The performance rating test was carried out following the test procedure given by the ASHRAE/ANSI Standard for rating the performance of residential boilers/furnaces [9]. The quantities required by the Standard were measured and then used to calculate the boiler seasonal fuel utilization efficiency and steady-state efficiency.
Figure 4  Sample screen dump of the displayed plots on a monitor
Space heating loads were simulated through the use of a load tank previously described. The water temperature within the load tank was controlled by means of the thermostatically controlled water pump. The thermostat's upper and lower limits were set before each test. No domestic water was drawn during a space load test and the controller supplied with the boiler controlled the burner operation. Using the water flow rate and the temperature difference between the boiler's supply and the return water, the amount of energy delivered to the load tank was computed. The effect of the water pump cycling rate on the boiler's energy consumption was also investigated.

Figure 5 illustrates how the burner and pump on/off status and the stack gas temperature changes with respect to time for a typical space load simulation test. Due to the limitation of the load tank cooling capacity, the cycle rate could not be increased over a certain limit. The duration of a typical test with repeatable cycles was usually between 2 and 3 hours.

Domestic hot water load simulation tests were carried out according to the ASHRAE 124P proposed Standard [1]. Even though the measured first hour rating was 138 gal, the maximum allowable total daily draw of 120 gal specified in the proposed Standard was used in all draw tests. After the 18-hour standby period, six equal draws of domestic hot water were imposed at the beginning of each hour. The sampling rate of data collection was one scan per 15 seconds.

During the water load simulation tests, no space load was applied. The lower and upper setpoints of the boiler controller were set to 190°F (87.78°C) and

10
Figure 5  The burner and pump on/off status and the stack gas temperature of a typical space load simulation test
210°F (98.89°C), respectively. The flow rate of domestic hot water was fixed as assigned by the Standard at 3.0 gal/min.

In the 18-hour standby period, the boiler water temperature was maintained between these setpoints by operating the burner to compensate the heat losses due to the stack gas flow, heat flow through the boiler jacket, and heat conduction to pipes.

By combining space load and domestic water load, combined load tests were performed. The simulation tests were, however, restricted to low space loads, due to the limited cooling capacity of the load tanks. The water pump circulated the space heating water with a constant flow rate, when space heating was demanded. To simulate the domestic water load simulation tests, one-sixth of the daily usage of hot water was drawn at a fixed rate at the beginning of each hour of the six-hour draw period. The combination of two space heating and domestic water heating loads resulted in complex cycles as, for example, shown in Figure 6. The status of the burner and circulating pump and the stack gas temperature are shown in this figure.

3. COMPUTER SIMULATIONS

The HVACSIM+ program was used for computer simulations of the boiler with a tankless coil. Component models consisting of a water boiler model, a simple heating coil model, and an algorithm for boiler control, were developed to be compatible with the HVACSIM+ program. These component models were connected to each other to form a model of the boiler with a tankless coil.
Figure 6  The status of the burner and circulating pump and the stack gas temperature of a combined load test
The boiler model was an empirical model that required reasonably good initial input data based on the actual data. The input data were prepared from laboratory tests and the boiler configuration. As will be discussed later in this report, a number of simplifying assumptions were made in modelling the boiler/tankless coil system.

3.1 Computer Model

3.1.1. Water Boiler Component Model

Figure 7 shows a cross-sectional view of the boiler that was modelled. As seen in the figure, a domestic water heating coil is located in the right-hand side of the heat exchanger. For modelling purpose, the boiler and the coil were considered as separate component models.

The empirical, residential, fossil fuel-fired, water boiler model was based on the simplified commercial boiler model by Chi [5]. The schematic diagram of the boiler model is depicted in Figure 8. The supply water temperature to the load was assumed to be the same as the boiler water temperature. The boiler water temperature, in turn, was assumed to be uniform inside the boiler. These assumptions were made to simplify the modelling task.

As shown in Figure 8, the boiler can be divided into the following five sections: combustion gas product, fire-box wall, heat exchanger wall, boiler water, and boiler jacket. The heat transfer phenomena within the boiler are different during the on and off periods of the burner.
Figure 7  The cross-sectional view of the boiler

Figure 8  A schematic diagram of the modelled boiler sections
3.1.1.1 Gas-side Heat Transfer

Referring to Figure 8, a heat balance on the gas-side can be represented by:

\[ \dot{Q}_{\text{input}} - \dot{Q}_{\text{lat}} - \dot{Q}_{f} - \dot{Q}_{h\times} - \dot{Q}_{\text{stk}} = 0. \]  

(1)

In this equation, \( \dot{Q}_{\text{input}} \) is the fuel input rate which is computed from the mass flow rate of fuel, \( \dot{m}_{\text{fuel}} \), and its higher heating value of fuel, HHV, using

\[ \dot{Q}_{\text{input}} = \dot{m}_{\text{fuel}} \times \text{HHV}. \]  

(2)

The quantity \( \dot{Q}_{\text{lat}} \) is the latent heat loss calculated using:

\[ \dot{Q}_{\text{lat}} = 2442.0 \times \dot{m}_{\text{fuel}} \times R_{\text{wtf}}, \]  

(3)

where \( R_{\text{wtf}} \) is the ratio of mass of water in the fuel to the total mass of the fuel and the constant 2442.0 (kJ/kg) is latent heat for evaporation of water. The term \( \dot{Q}_{f} \) is the heat flow rate from the combustion gas/draft air to the boiler water through the wall of the fire-box. The term \( \dot{Q}_{h\times} \) denotes the heat transfer rate between the gas and the boiler water through the heat-exchanger. Once these four heat flow rates are determined, the heat loss through the stack is \( \dot{Q}_{\text{stk}} \) and is obtained using equation (1).

3.1.1.2 Fire-box Wall Heat Transfer

Heat transfer through the fire-box wall during the burner on-period was
calculated using the well-stirred combustion chamber theory [10]. The radiative and convection heat transfer from combustion gas to a sink surface is given by:

$$\dot{Q}_{f, on} = A_{rc} \sigma (T_{g, ave}^4 - T_{ks}^4), \quad (4)$$

where \(\sigma\) is the Stefan-Boltzmann constant (5.67*10^-11). The absolute temperature \(T_{g, ave}\) is the average gas absolute temperature of the fire-box exit gas temperature and the absolute adiabatic flame temperature, \(T_{af}\). The absolute adiabatic flame temperature is given by:

$$T_{af} = T_{ra} + (HHV - 2442 R_{wtf})/(C_{p, product} R_{ptf}) + 273.15, \quad (5)$$

where \(T_{ra}\), \(C_{p, product}\) and \(R_{ptf}\) are the boiler room air temperature, the specific heat of the combustion products and the mass ratio of combustion products to fuel, respectively. The absolute temperature of the sink surface, \(T_{ks}\), is assumed to be the same as the absolute boiler water temperature. The quantity \(A_{rc}\) is an effective emissivity, the sum of radiative and convective heat transfer parts and given by:

$$A_{rc} = C_s (1 - K^3)/(1 - K^4) + 2 A_{cf} h_c/[(\sigma (T_{g, ave} + T_{ks})^3)], \quad (6)$$

where

$$C_s = (A_{rf} + A_{cf})/[1 / \epsilon_{gas} + 1 / (C_s \epsilon_{sink}) - 1], \quad (7)$$

$$K = T_{ks} / T_{g, ave}.$$
In the above equation, $A_c$ and $A_r$ are the surface areas of convective heat transfer and radiative heat transfer, respectively; $h_c$ is the convective heat transfer coefficient; $\varepsilon_{gas}$ and $\varepsilon_{sink}$ are the gas emissivity and the sink surface emissivity of the boiler fire-box; and $C_s$ is the area ratio of boiler fire-box effective radiation heat transfer area to the total boiler fire-box area.

Using the Nusselt number, $Nu$, expressed in terms of Reynolds number, $Re$, and Prandtl number, $Pr$, the convective heat transfer coefficient, $h_c$ can be evaluated:

$$Nu = 0.023 \, Re^{0.8} \, Pr^{0.4} \quad \text{for } Re \geq 2000,$$  \hspace{1cm} (8)

$$Nu = 3.66 \quad \text{for } Re < 2000,$$  \hspace{1cm} (9)

and

$$h_c = Nu \, k / d_h,$$  \hspace{1cm} (10)

where $k$ is the thermal conductivity, and the hydraulic diameter, $d_h$, can be represented in terms of the volume of fire-box gas, $V_{gf}$ and the gas path length, $L_{gpf}$, using:

$$d_h = \left[ \frac{4 \, V_{gf}}{\pi \, L_{gpf}} \right]^{1/2}.$$  \hspace{1cm} (11)

During the on-period of the boiler burner, the mass flow rate of combustion product, $m_{g, on}$, is given by:

$$m_{g, on} = m_{fuel} \, R_{ptf}.$$  \hspace{1cm} (12)
The Reynolds number and Prantl number used in equation (8) are given by

\[
Re = \frac{\dot{m}_{8, on} \cdot d_n}{\mu A_{cross}}, \quad \text{and}
\]

\[
Pr = \frac{\mu C_p}{k},
\]

where \(\mu\) is the dynamic viscosity, \(C_p\) is the specific heat, and \(A_{cross}\) is the cross sectional area through which a fluid passes.

During the off-period of the burner, the mass flow rate of the draft air, \(\dot{m}_{8, off}\), can be obtained using an equation similar to the one used in ASHRAE/ANSI Standards [9], or in the report by Kelly, Chi, and Kuklewicz [11]:

\[
\dot{m}_{8, off} = \dot{m}_{8, on} \left[\frac{(T_{stk} - T_{ra})}{(T_{stk, ss} - T_{ra})}\right]^{0.56} 
\times \left[\frac{(T_{stk, ss} + 273.15)}{(T_{stk} + 273.15)}\right]^{1.19},
\]

where \(T_{stk, ss}\) is the stack gas temperature at steady state.

The effectiveness method for a compact heat exchanger [12,13] is applied to calculate the off-period convective heat transfer, \(\dot{Q}_{t, off}\):

\[
\dot{Q}_{t, off} = C_p a \cdot \dot{m}_{8, off} (T_{ra} - T_{bw}) (1 - e^{-NTU}),
\]

where \(NTU = A_{st} h_c / (C_p a \cdot \dot{m}_{8, off})\).

NTU is the number of heat transfer units, \(C_p a\) is the specific heat of air, and \(T_{bw}\) is the boiler water temperature. The exit gas temperature of the fire-
box during the off-period, $T_{ex,g,f}$, is obtained using equation (16):

$$T_{ex,g,f} = T_{ra} - \frac{\dot{Q}_{f,off}}{(C_p m_{g,off})}.$$  \hspace{1cm} (18)

During the on-period, the exit gas temperature is estimated iteratively using Newton's method.

3.1.1.3 Heat Exchanger Heat Transfer

The number of heat transfer units between the gas and the boiler water at the full load condition, $NTU_f$, can be determined from the boiler test data using a semi-empirical equation [14]:

$$NTU_f = \ln(1 - (\eta_{ss} \dot{Q}_{input} - \dot{Q}_f - \dot{Q}_j)/[C_p \dot{m}_{g,on}(T_{in,hx} - T_{sw})])^{-1} \hspace{1cm} (19)$$

where $\eta_{ss}$, $\dot{Q}_j$, $C_p$, $T_{in,hx}$, and $T_{sw}$ are the steady-state efficiency, the jacket heat loss rate, the specific heat of gas, the gas temperature at the inlet of the heat exchanger, and the supply water temperature, respectively. With the boiler heat exchanger heat transfer number at full load given by equation (19), the number of heat transfer units at part load, $NTU_{on}$, can be evaluated by scaling as follows:

$$NTU_{on} = NTU_f \left(\frac{\dot{m}_{g,on,f}}{\dot{m}_{g,on,p}}\right)^{0.2} \left(\frac{\mu_{g,on,f}}{\mu_{g,on,p}}\right)^{0.4} \left(\frac{C_p, on, f}{C_p, on, p}\right)^{0.6} \left(\frac{k_{on,p}}{k_{on,f}}\right)^{0.6}, \hspace{1cm} (20)$$

where the subscript $p$ indicates part-load condition and $f$ indicates full load.
The heat flow rate during the on-period between the combustion gas products and the boiler water, \( \dot{Q}_{hx, on} \), is obtained using equation (20),

\[
\dot{Q}_{hx, on} = C_{pg, on} \dot{m}_{g, on} (T_{in, hx} - T_{sw}) (1 - e^{-NTU_{on}}).
\] (21)

Similarly, the heat flow rate during the off-period is

\[
\dot{Q}_{hx, off} = C_{pg, off} \dot{m}_{g, off} (T_{in, hx} - T_{sw}) (1 - e^{-NTU_{off}}).
\] (22)

The off-period number of heat transfer units, NTU_{off}, is determined based on gas properties during the off-period. When the gas flow rate is very small, equation (20) becomes infinite, and the following expression is instead used:

\[
\dot{Q}_{hx, off} = C_{pg, off} \dot{m}_{g, off} (T_{in, hx} - T_{sw}).
\] (23)

3.1.1.4 Boiler Water Heat Transfer

Dynamic changes in the boiler water temperature, the most important quantity in the boiler model, are considered using an ordinary differential equation as follows:

\[
C_{pw} M_w \frac{dT_{bw}}{dt} = C_{pw} \dot{m}_w (T_{bw} - T_{bw}) + \dot{Q}_{sw},
\] (24)

For this relation, the boiler water temperature is assumed to be the same as the supply water temperature to the space load. \( C_{pw} \) is the specific heat of the boiler water, \( M_w \) is the mass of boiler water, \( \dot{m}_w \) is the circulating
water flow rate, $T_{rw}$ is the return water temperature, and $\dot{Q}_{ss}$ is the heat gain rate of the boiler water given by

$$\dot{Q}_{ss} = \dot{Q}_f + \dot{Q}_{hx} - \dot{Q}_j - \dot{Q}_{cw},$$

(25)

where $\dot{Q}_{cw}$ is the heat flow rate from the boiler water to the tankless coil water.

Considering the temperature lag due to the thermal mass of the heat exchanger and boiler water, the heat gain at the current time can be replaced by the heat gain at the previous time step. In addition, the capacitance of the boiler water, $C_{pw}M_w$, can be given as the nominal time constant times a constant, $I_{cfw}$, that is determined empirically. Equation (24) can thus be written as

$$I_{cfw} r_w (dT_{bw}/dt) = C_{pw} \dot{m}_w (T_{rw} - T_{bw}) + \dot{Q}_{ss,-1},$$

(26)

where

$$\dot{Q}_{ss,-1}(t) = \dot{Q}_{ss}(t - \Delta t),$$

(27)

$I_{cfw}$ is an empirically determined integration constant, and $r_w$ is the nominal boiler water time constant.

### 3.1.1.5 Boiler Jacket Heat Transfer

Heat transfer through the boiler jacket from the boiler water to the ambient air is calculated from the overall heat transfer coefficient, $U_j$, the jacket area, $A_j$, and the temperature difference across the jacket, $\Delta T$.

$$\dot{Q}_j = A_j U_j \Delta T = A_j U_j (T_{bw} - T_{ra})$$

(28)
Since the mass of the jacket is much lower than the mass of the boiler water or that of the heat exchanger, instantaneous thermal response is assumed in the equation above.

3.1.1.6 Stack Gas Temperature

Thermal properties of the gas in the heat exchanger such as $\mu$, $C_p$, and $k$, are determined using the average temperature of the inlet and outlet gas temperature of the heat exchanger. The inlet gas temperature is the exit gas temperature of the fire-box, but the outlet gas temperature is the stack gas temperature as shown in Figure 8. Moreover, the off-period mass flow rate of the gas depends upon the stack gas temperature (see equation 15).

Separate differential equations for the stack gas temperature are considered for the on-period and the off-period, since the patterns of rising and decay of the stack gas temperature are usually different in each case. During the on-period,

$$I_{cfg, on} \tau_g (dT_{stk}/dt) + T_{stk} = T_{stk, ss}$$  \hspace{1cm} (29)

and during the off-period,

$$I_{cfg, off} \tau_g (T_{stk}/dt) + T_{stk} = w T_{bw, ref} + (1 - w) T_{ra},$$  \hspace{1cm} (30)

where $\tau_g$ is a nominal gas time constant, and $I_{cfg, on}$ and $I_{cfg, off}$ are integration constants. Appropriate integration constants and the real time constants, $\tau_g$ for the on-period and $\tau_g$ for the off-period, can be determined
based on laboratory test results. The quantity $T_{stk,s}$ is the steady-state stack gas temperature, $T_{bw,ref}$ is a reference boiler water temperature corresponding to the stack gas temperature at an equilibrium state, and $w$ is a weighting factor that is used to obtain a good fit to the measured stack gas temperature decay curve. The values of $T_{bw,ref}$ and $w$ used in most of computer simulations were 97.5°C and 0.8 respectively. These assigned values can be changed depending upon the characteristics of a boiler of interest.

It should be noted that the stack gas temperature specified by equations (29) and (30) bound the heat transfer rates of the heat exchanger during the on- and off-periods.

3.1.2. Domestic Water Heating Coil Model

The coil model for domestic water heating was developed. This model was an extension of a simplified approach for calculating the heat transfer resulting from flow through a pipe with a constant surface temperature, $T_{surf,c}$ [14]. For the model, the boiler water temperature is assumed to be uniform everywhere inside the boiler, and the capacitance of the coil wall is neglected. Properties of the water in the coil are evaluated at the average temperature of the coil inlet and outlet temperatures.

The convective heat transfer coefficient between the coil wall and the coil water, $h_{cw}$, is calculated in a similar manner as given by equation (10). The value of $h_c$ is obtained for given values of the pipe diameter, $d_c$, the pipe length, $l_c$, the inlet temperature, $T_{in,cw}$, and the mass flow rate of
coil water, $m_{cw}$. The outlet temperature of the coil water, $T_{out,cw}$, and the heat transfer rate, $Q_{cw}$, can be computed from:

$$T_{out,cw} = T_{surf,c} - (T_{surf,c} - T_{in,cw}) e^{-N},$$  \hspace{1cm} (31)$$
$$Q_{cw} = h_{cw} A_{surf,c} \Delta T_{lm}$$  \hspace{1cm} (32)$$

where

$$\Delta T_{lm} = \frac{(T_{out,cw} - T_{in,cw})}{\ln[(T_{surf,c} - T_{in,cw}) / (T_{surf,c} - T_{out,cw})]}$$  \hspace{1cm} (33)$$
$$h_{cw} = Nu_{cw} k_{cw} / d_c,$$  \hspace{1cm} (34)$$
$$N = h_{cw} A_{surf,c} / (m_{cw} C_{pcw}),$$  \hspace{1cm} (35)$$

and the subscript $cw$ denotes the water in the tankless coil.

### 3.1.3. Boiler Control

The burner and the space heating water circulating pump are controlled by on/off control at upper/lower setpoints. A high/low temperature limit switch for space heating load control governs the circulating pump with an option of manual override. When the boiler water temperature was greater than, or equal to, the upper setpoint, the burner was turned off. When the boiler water temperature was less than, or equal to, the lower setpoint, then the burner was turned on. Similarly, when the space load-side temperature was greater than, or equal to, the upper limit, the pump was turned off. When the temperature was less than, or equal to, the lower limit, the pump was turned on. In addition, in order to achieve better convergence of computer simulations with the HVACSIM$^p$ program, a very small amount (typically 0.7% of the total flow rate) of circulating water was allowed to flow through the pump even if the limit controller called for no water flow.
3.2. **Computer Simulation Procedures**

3.2.1. **Source Program**

The boiler component models described previously were coded in the Fortran 77 language as subroutines bearing names as:

- **TYPE62** for hot water boiler
- **TYPE63** for domestic hot water heating coil
- **TYPE64** for boiler control

The subroutine **TYPE62** calls many routines as shown in Figure 9. Brief descriptions of these routines are given below.

- **BLINIT**: setting initial conditions at full load
- **BLFLD**: boiler heat exchanger performance at full load
- **BLHX**: boiler heat exchanger performance at part load
- **BLFON**: boiler fire-box performance during the on-period of the burner
- **BLOFF**: boiler fire-box performance during the off-period of the burner
- **CPF**: specific heat of the combustion products
- **GEF**: gas emissivity
- **GS**: radiation exchange area
- **HCOF**: convective heat transfer coefficient
- **PRDPP**: mass ratios of combustion product
- **PRDPR**: viscosity and thermal conductivity of combustion product
- **TAFF**: adiabatic flame temperature
- **CPCVA**: specific heat of air
- **WCP**: specific heat of water
Figure 9  The routines called by the subroutines, TYPE62 and TYPE63
All routines called by the TYPE62 subroutine are included in Appendix A, except for CPCVA and WCP, which are part of the TYPES subroutine in the HVACSIM+ program.

The subroutine TYPE63 needs four routines:

- **WMU**: viscosity of water,
- **WK**: thermal conductivity of water,
- **WCP**: specific heat of water, and
- **HCOVF**: convective heat transfer coefficient.

The subroutine TYPE64 does not call any other routine. The WMU and WK routines are also included in the HVACSIM+ TYPES subroutine. The TYPE63 and TYPE64 are included in Appendix A.

### 3.2.2. Input Data Preparation

As shown in Figure 10, UNIT numbers were assigned to three component models (TYPE62, TYPE63, and TYPE64) and index numbers were assigned to state variables according to the HVACSIM+ program documentation [15,16,17]. The characters, P, M, T, and C, in Figure 10 represent pressure, mass flow rate, temperature, and control variables, respectively.

The simulation setup was accomplished by invoking the front end program HVACGEN, which is included in the HVACSIM+ program package. A simulation work file was generated. The hierarchical structure of the simulation work file contains SUPERBLOCK, BLOCK, and UNIT. In this boiler simulation, however, there is only one SUPERBLOCK that has only one BLOCK containing three
Figure 10  Block diagram of the boiler model for use with HVACSIM*
UNITs. This simulation setup is shown in Appendix B. It was generated using the "View All" command in HVACGEN.

The model definition file, which is required as an input file to the main program MODSIM, is created by the program SLIMCON. Whenever information required for the simulation work file is changed, the work file and the model definition file are updated.

A boundary data file, whether used or not, must be provided prior to a simulation along with the model definition file. The boundary data file may, however, be empty. For the simulations in this study, the on- and off-times of the water pump and the flow rate of domestic hot water drawn were included in the boundary data file. Because large step changes of a variable in the boundary data file often induce instability in a simulation, all large step changes were approximated by a number of small incremental changes. A program, CRBND, generating such incremental step changes in a boundary data file is listed in Appendix C.

The process of making a boundary data file is reasonably simple using the program CRBND, when either space water heating only or domestic hot water heating only is being performed. However, when space heating and domestic water heating are combined, the output of CRBND must be manually edited with great care.

3.2.3. Execution of the Simulation

The main simulation program, MODSIM, was compiled using an optimized Fortran
77 compiler and was linked with necessary library routines on a mini-computer. The MODSIM program calls the equation solver routine that uses the Newton-Gauss method. With this method, good estimation of initial conditions is essential to achieve good convergence of the solution. Simulations were performed using two input files: the model definition file and boundary data file. The minimum and maximum time steps for simulations were assigned 0.5 sec and 200 sec, respectively. The MODSIM program automatically chooses the time step and order of integration between these two limits.

3.2.4. Analysis of Simulation Outputs

Computer simulation results were analyzed using a number of small programs. During this post-processing phase, the simulation output files were reformatted to be usable by a graphics routine, the heat transfer rates were integrated to obtain energy values, and the load factors and fuel utilization efficiencies were calculated. When interpolation of data was needed, a routine implementing a cubic B-spline method was employed. In addition, a commercial spreadsheet program was also used to analyze some of the simulation outputs.

4. RESULTS AND DISCUSSION

Using laboratory test results, the boiler model with the tankless coil was simulated and tuned. The tuned model was then verified with additional laboratory measurements. After verification, the computer model was used to simulate the boiler operation in both the summer and winter seasons.
Computer simulations for heat-up and cool-down operations were repeated without an external load until reasonably good agreement was reached between computer simulation results and experimental measurements. Figure 11 shows the stack gas and boiler water temperatures of the computer simulation and the laboratory measurements during the heat-up and cool-down periods. The integration constants \( I_{cfg, on} \), \( I_{cfg, on} \), and \( I_{cfg, off} \) used in equations (26), (29), and (30) were determined as a part of this process.

Figure 12 shows a simulation of part-load operation in space heating only mode. Cyclic stack gas and boiler water temperatures are compared. In this case, space heating water was circulated continuously and no domestic hot water was withdrawn. The burner was turned on or off depending upon the boiler water temperature. It should be noted that the measured boiler water temperature was not an average boiler water temperature but a local temperature measured at the location of the temperature sensor. The boiler temperature predicted by the computer simulations represented the average temperature throughout the boiler. From the cyclic operation simulations, some further adjustment were made to the time constants for the stack gas and boiler water during burner on- and off-periods.

The simulated pattern of domestic hot water use was investigated following the test procedure in the ANSI/ASHRAE 124P proposed standard [1]. An 18-hour standby period followed by a 6-hour draw period were studied using laboratory tests and computer simulations. The stack gas and boiler water temperatures are compared in Figure 13. Figure 14 depicts the boiler water
Figure 11  The stack gas and boiler water temperatures during the heat-up and cool-down periods

Figure 12  Part-load operation in space heating only
Figure 13  The stack gas and boiler water temperatures of a domestic hot water draw simulation
Figure 14  The boiler water temperature changes during a part of the standby period

Figure 15  The tankless coil outlet temperatures during a part of the draw period
### Table 1  24-hour Draw Test

<table>
<thead>
<tr>
<th>EVENT</th>
<th>OIL Qinp,exp (kg)</th>
<th>OIL Qinp,sim (kJ)</th>
<th>ELECTRIC Qele,exp (Wh)</th>
<th>ELECTRIC Qele,sim (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standby</td>
<td>1.455</td>
<td>65389</td>
<td>67310</td>
<td>78.1</td>
</tr>
<tr>
<td>Reheat</td>
<td>0.140</td>
<td>6292</td>
<td>6714</td>
<td>7.2</td>
</tr>
<tr>
<td>Draw 3</td>
<td>0.500</td>
<td>22471</td>
<td>22800</td>
<td>27.1</td>
</tr>
<tr>
<td>Draw 4</td>
<td>0.550</td>
<td>24718</td>
<td>22800</td>
<td>29.8</td>
</tr>
<tr>
<td>Draw 5</td>
<td>0.540</td>
<td>24268</td>
<td>22800</td>
<td>29.5</td>
</tr>
<tr>
<td>Draw 6</td>
<td>0.555</td>
<td>24942</td>
<td>22800</td>
<td>29.5</td>
</tr>
<tr>
<td>Draw 7</td>
<td>0.545</td>
<td>24493</td>
<td>22800</td>
<td>29.9</td>
</tr>
<tr>
<td>Draw 8</td>
<td>0.545</td>
<td>24493</td>
<td>22800</td>
<td>29.4</td>
</tr>
<tr>
<td>Total</td>
<td>4.83</td>
<td>217065</td>
<td>210824</td>
<td>260.5</td>
</tr>
</tbody>
</table>

Ratio of electricity to oil = 0.004320
temperature changes with respect to time during a part of the 18-hour standby period, while Figure 15 shows the tankless coil output temperatures during a part of the 6-hour draw period. The results of computer simulations and experiments agree reasonably well. Fuel input energy consumption was used as one of the key variable in the comparison of the laboratory measurements and the computer model simulation outputs. Table 1 shows fuel consumption figures.

4.2. Simulations of Summer Operating Mode

Using the verified computer model, simulations of summer operation were performed to determine input energy consumptions at various water loads and to evaluate the effect of boiler room temperature on the standby loss. Integration of power to obtain energy was achieved using a utility program, ENERGY. This program used a simple trapezoidal integration routine and is included in Appendix D.

Figure 16 shows the energy factor defined as the ratio of output energy to input energy without space heating, as a function of the domestic hot water load. The values appearing in this figure, however, were calculated without taking into account the electrical energy consumption. According to laboratory measurements, the electrical energy consumed by the oil burner represented approximately 0.43 % of the total energy input for a 24-hour test period (see Table 1).

Standby loss variation due to boiler room air temperature was also studied. A series of computer simulations were made with different room air temperatures.
Figure 16  Energy factor for different domestic hot water use level. Note that typical average daily water use specified by DOE Test Procedure for water heaters is 64.3 gal/day.
The ratio, in percent, of the energy consumption for maintaining the boiler water temperature within the specified range during the standby period to the fuel input energy, \( \frac{Q_{\text{input},sb}}{Q_{\text{input}}} \), is shown in Figure 17. The ratio is plotted against a dimensionless parameter that is the difference of room air temperature and boiler water temperature normalized by the boiler water temperature, \( \frac{T_{bw} - T_{ra}}{T_{bw}} \). Also Figure 18 shows the ratio, in percent, of jacket loss to input energy against the same dimensionless parameter. Figures 17 and 18 show that the room air temperature does affect boiler standby loss. Laboratory tests were attempted to confirm these simulation results, but no conclusion reached due to difficulty in maintaining the laboratory room air temperature constant for an 18-hour standby period.

4.3. Simulations of Winter Operating Mode

The effect of a combined space heating and domestic hot water heating load on boiler performance was also studied using computer simulations. Prior to the simulations, a typical thermostat cycle rate curve to meet space heating loads was selected from the report by Kao, Mastascusa, and Chi [18]. The circulating pump on- and off-periods were determined for various cycle rates using this curve. A boundary data file was generated, which incorporated the pump on/off periods used in the simulations.

The space load factor is given by:

\[
x_{\text{space}} = \frac{\dot{Q}_{s,\text{out}}}{\eta_{ss} \dot{Q}_{\text{input}}} \tag{36}
\]

where \( \dot{Q}_{s,\text{out}} \) is the average delivered heat flow rate to the space during the simulation period.
Figure 17  The energy consumption during the standby period showing the room temperature effect

Figure 18  The jacket loss during the standby period showing the room temperature effect
Figure 19 represents a curve of fuel utilization efficiency, $\eta_u$, with respect to space load factor, $x_{\text{space}}$, for space heating only. This curve was created by smoothing raw simulation outputs of MODSIM by using the program SPLINE (see Appendix E).

With combined loads of space heating and water heating, computer simulations were carried out for 12 instead of 24 hours to save computational time. The first 6-hour period was for space heating only, while the second 6-hour period was for combined space and water heating. The energy outputs of the first period were then multiplied by a factor of three to obtain the energy values during the 18-hour period during which there is no water heating load. Since the room air temperature was assumed to be constant, this multiplication is justified. In addition, the boiler inlet water temperature (returning from the heated space) and the tankless coil inlet water temperature were modelled as remaining constants in the simulations.

The fuel utilization efficiency for combined loads is plotted against the space load factor in Figure 20. The amount of hot water drawn daily is shown as a parameter. At $x_{\text{space}} = 0$, the efficiency is the energy factor, EF. From this figure, we can see that the water load causes the efficiency to increase when the space load is low. This efficiency increase diminishes, however, as the space load increases.

5. A METHOD FOR DETERMINING THE COMBINED SEASONAL EFFICIENCY

On the basis of computer simulations and laboratory experiments, a simple method for determining the combined seasonal efficiency of Type I appliances
Figure 19  Fuel utilization efficiency with respect to the space load factor for space heating only

Figure 20  Fuel utilization efficiency for combined loads
is presented here. The primary design function of Type I appliances is space heating and the secondary function is domestic water heating.

Step 1: Generate a fuel utilization part-load efficiency curve as a function of space heating loads for zero domestic water load having the form:

\[
\eta = \left( a \frac{x}{x + b} \right) + c, \tag{37}
\]

and satisfying the following conditions:

\[
\begin{align*}
\eta &= 0.0 \quad \text{at } x = 0 \\
\eta &= \eta_{225} \quad \text{at } x = 0.225 \\
\eta &= \eta_{ss} \quad \text{at } x = 1.0.
\end{align*}
\]

In equation (37), \( x \) is the space load factor, \( \eta_{225} \) is the part-load efficiency at 22.5\% load obtained using ANSI/ASHRAE 103 Standard, \( \eta_{ss} \) is the steady-state efficiency, and \( a, b, \) and \( c \) are constants. For Type I appliances these constants can be calculated as follows:

\[
\begin{align*}
a &= (\eta_{ss} - c) (1 + b) \\
b &= -0.225 \left( \eta_{ss} - \eta_{225} \right) / \left( 0.225 \eta_{ss} - \eta_{225} + 0.775 \right) \\
c &= 0
\end{align*}
\]

Figures 21 and 22 show efficiency curves resulting from the computer simulation and the equation (37) at 60 and 120 gallons of daily domestic hot water use, respectively.
Figure 21  Efficiency curves from computer simulation and the equation at $U = 60$ gal

Figure 22  Efficiency curves from computer simulation and the equation at $U = 120$ gal
Step 2: Using the equation (37), find the efficiency, $\eta_c^*$, at the load $x=0.225 + x_{\text{water}}$, where the average domestic water load factor, $x_{\text{water}}$, is given by:

$$x_{\text{water}} = \frac{\dot{Q}_{\text{w, out}}}{Q_{\text{input}}} = \eta_{\text{ss}} \frac{\dot{Q}_{\text{input}}}{Q_{\text{input}}}$$ \hspace{1cm} (38)

where $\dot{Q}_{\text{w, out}}$ is the average heat flow rate for domestic water heating.

Step 3: Use the same form of equation (37) to generate a curve of the form:

$$\eta' = (a'x / (x + b')) + c'$$ \hspace{1cm} (39)

which satisfies three conditions:

$$\eta' = EF \hspace{1cm} \text{at } x = 0$$
$$\eta' = \eta_c^* \hspace{1cm} \text{at } x = 0.225$$
$$\eta' = \eta_{\text{ss}} \hspace{1cm} \text{at } x = 1.0$$

This curve represents the combined efficiency of the boiler as function of space heating load for a daily water usage corresponding to a domestic water load factor of $x_{\text{water}}$.

Step 4: It is needed to bin on equation (37) to find a correction factor that relates the trimmed result to the value $\eta_{22.5}$ found by the ASHRAE 103 test procedure. Using the hourly bin data given in the report by Parken, Kelly, and Didion [19], apply the bin method on the curve represented by equation (39) to find a combined heating seasonal efficiency for the appliance.
Figure 23 illustrates Step 1 through Step 3, and Table 2 shows the output of a spreadsheet program for the boiler with a tankless coil when the daily usage of hot water is 120 gal.

6. CONCLUSION

A residential, fossil fuel-fired, hot water boiler model with a tankless domestic water heating coil was developed based upon laboratory tests, and used with the HVACSIM⁺ program. The computer model was verified with some of the experimental data and used to evaluate the boiler performance through simulations.

Laboratory tests were performed mainly to obtain parameter values used in the computer model verification. The computer model can also be used to simulate other residential boilers with/without domestic water heating coils.

A method utilizing a curve-fitted equation and the bin method is proposed to determine the combined efficiency of a Type I integrated appliance of which primary function is space heating. No comparison was, however, made between this procedure and draft ASHRAE 124P Standard [1]. Thus, there is a need for additional research on combined space and domestic water heating appliances, especially Type II appliances whose primary functions are domestic water heating.
Figure 23  Illustration of Steps 1 through 3 of the NIST's recommended procedure
### Table 2: Bin Data Analysis

#### BIN DATA ANALYSIS

Region IV  
Design outdoor temperature = 5°F  
Oversizing factor = 0.7  
Daily domestic hot water use = 120 gal  

<table>
<thead>
<tr>
<th>Bin #</th>
<th>Tj (F)</th>
<th>Nj</th>
<th>Xspace</th>
<th>Xload</th>
<th>Nj*Xload</th>
<th>Nj*Xload/Effu</th>
<th>Xwater</th>
<th>Effu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62</td>
<td>0.132</td>
<td>0.0294</td>
<td>0.0525</td>
<td>0.0039</td>
<td>0.0064</td>
<td>0.0231</td>
<td>0.4550</td>
</tr>
<tr>
<td>2</td>
<td>57</td>
<td>0.111</td>
<td>0.0784</td>
<td>0.1015</td>
<td>0.0087</td>
<td>0.0123</td>
<td>0.0231</td>
<td>0.7055</td>
</tr>
<tr>
<td>3</td>
<td>52</td>
<td>0.103</td>
<td>0.1275</td>
<td>0.1506</td>
<td>0.0131</td>
<td>0.0175</td>
<td>0.0231</td>
<td>0.7483</td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>0.093</td>
<td>0.1765</td>
<td>0.1996</td>
<td>0.0164</td>
<td>0.0213</td>
<td>0.0231</td>
<td>0.7723</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>0.100</td>
<td>0.2255</td>
<td>0.2486</td>
<td>0.0225</td>
<td>0.0286</td>
<td>0.0231</td>
<td>0.7878</td>
</tr>
<tr>
<td>6</td>
<td>37</td>
<td>0.109</td>
<td>0.2745</td>
<td>0.2976</td>
<td>0.0299</td>
<td>0.0375</td>
<td>0.0231</td>
<td>0.7985</td>
</tr>
<tr>
<td>7</td>
<td>32</td>
<td>0.126</td>
<td>0.3235</td>
<td>0.3466</td>
<td>0.0408</td>
<td>0.0506</td>
<td>0.0231</td>
<td>0.8064</td>
</tr>
<tr>
<td>8</td>
<td>27</td>
<td>0.087</td>
<td>0.3725</td>
<td>0.3956</td>
<td>0.0324</td>
<td>0.0399</td>
<td>0.0231</td>
<td>0.8125</td>
</tr>
<tr>
<td>9</td>
<td>22</td>
<td>0.055</td>
<td>0.4216</td>
<td>0.4447</td>
<td>0.0232</td>
<td>0.0284</td>
<td>0.0231</td>
<td>0.8173</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>0.036</td>
<td>0.4706</td>
<td>0.4937</td>
<td>0.0169</td>
<td>0.0206</td>
<td>0.0231</td>
<td>0.8212</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>0.026</td>
<td>0.5196</td>
<td>0.5427</td>
<td>0.0135</td>
<td>0.0164</td>
<td>0.0231</td>
<td>0.8244</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>0.013</td>
<td>0.5686</td>
<td>0.5917</td>
<td>0.0074</td>
<td>0.0089</td>
<td>0.0231</td>
<td>0.8271</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>0.006</td>
<td>0.6176</td>
<td>0.6407</td>
<td>0.0037</td>
<td>0.0045</td>
<td>0.0231</td>
<td>0.8294</td>
</tr>
<tr>
<td>14</td>
<td>-3</td>
<td>0.002</td>
<td>0.6667</td>
<td>0.6898</td>
<td>0.0013</td>
<td>0.0016</td>
<td>0.0231</td>
<td>0.8314</td>
</tr>
<tr>
<td>15</td>
<td>-8</td>
<td>0.001</td>
<td>0.7157</td>
<td>0.7388</td>
<td>0.0007</td>
<td>0.0009</td>
<td>0.0231</td>
<td>0.8331</td>
</tr>
</tbody>
</table>

**SUM**  
0.234558 0.295306  

Seasonal Efficiency = 0.794289
7. REFERENCES


SUBROUTINE TYPE62(XIN,OUT,PAR,SAVED,IOSTAT)

January 21, 1988  Cheol Park
Revised:  June 22, 1988

INPUTS:
TSTK  Stack gas temperature (C)
TRA   Room air temperature (C)
TOA   Outdoor air temperature (C)
TBLW  Boiler water temperature (C)
PSW   Supply boiler water pressure (kPa)
WSW   Supply boiler water flowrate (kg/s)
TRW   Return boiler water temperature (C)
QCW   Heat flow rate to the tankless coil (kW)
SWCH  Switch for controlling on/off
       1 for burner on and 0 for burner off

OUTPUTS:
TSTK  Stock gas temperature (C) — Diff. eq.
TBLW  Boiler water temperature (C) — Diff. eq.
TSW   Supply water temperature (C)
QHWT  Heat flow to water (kW)
QSTK  Heat loss from the stack (kW)
QINPUT Input heat flow (kW)
QLNT  Latent heat loss (kW)
QJAKT Heat loss from the boiler jacket (kW)
QSS   Heat flow to boiler water (kW)

PARAMETERS:
VGF   Volume of gas in the boiler fire-box (m3)
ASF   Boiler fire-box effective radiation heat transfer area (m2)
ARF   Boiler fire-box refractory surface area (m2)
LGPF  Gas-path length in the fire-box (m)
EMISF Fire-box surface emissivity in fraction
VWB   Volume of water in the boiler (m3)
AJAKT Boiler jacket surface area (m2)
UJAKT Boiler jacket U-factor (kW/m2-C)
CARB  Atomic ratio of carbon in fuel
HYDR  Atomic ratio of hydrogen in fuel
OXYG  Atomic ratio of oxygen in fuel
XNTR  Atomic ratio of nitrogen in fuel
SULF  Atomic ratio of sulfur in fuel
HFUEL Fuel higher heating value (kJ/kg)
CPFUEL Fuel specific heat value (kJ/kg-C)
WFUEL Fuel supply rate (kg/s)
TFUEL Fuel temperature (C)
XAIR  Excess air for combustion (-)
EFFYSS Steady-state boiler efficiency in fraction (-)
TBLWS Boiler water temperature at steady state (C)
TSGS  Stack gas temperature at full load (C)
ICFGC Integration control factor for on-period stack gas temp.
ICFGO Integration control factor for off-period stack gas temp.
ICFW  Integration control factor for water temperature
DTFG  Short start period for burner on/off cycle (s)
ICFGNS Integration control for short start on-period
ICFGFS Integration control for short start off-period
DTBN  Minimum time interval for updating QSS (s)

PARAMETER (NSAVED=5,NDE=2,NIN=9,NOUT=9,NPAR=28)

LOGICAL COMINT
REAL LGPF,ICFGC,ICFGO,ICFW,ICFGNS,ICFGFS
DIMENSION XIN(NIN),OUT(NOUT),PAR(NPAR),IOSTAT(NOUT),SAVED(NSAVED)
COMMON /CHRONO/TIME,TSTEP,TTIME,TMIN,ITIME
COMMON /PRODUCT/ PT, PCO2, PH2O, PN2, PO2, PSO2, RATF, RWTF, RPTF
COMMON /CONFIG/ VGF, ASF, ARF, LGPF, EMISF, WB, AJAKT, UJAKT
COMMON /FUEL/ HFUEL, CPFUEL, WFUEL, TFUEL
COMMON /FULLD/ CNTU, TSGS, QINP, TAUQ, TAUP
DATA COMINT/.TRUE./
DATA WTFAC /0.8/, TBLREF/97.5/
C* DATA WTFAC /0.8/, TRAREF/23.0/, TBLREF/97.5/
C* NAMELIST /NAM1/ QINP
C* NAMELIST /NAM2/ TIME, SWCH, OSS, TSTK, TBLW, OF, OHXC,
C* & DTSTK, DTBLW, TXGF, WGOFF, WTL
C* NAMELIST /NAM3/ TIME, IONOFF, TIME0, DELT, ICFGON, ICFGOF
C* NAMELIST /NAM4/ TIME, TIME1, DELTB, OSS, OSS1
C* NAMELIST /NAM5/ TIME, TBLW, TSTK, QCW
C* NAMELIST /NAM6/ TIME, QINPUT, QLINT, QSTK, QJAKT, QHWT, QSS

INPUTS:

TSTK = XIN(1)
TRA = XIN(2)
TOA = XIN(3)
TBLW = XIN(4)
PSW = XIN(5)
WSW = XIN(6)
TRW = XIN(7)
QCW = XIN(8)
SWCH = XIN(9)

PARAMETERS:

VGF = PAR(1)
ASF = PAR(2)
ARF = PAR(3)
LGPF = PAR(4)
EMISF = PAR(5)
VWB = PAR(6)
AJAKT = PAR(7)
UJAKT = PAR(8)
CARB = PAR(9)
HYDR = PAR(10)
OXYG = PAR(11)
XNTR = PAR(12)
SULF = PAR(13)
HFUEL = PAR(14)
CPFUEL = PAR(15)
WFUEL = PAR(16)
TFUEL = PAR(17)
XAIR = PAR(18)
EFFYSS = PAR(19)
TBLWS = PAR(20)
TSGS = PAR(21)
ICFGON = PAR(22)
ICFGOF = PAR(23)
ICFW = PAR(24)
DTFG = PAR(25)
ICFGNS = PAR(26)
ICFGFS = PAR(27)
DTBW = PAR(28)

Assume that the boiler supply water temperature is the same as the boiler water temperature, i.e. TSW=TBLW.

TSW=TBLW

Initial conditions at steady state. Input data at beginning of simulation must be entered using a steady-state values.

IF(ITIME.EQ.1 .AND. COMINT) THEN
PT=1.
TSTK=TSGS
TBLW=TBLWS
TWS=TBLWS
CALL BLINEIT(CARB, HYDR, OXYG, XNTR, SULF, XAIR, TRA, TBLWS, TWS, EFFYSS, WGON)
COMINT=.FALSE.
SAVED(1)=TIME
SAVED(2)=WGON
SAVED(3)=0.0
SAVED(4)=1
PRINT NAM1
ELSE
WGON=SAVED(2)
ENDIF
Burner off
IF (TIME .GT. SAVED(1)) THEN
IF (SWCH .LE. 0.5) THEN
CALL BLFOFF(TSTK, TRA, TBLW, WGON, WGOFF, QFC, TEXGF)
CALL BLH(TSW, TEXGF, TSTK, WGOFF, QHXC)
CALL CPCVA(TRA, CPA, DUMMY, DUMMY, DUMMY)
QF=QFC
IONOFF=0
CAPG=WGOFF*CPA
Burner on
ELSE
CALL BLFON(TRA, TBLW, WGON, OFC, TAFC, TEXGF)
CALL BLH(TSW, TEXGF, TSTK, WGON, QHXC)
QF=QFCR
IONOFF=1
CAPG=WGON*CFC(TRA, TSTK)
ENDIF
ENDIF
Heat fluxes
CAPW=WSW+WCP(TBLW)
QINPUT=WFuel*HFUEL+IONOFF
QLTNT=2442.*WFuel*RTWF*IONOFF
QJAKT=AJAKT*(TBLW-TRA)
QHWT=CAPW*(TSTK-TRW)+QOW
OSTK=QINPUT-QLTNT-QF-QHXC
OSS=QF-QHXC-QJAKT-QOW
OSS1=SAVED(3)
Setting up a short time interval of rapid change of gas temperature and using different integration constants
IF (TIME .GT. SAVED(1)) THEN
IBURN=SAVED(4)+0.001
IF (IONOFF .NE. IBURN) THEN
TIME0 = TIME
ELSE
DELT = TIME-TIME0
ENDIF
SAVED(4) = IONOFF
ENDIF
IF (DELT .LT. DTFG) THEN
ICFGON = ICFGNS
ICFGOF = ICFGFS
ENDIF
Introducing time-delay to the boiler water temperature,
QSS is updated every time-interval of DELTB, if DELTB is
greater than or equal to the specified minimum value of DTBW.
At the same time, the reference time, TIME1,
is also changed. It is assumed that OSS holds a steady value
in the time-interval.

NOTE that DELTB depends upon the specified maximum time step,
TMAX. Due to this fact, the use of different TMAX's could result
in different simulation results.

IF(TIME.EQ.1) THEN
  TIME1=TIME
  SAVED(5)=TIME1
ENDIF

IF(TIME.GT.SAVED(1)) THEN
  TIME1=SAVED(5)
  DELTB=TIME-TIME1
  IF(DELTB.GE.DTBW) THEN
    SAVED(3)=OSS
    TIME1=TIME
    SAVED(5)=TIME1
  ENDIF
ENDIF

Derivatives of stock gas and boiler water temperatures

IF(IOFF.EQ.1) THEN
  DTSTK=(TSGS-TSTK)/(ICFON.TAUG)
ELSEIF(IOFF.EQ.8) THEN
  TINF=WTFAC*TLBREF+(1.-WTFAC)*TRA
  DTSTK=(TINF-TSTK)/(ICFGOF.TAUG)
ENDIF

DTBLW=(CAPW*(TRW-TSW)+OSS1)/(ICFW*TAUW)

Outputs

OUT(1) =DTSTK
OUT(2) =DBLW
OUT(3) =TSW
OUT(4) =QHWT
OUT(5) =QSTK
OUT(6) =QINPUT
OUT(7) =QLTNT
OUT(8) =QJAKT
OUT(9) =OSS

IF(TIME.GT.SAVED(1)) THEN
  PRINT NAM2
  PRINT NAM3
  PRINT NAM4
  PRINT NAM5
  PRINT NAM6
ENDIF

SAVED(1) =TIME

ISTAT(1)=0
ISTAT(2)=0
ISTAT(3)=0
ISTAT(4)=1
ISTAT(5)=1
ISTAT(6)=1
ISTAT(7)=1
ISTAT(8)=1
ISTAT(9)=1

RETURN
END

SUBROUTINE BLINIT(CARB, HYDR, OXYG, XNTR, SULF, XAIR.)
& TRA,TBLW,TSW,EFFYSS,WGON)

CNTU  Modified boiler HX heat transfer number at full load
TAUG  Modified boiler stack gas time constant
TAUW  Modified boiler water time constant

REAL  LGPF
COMMON /PRODCT/ PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RMTF,RPTF
COMMON /CONFIG/ VGF,ASF,ARF,LGPF,EMISF,VMB,AJAKT,UFJKT
COMMON /FUEL/ HFUEL,CFUEL,WFUEL,TFUEL
COMMON /FULLD/ CNTU,TSGS,QINP,TAUG,TAUW

C*  NAMELIST /NAMINI/ WGON,QFCR,TAFC,TEXGF,QJAKT,QFNS,TAUG,TAUW

Combustion gas properties

CALL PRDPP(CARB,HYDR,OXYG,XNTR,SULF,XAIR)

Estimate the gas path length in the boiler fire-box by matching the calculated and the measured gas temperatures at the exit of the fire-box.

CALL BLFON(TRA,TBLW,WGON,QFCR,TAFC,TEXGF)

Steady-state condition

QJAKT=AJAKT*UJAKT*(TBLW-TRA)
TINHX=TEXGF
QFNS=QFCR-QJAKT
CALL BLFLD(WGON,QFNS,TINHX,EFFYSS,TSW)

Time constants of gas and water

IF(TAUG.LT.1.E-10) THEN
  T1G=(TFUEL+RATF*TRA)/RPTF
  T2G=TSGS
  CPG=CPF(T1G,T2G)
  CAPG=CPG*WGON
  TAUG=1.0/CAPG
ENDIF

IF(TAUW.LE.1.E-10) THEN
  TAUW=4200.*WMB
ENDIF

PRINT NAMINI
C

RETURN
END

SUBROUTINE BLFLD(WGON,QFNS,TINHX,EFFYSS,TSW)

Boiler heat exchanger performance at full load. Calculation of the number of heat transfer unit.

REAL  K,MU,NTU
COMMON /FULLD/ CNTU,TSGS,QINP,TAUG,TAUW
C*  NAMELIST /NAMFLD/ GHKSS,NTU,CNTU

The specific heat of gas passing through the heat exchanger by using the measured stack gas temperature at a steady state.

CP=CPF(TINHX,TSGS)
The number of transfer units at full load

\[ \text{QHXXS = EFYSS*QINP*QFNS} \]
\[ \text{ENTU = 1.0 - QHXXS/(CP*WGN*(TINHX-TSW))} \]
\[ \text{IF(ENTU.GT.1.0E-20) THEN} \]
\[ \text{NTU = LOG(1.0/ENTU)} \]
\[ \text{ELSE} \]
\[ \text{NTU = 50.} \]
\[ \text{CP = CPF(TINHX, TSW)} \]
\[ \text{TAVE = 0.5*(TINHX+TSW)} \]
\[ \text{PRINT *, ' TOO LARGE EFFICIENCY VALUE ' END} \]
\[ \text{ENDIF} \]
\[ \text{CALL PRDPR(TAVE, MU, K)} \]
\[ \text{CNTU = NTU*WGON*0.2*MU*0.4*(CP/K)**0.6} \]
\[ \text{PRINT NAMFND} \]
\[ \text{RETURN} \]
\[ \text{END} \]

```
SUBROUTINE BLHX(TSW, TINHX, TEXHX, WG, QHXC)

Boiler heat-exchanger part load performance

REAL K, MU, NTU
COMMON /FULLD/, CNTU, TSGS, QINP, TAUW, TAUW

The number of transfer unit for boiler heat exchanger at part load condition.

TAVE = 0.5*(TINHX+TEXHX)
IF(ABS(TINHX-TEXHX) .GT. 0.001) THEN
  CP = CPF(TINHX, TEXHX)
ELSE
  CALL CPCVA(TAVE, CPA, DUMMY, DUMMY, DUMMY)
ENDIF

CALL PRDPR(TAVE, MU, K)

Convective heat transfer rate

IF(WG.GT.1.0E-6) THEN
  NTU = CNTU/(WG*0.2*MU*0.4*(CP/K)**0.6)
  QHXC = CP*WG*(TINHX-TSW)*(1.0-EXP(-NTU))
ELSE
  QHXC = CP*WG*(TINHX-TSW)
ENDIF

RETURN
END
```

```
SUBROUTINE BLFON(TRA, TBLW, WGON, QFCR, TAFC, TEXGF)

Simulation of boiler fire-box performance during on-period

PT Gas pressure (atm)
PCO2 Number of moles of CO2
PH2O Number of moles of H2O
PSO2 Number of moles of SO2
PO2 Number of moles of O2
PN2 Number of moles of N2
RATF Mass ratio of air to fuel
RWTF Mass ratio of water to fuel
```
RPTF  Mass ratio of combustion product to fuel
TS  Fire-box surface temperature (C)
QFCR  Fire-box heat transfer rate (kW)
TAF  Adiabatic flame temperature (C)
TEXGF  Fire-box exit gas temperature (C)

REAL  K, MU, LGPF
COMMON  /PRODUCT/ PT, PCO2, PH2O, PN2, PO2, PSO2, RATF, RWTF, RPTF
COMMON  /CONFIG/ VGF, ASF, ARF, LGPF, EMISF, VWB, AJAKT, UJAKT
COMMON  /FUEL/ HFUEL, CPFUEL, WFUEL, TFUEL
COMMON  /FULLD/ CNTU, TSGS, QINP, TAUG, TAUW
DATA  SIGMA/5.670E-11/, CKELVN/273.15/., PI/3.14159/

Fuel input

HHV=HFUEL+CPFUEL*(TFUEL-TRA)
QINP=WFUEL*HHV

Set the fire-box surface temperature to be the same as the boiler water temperature.

TS=TBLW

Convert temperature unit into absolute unit

TKS=TS+CKELVN
TKA=TRA+CKELVN

The gas and water vapor flow rates during on-cycle

WGON=WFUEL*RPTF
WH2O=WFUEL*RWTF
HF=WFUEL*HHV-2442

\[ WGON = WFUEL \times RPTF \]
\[ WH2O = WFUEL \times RWTF \]
\[ HF = WFUEL \times HHV - 2442 \]

Adiabatic flame temperature

TAF=(HHV,TRA)
TAF=TAF+CKELVN

The heat transfer rate due to radiation and convection using the well-stirred furnace theory

\[ TG2=TAFF(HHV,TRA) \]
\[ T2C=TAFF(HHV,TRA)-250 \]
\[ ITR=I+1 \]
\[ TG2C=TG2-250 \]
\[ ITA=I+1 \]
\[ TAVE=0.5 \times (TAF+TG2) \]
\[ CPDE=CPF(TRA, TG2C) \]
\[ CPAE=CPF(TG2C, TAF) \]
\[ CP0A=CPF(TRA, TAF) \]
\[ TT=TAGAVE-CKELVN \]
\[ CALL PRDPR(TT, MU, K) \]
\[ PR=MU \times CPAEA \]
\[ AC=VGF/LGPF \]
\[ DH=SQRT(4.0 \times AC/PI) \]
\[ RE=WGON+DH/(MU \times AC) \]
\[ HC0V=HC0VF(RE, PR, K, DH) \]
\[ GE=GEF(PCO2, PH2O, AL, TT) \]
\[ AGS=GS(ATTA, CS, GE, EMISF) \]
\[ TRATIO=TKS/TAVE \]
\[ AGS=AGS \times 0.83/(1.0-TRATIO^3)/(1.0-TRATIO^4) \]
\[ AGS=AGS+2.0-ASF+HC0V/(SIGMA*(TAVE+TKS)^3) \]
\[ QFCR=AGS+SIGMA*(TAVE-4-TKS^4) \]

A new estimate of gas temperature by using Newton's method
CAPWOE=CPOE*WGON
CAPWOA=CPOA*WGON
CCOAT=CAPWOA*(TAF-TKA)*(HF-QFCR)
CCOE=CAPWOE+HF
TGCA=CCOAT/CCOE+TKA
DTG2=TGCA-TG2
IF(ABS(DTG2).GT.10.) THEN
  IF(ITR.GT.1) THEN
    TG=GT1-DTGI+(TG2-TG1)/(DTG2-DTGI)
    DTG1=DTG2
    TG1= TG2
    ELSE
      DTG1=DTG2
      TG1= TG2
      TG2= TG2+100.
      IF(DTGI.LT.0.) THEN
        TG2=200.
      ENDIF
   ENDIF
  ENDIF
  ELSE
    DTG1=DTG2
    TG1= TG2
    TG2= TG2+100.
  ENDIF
ENDIF
GOTO 10
ENDIF
RETURN
END

SUBROUTINE BLFOFF(TSTK,TRA,TBLW,WGON,WOFF,QFC,TEXGF)

Boiler fire-box performance during off-period

REAL K,MU,NTU,LGPF
COMMON /CONFIG/VGF,ASF,ARF,LPF,EMISF,VW,JAJKT,UJAKT
COMMON /FULLD/CNTU,TSGS,QINP,TAUG,TAUW
DATA CKELVN/273.15/,PI/3.14159/

IF(TSTK-TRA.GT.0.01) THEN
  IF(ABS(TSTK-TRA).GT.0.01) THEN
    WGOFF=WGON*(((TSTK-TRA)/(TSGS-TRA))**0.56 + ((TSGS+CKELVN)/(TSTK+CKELVN))**1.19)
    DS=0.4
    WGOFF=DS*WGOFF
  ELSE
    WGOFF=0.0
  ENDIF
ENDIF

The properties of gas in the boiler fire-box:
The dynamic viscosity, thermal conductivity, specific heat capacity, Prandtl number, and Reynolds number based on the hydraulic diameter.
TAVE=0.5*(TRA+TEXGF)
CALL PRDPR(TAVE,MU,K)
CALL CPCVA(TEXGF,CPA,DUMMY,DUMMY,DUMMY)
PR=MU*CPA/K
AC=VGF/LGPF
DH=SQR(T4.8*AC/P1)
RE=WGOFF*DH/(MU+AC)

The convective heat transfer coefficient.
The off-cycle heat transfer rate using the effectiveness method of a heat exchanger. The gas temperature at the exit of the boiler fire-box.

\[
\text{CAPA} = \text{CPA} \times WGOFF \\
\text{IF}(WGOFF \geq 0.001) \text{ THEN} \\
\text{NTU} = \frac{\text{HCOV} \times \text{CAPA}}{\text{ASF}} \\
\text{QFC} = \text{CAPA} \times (\text{TRA} - \text{TBLW}) \times (1 - \exp(-\text{NTU})) \\
\text{TEXGF} = \text{TRA} - \text{QFC} \times (1 / \text{CAPA}) \\
\text{ELSE} \\
\text{QFC} = 0.0 \\
\text{TEXGF} = (\text{TRA} + \text{TBLW}) / 2. \\
\text{ENDIF} \\
\text{RETURN} \\
\text{END}
\]

SUBROUTINE TYPE63(XIN,OUT,PAR,SAVED,IOSTAT)

TYPE 63: HOT WATER COIL WITH CONSTANT WALL TEMPERATURE

February 16, 1988 Cheol F rk
Revised : April 15, 1988

INPUTS:
- TBLW Boiler water temperature (C)
- WCW Water flow rate through the coil (kg/s)
- TICW Inlet coil water temperature (C)

OUTPUTS:
- TOCW Outlet coil water temperature (C)
- QCW Heat flow rate from boiler water to coil water (kW)

PARAMETERS:
- DCOIL Diameter of coil
- LCOIL Length of coil

PARAMETER (NSAVED=2,NDE=0,NIN=3,NOUT=2,NPAR=2)

REAL K, LCOIL, LMTD, MU
DIMENSION XIN(NIN), OUT(NOUT), PAR(NPAR), IOSTAT(NOUT), SAVED(NSAVED)
COMMON /CHRONO/ TIME, TSTEP, TTIME, TMIN, ITIME
DATA PI/3.14159/

NAMELIST /NAM1/ HCOV, TOCW, LMTD, QCW
NAMELIST /NAM2/ TIME, TBLW, WCW, TICW, TOCW, QCW

Inputs:
- TBLW = XIN(1)
- WCW = XIN(2)
- TICW = XIN(3)

Parameters:
- DCOIL = PAR(1)
- LCOIL = PAR(2)

Temporarily set the wall temperature of the water coil equal to the boiler water temperature.

TS = TBLW

Water properties: dynamic viscosity, thermal conductivity, and specific heat of water from the subroutine WATPR with average
temperature except at the beginning.

IF(ITIME.EQ.1) THEN
   TAVE=0.5*(TBLW+TICW)
   SAVED(1)=TIME
   SAVED(2)=TICW
ELSE
   TOCW=SAVED(2)
   TAVE=0.5*(TOCW+TICW)
ENDIF
MU=WMU(TAVE)
K=WK(TAVE)
CP=WCP(TAVE)

The coil surface area, and wetted cross-sectional area.

AS=PI*DCOIL+LCOIL
AC=PI*DCOIL+DCOIL/4.0

Reynolds number and Prandtl number of the coil water

RE=WCW*DCOIL/(AC*MU)
PR=MU*CP/K
HCOV=HCOVF(RE,PR,K,DCOIL)

The outlet temperature and the heat flow rate when the coil surface temperature is constant.

IF(WCW.GT.0.001) THEN
   A=HCOV+AS/(WCW*CP)
   TOCW=TS-(TS-TICW)*EXP(-A)
   LMTD=((TOCW-TICW)/LOG((TS-TICW)/(TS-TOCW)))
   OCW=HCOV*AS*LMTD
ELSE
   TOCW=TS
   OCW=0.0
ENDIF

Outputs:

OUT(1)=TOCW
OUT(2)=OCW
SAVED(2)=TOCW

IF(TIME.GT.SAVED(1)) THEN
   PRINT NAM1
   PRINT NAM2
ENDIF
SAVED(1)=TIME
IOSTAT(1)=0
IOSTAT(2)=0
RETURN
END

SUBROUTINE TYPE64(XIN,OUT,PAR,SAVED,IOSTAT)

TYPE 64: BOILER BURNER AND CIRCULATING PUMP CONTROLS
February 17, 1988 Cheol Park
Revised : June 6, 1988

INPUTS:
TBURN Burner control temperature (C)
TBLW Boiler water temperature (C)
TLOAD Load temperature (C)
CTHERM Thermostat control indicator for the burner
          1 for thermostat control, 0 for manual control (-)

60
PARAMETERS:
- TBURON: Boiler burner-on temperature (°C)
- TBUROF: Boiler burner-off temperature (°C)
- TPMON: Boiler water circulating pump-on temperature (°C)
- TPMPOF: Boiler water circulating pump-off temperature (°C)
- WPUMP: Circulating water flow rate (kg/s)
- RATEOF: Minimum water flow rate ratio during off-period of pump (-)

PARAMETER (NSAVED=1, NDE=0, NIN=5, NOUT=2, NPAR=6)

DIMENSION XIN(NIN), OUT(NOUT), PAR(NPAR), IOSTAT(NOUT), SAVED(NSAVED)

COMMON /CHRONO/ TIME, TSTEP, TTIME, TMIN, ITIME

NAMELIST /NAM1/ TIME, TBUROF, TBURON, TBGW, SWCH, WCW

Inputs:
- TBURN = XIN(1)
- TBLW = XIN(2)
- TLOAD = XIN(3)
- CHERM = XIN(4)
- WCW = XIN(5)

Parameters:
- TBURON = PAR(1)
- TBUROF = PAR(2)
- TPMON = PAR(3)
- TPMPOF = PAR(4)
- WPUMP = PAR(5)
- RATEOF = PAR(6)

IF(TIME.EQ.1) THEN
  SAVED(1)=TIME
ENDIF

Boiler burner control
The burner is controlled by the thermostat sensing the boiler water temperature if the indicator, CHERM, is greater than or equal to 0.5. Otherwise TBURN controls the burner. The values of CHERM and TBURN must be present in the boundary data file.

IF(CTHERM.GE.0.5) THEN
  TBURN=TBLW
ENDIF

Turn on and off the burner and the pump only when the time step varies to prevent false action due to numerical instability during the large change of a variable.

IF(TIME.GT.SAVED(1)) THEN
  IF(TBURN.GE.TBUROF) THEN
    SWCH=0.0
  ELSEIF(TBURN.LE.TBURN) THEN
    SWCH=1.0
  ENDIF
ENDIF

Boiler water circulating pump control

IF(TLOAD.LE.TPMON) THEN
  WSW=WPUMP
ELSEIF(TLOAD.GE.TPMPF) THEN

61
\[ WSW = \text{RATEOF} \times \text{WPUMP} \]

ENDIF

ENDIF

\textbf{Outputs:}

\begin{align*}
\text{OUT}(1) &= \text{SWCH} \\
\text{OUT}(2) &= \text{WSW} \\
\text{IOSTAT}(1) &= 0 \\
\text{IOSTAT}(2) &= 0
\end{align*}

\textbf{C*} IF (TIME .GT. SAVED(1)) THEN
\textbf{C*} PRINT NAM1
\textbf{C*} ENDIF
\textbf{C*} SAVED(1) = TIME

RETURN

END
FUNCTION CPF(TC1, TC2)

Combustion product specific heat

INPUTS:
TC1 Air temperature (C)
TC2 Combustion product temperature (C)
PC02 Number of moles of CO2
PH20 Number of moles of H2O
PO2 Number of moles of O2
PS02 Number of moles of SO2
PN2 Number of moles of N2

OUTPUT:
CPF Specific heat of combustion product (kJ/(kg·C))

COMMON/PRODCT/PT, PC02, PH20, PN2, PO2, PS02, RATF, RWTF, RPTF

DIMENSION C(6,2)
DIMENSION A(30), B(30)

DATA A/4.2497678E-6, -6.912652E-3, 3.1602134E-5, -2.9715432E-8,
& 9.518358E-12, 2.1701, 1.0378115E-2, -1.0733938E-5, 6.3459175E-9, -1.628
& 7.81E-12, 4.1565016E-1, -1.7244334E-3, 5.6982316E-6, -4.5930044E-9, 1.4233
& 6.5E-12, 1.2, 3.6916148E-3, 2.6503115E-6, -9.768834E-10, -9.977223
& 1.4E-14, 3.7189904E-6, 2.5167288E-3, 3.8587353E-6, -8.2998716E-9, 2.708218E
& -12.3, 2.257132E-5, 6.551207E-3, -2.4976288E-7, -4.2286766E-9, 2.1392733E-12/

DATA B/1.1795714, 1.0856594E-2, -4.0622138E-6, 7.13702818E-10,
& 4.7496353E-14, 4.1429266E-3, 1.922896E-3, -1.2978235E-6, 2.4147446E-10
& 1.875088E-14, 2.670532E-3, 0.3171115E-3, -8.5351575E-7, 1.1790853E-10,
& 6.1510568E-15, 2.6445761E-1, 5.9763163E-3, -6.2566254E-7, 1.315849E-14
& -11, 3.3460204E-15, 5.1982451, 2.0595095E-3, -8.6254450E-7,
& 1.6636523E-10, -1.1847837E-14/

Set T1 and T2 in degree K

T1=273.15+TC1
T2=273.15+TC2
TM=1000.
DO 10 I=1,6
DO 10 J=1,2
C(I,J)=0.
10 CONTINUE

IF(T1.LT.1000.) THEN
  IF(T2.LT.1000.) THEN
    DO 30 I=1,6
    M=5*(I-1)
    DO 20 J=1,5
    JJ=M+J
    C(I,1)=C(I,1)+A(JJ)*(T2**J-T1**J)/J
    CONTINUE
    C(I,1)=C(I,1)+B(JJ)*(T2**J-TM**J)/J
    CONTINUE
    CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)
+PO2*C(5,1)+PS02*C(6,1))/(PC02+44.
+PH20+18.+PN2+28.+PO2+32.+PS02+64.)
  ELSE
    DO 50 I=1,6
    M=5*(I-1)
    DO 40 J=1,5
    JJ=M+J
    C(I,1)=C(I,1)+A(JJ)*(T2**J-T1**J)/J
    CONTINUE
    C(I,1)=C(I,1)+B(JJ)*(T2**J-TM**J)/J
    CONTINUE
    CPF=(C(I,1)+C(I,2))*8.32066/(T2-T1)
  END IF
END IF

63
CONTINUE
CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)
+PO2*C(5,1)+PS02*C(6,1))/(PC02*44.
+PH20*18.+PN2*28.+PO2*32.+PS02*64.)
ENDIF
ELSE
IF(T2.GT.1000.) THEN
DO 70 I=1,6
DO 60 J=1,5
JJ=4+J
C(1,2)=C(1,2)+B(JJ)*(T2**J-T1**J)/J
CONTINUE
C(1,2)=C(1,2)+8.32066/(T2-T1)
70 CONTINUE
CPF=(PC02*C(2,2)+PH20*C(3,2)+PN2*C(4,2)
+PO2*C(5,2)+PS02*C(6,2))/(PC02*44.
+PH20*18.+PN2*28.+PO2*32.+PS02*64.)
ELSE
DO 90 I=1,6
DO 80 J=1,5
JJ=5*(I-1)
C(1,1)=C(1,1)+A(JJ)*(T1**J-T2**J)/J
C(1,2)=C(1,2)+B(JJ)*(T1**J-TM**J)/J
80 CONTINUE
C(1,1)=C(1,1)+C(1,2)*8.32066/(T1-T2)
90 CONTINUE
CPF=(PC02*C(2,1)+PH20*C(3,1)+PN2*C(4,1)
+PO2*C(5,1)+PS02*C(6,1))/(PC02*44.
+PH20*18.+PN2*28.+PO2*32.+PS02*64.)
ENDIF
ENDIF
RETURN
END
FUNCTION GEF(PPC02,PPH20,XL,TG)
Gas emissivity

INPUTS:
PPC02 Partial pressure of CO2 (atm)
PPH20 Partial pressure of H2O (atm)
XL Length of combustion (ft)
TG Radiating gas temperature (C)

OUTPUT:
GEF Gas emissivity

Select gas emissivity constants C1 & C2

XX=3.2808*XL*(PPC02+PPH20)
IF(XX.GT.0.2) THEN
C1=287.
C2=0.4
ELSE
C1=406.9
C2=0.62
ENDIF
Compute gas emissivity

TRG=1.8*(TG+273.15)
GEX=XX**C2*C1/TRG
GEF=GEX
RETURN
END
FUNCTION GS(AT,CS,GE,SE)

Gas/Sink exchange area

INPUTS:
AT Total area (m2)
CS Ratio of active furnace surface area to total area
GE Gas emissivity
SE Active surface emissivity

OUTPUT:
GS Radiation exchange area (m2)

GSX=1./GE+1./(CS*SE)-1.
GSX=AT/GSX
GS=GSX
RETURN
END

FUNCTION HCOVF(RE,PR,K,D)

Convective heat transfer coefficient

INPUTS:
RE Reynolds number
PR Prandtl number
K Thermal conductivity (kW/(m-C))
D Hydraulic diameter (m)

OUTPUT:
HCOVF Convective heat transfer coefficient (kW/(m2-C))

REAL K,NSN

Test if the flow is laminar or turbulent based on Reynolds number.
IF (RE.GE.2000.0) THEN
   NSN=0.023*RE**0.8*PR**0.4
ELSE
   NSN=3.66
ENDIF

Calculate the convective heat transfer coefficient using the Nusselt number.
HCOVF=NSN*K/D
RETURN
END

SUBROUTINE PRDPP(CARB, HYDR, OXYG, XNTR, SULF, XAIR)

Combustion products

INPUTS:
PT Pressure (atm)
SUBROUTINE PRDPR(T,AMM,AKK)

COMMON/PRODCT/PT,PC02,PH20,PN2,PO2,PS02,RATF,RWTF,RPTF

Moles of oxygen and nitrogen to be added
R00=2.*Ca*B+0.5*HYDR+2.*SULF-OXYG
RN0=3.76*R00

Moles of CO2, H2O, O2, SO2 and N2 in products
PC02=CARB
PH20=0.5*HYDR
PO2=0.5*R00*XAIR
PS02=SULF
PN2=0.5*XNTR+0.5*RN0*(1.+XAIR)

Weight of fuel, air, and products
WTF=12.*CARB+HYDR+16.*OXYG+14.*XNTR+32.*SULF
WTA=16.*R00+14.*RN0+(1.+XAIR)
WTP=(44.*PC02+18.*PH20+32.*PO2+64.*PS02+28.*PN2)
WTW=18.*PH20

Compute partial pressures and mass ratios
AMULT=PT/(PC02+PH20+PO2+PS02+PN2)
PC02=PC02*AMULT
PH20=PH20*AMULT
PS02=PS02*AMULT
PO2=PO2*AMULT
PN2=PN2*AMULT
RATF=WTA/WTF
RPTF=WTP/WTF
RWTF=WTW/WTF
RETURN

END

SUBROUTINE PRDPR(T,AMM,AKK)

Viscosity and conductivity of combustion product

INPUTS:
PC02 Partial pressure of CO2 (atm)
PH20 Partial pressure of H2O (atm)
PS02 Partial pressure of SO2 (atm)
PN2 Partial pressure of N2 (atm)
PO2 Partial pressure of O2 (atm)

OUTPUTS:
AMM Product dynamic viscosity (kg/(m-s))
AKK Product thermal conductivity (kW/(m-C))
COMMON/PRODUCT/PT,PCO2,PH2O,PN2,P02,PS02,RATF,RWT,F,RPTF

DIMENSION X(11),A(11),AM(5),AK(5)
DATA X/-10.,260.,440.,620.,800.,1070.,
&1520.,2420.,3140.,3560.,4160./
DATA A/0.0387,0.0553,0.0648,0.073,0.0806,0.0911,
&0.1062,0.1320,0.1500,0.1583,0.1710/
DATA B/0.01287,0.01944,0.02333,0.02692,0.03022,
&0.03483,0.04178,0.05348,0.0612,0.0646,0.0709/
DATA AM/0.889,0.885,1.123,0.964,0.889/
DATA AK/0.925,0.906,1.037,0.983,0.925/

NP=11
AM=PCO2*AM(1)+PH2O*AM(2)+P02*AM(3)+PN2*AM(4)+PS02*AM(5)
AK=PCO2*AK(1)+PH2C*AK(2)+P02*AK(3)+PN2*AK(4)+PS02*AK(5)
TF=32.+1.8*T
AMM=(4.1333E-04)*AM+TAB1(NP,X.A,T)
AKK=(1.731E-03)*AK+TAB1(NP,X.B,T)
RETURN
END

FUNCTION TAF(HHV,TBS)

Adiabatic flame temperature

INPUTS:
HHV Higher heating value of fuel (kJ/kg)
RWT Weight of H2O per kg of fuel (kg/kg)
P02 Mole of CO2
PH2O Mole of H2O
P02 Mole of O2
PN2 Mole of N2
TBS Base temperature (C)

OUTPUT:
TAF Adiabatic flame temperature (C)

FUNCTION TAB1(NP,X,Y,XI)

Determine Y(X1) value from tabulated Y vs X values

INPUTS/OUTPUTS:

67
DIMENSION X(NP), Y(NP)

Set out the range Y1(X1) values

XMIN = X(1)
XMAX = X(NP)
IF(X1 .LE. XMIN) THEN
  Y1 = Y(1)
ELSEIF(X1 .GT. XMAX) THEN
  Y1 = Y(NP)
ELSE
  Interpolate for Y1(X1) value

  I = 1
  10 IF(X1 .LE. X(I)) THEN
      DX = X(I) - X(I-1)
      DY = Y(I) - Y(I-1)
      RX = 1./DX
      DYDX = DY = RX
      DX = X1 - X(I-1)
      Y1 = Y(I-1) + DX * DYDX
    ELSE
      I = I + 1
    GOTO 10
  ENDIF
ENDIF
TAB1 = Y1
RETURN
END
APPENDIX B  Boiler Simulation Model Setup

al

BLC22D - Reduced number of reported variables to BLC22C 880628

SUPERBLOCK 1
BLOCK 1
UNIT 1  TYPE 62 - BOILER MODEL WITH A TANKLESS COIL
UNIT 2  TYPE 63 - DOMESTIC HOT WATER COIL
UNIT 3  TYPE 64 - BOILER BURNER AND WATER PUMP CONTROL

UNIT 1  TYPE 62
BOILER MODEL WITH A TANKLESS COIL

1  INPUTS:
| TEMPERATURE 1 - TSTK : Stack gas temperature (DE) |
| TEMPERATURE 2 - TRA : Room air temperature          |
| TEMPERATURE 3 - TOA : Outdoor air temperature       |
| TEMPERATURE 4 - TBLW : Boiler water temperature     |
| PRESSURE 1 - PSW : Supply water pressure             |
| FLOW 1 - WSW : Supply water flowrate                 |
| TEMPERATURE 5 - TRW : Return water temp.            |
| POWER 1 - QCW : Heat flowrate to domestic hot water coil |
| CONTROL 1 - SWCH : Control switch for on/off        |

2  OUTPUTS:
| TEMPERATURE 1 - TSTK : Stack gas temperature (DE) |
| TEMPERATURE 4 - TBLW : Boiler water temp. (DE)     |
| TEMPERATURE 6 - TSW : Supply water temp.           |
| POWER 2 - QHWT : Heat gain of water                |
| POWER 3 - QSTK : Heat loss from stack              |
| POWER 4 - QINPUT : Heat input rate                 |
| POWER 5 - QLNTT : Latent heat loss                 |
| POWER 6 - QJAKT : Heat loss thru boiler jacket     |
| POWER 7 - QSS : Heat flow rate to boiler water     |

3  PARAMETERS:
<p>| 0.736000E-01 VGF : Volume of gas in the boiler fire-box (m3) |
| 0.175500 ASF : Boiler fire-box effective radiation heat trans |
| 0.000000 ARF : Boiler fire-box refractory surface area (m2) |
| 0.381000 LGPF : Gas-path length in the boiler fire-box (m) |
| 0.800000 EMISF : Fire-box surface emissivity value in fraction |
| 0.776000E-01 VWB : Volume of water in the boiler (m3) |
| 2.60000 AJAKT : Boiler jacket surface area (m2) |
| 0.169290E-02 UJAKT : Boiler jacket U-factor (kW/m2-C) |
| 1.00000 CARB : Atomic ratio of carbon in fuel        |
| 1.84400 HYDR : Atomic ratio of hydrogen in fuel      |
| 0.000000 OXYG : Atomic ratio of oxygen in fuel       |
| 0.000000 XNTR : Atomic ratio of nitrogen in fuel     |
| 0.300000E-02 SULF : Atomic ratio of sulfur in fuel   |
| 45327.0 HFUEL : Fuel higher heating value (kJ/kg)    |
| 0.839000 CPFUEL : Fuel specific heat value (kJ/kg-C)  |
| 0.126600E-02 WFUEL : Fuel supply rate (kg/s)         |
| 26.5000 TFUEL : Fuel temperature (C)                |</p>
<table>
<thead>
<tr>
<th>UNIT 2</th>
<th>TYPE 63</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOMESTIC HOT WATER COIL</strong></td>
<td></td>
</tr>
<tr>
<td><strong>INPUTS:</strong></td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>4 - TBLW : Boiler water temperature</td>
</tr>
<tr>
<td>FLOW</td>
<td>2 - WCW : Water flowrate thru the coil</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>7 - TICW : Coil inlet water temp.</td>
</tr>
<tr>
<td><strong>OUTPUTS:</strong></td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>8 - TOCW : Coil outlet water temperature</td>
</tr>
<tr>
<td>POWER</td>
<td>1 - QCW : Heat flowrate to the coil water</td>
</tr>
<tr>
<td><strong>PARAMETERS:</strong></td>
<td></td>
</tr>
<tr>
<td>0.193000E-01 DCOIL : Diameter of the coil (m)</td>
<td></td>
</tr>
<tr>
<td>4.206000 LCOIL : Length of the coil (m)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UNIT 3</th>
<th>TYPE 64</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOILER BURNER AND WATER PUMP CONTROL</strong></td>
<td></td>
</tr>
<tr>
<td><strong>INPUTS:</strong></td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>10 - TBURN : Burner control temperature</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>4 - TBLW : Boiler water temperature</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>9 - TLOAD : Load temperature</td>
</tr>
<tr>
<td>CONTROL</td>
<td>2 - CHERM : Thermostat control indicator 1/0 for auto/</td>
</tr>
<tr>
<td>FLOW</td>
<td>2 - WCW : Water flowrate thru the coil</td>
</tr>
<tr>
<td><strong>OUTPUTS:</strong></td>
<td></td>
</tr>
<tr>
<td>CONTROL</td>
<td>1 - SWCH : Burner control on/off signal</td>
</tr>
<tr>
<td>FLOW</td>
<td>1 - WSW : Boiler circulating water flowrate</td>
</tr>
<tr>
<td><strong>PARAMETERS:</strong></td>
<td></td>
</tr>
<tr>
<td>85.0000 TBURON : Boiler burner-on temp. (C)</td>
<td></td>
</tr>
<tr>
<td>98.9000 TBUROF : Boiler burner-off temp. (C)</td>
<td></td>
</tr>
<tr>
<td>70.0000 TPMON : Boiler water pump-on temperature (C)</td>
<td></td>
</tr>
<tr>
<td>80.0000 TPMPOF : Boiler water pump-off temperature (C)</td>
<td></td>
</tr>
<tr>
<td>0.286100 WPUMP : Circulating water flowrate (kg/s)</td>
<td></td>
</tr>
<tr>
<td>0.100000E-03 RATEOF : Minimum water flow rate ratio when pump off</td>
<td></td>
</tr>
</tbody>
</table>

Initial Variable Values:

---

Excess combustion air (-)
Boiler full load efficiency (-)
Boiler water temp. at steady state (C)
Stack gas temp. at full load (C)
Integration control for on-period stack gas
Integration control for off-period stack gas
Integration control for boiler water temperature
Short start period for burner on/off cycle (s)
Integration control for short start on-period
Integration control for short start off-period
Time interval for updating QSS (s)

**UNIT 2**
**DOMESTIC HOT WATER COIL**

**INPUTS:**
- TEMPERATURE (4 - TBLW): Boiler water temperature
- FLOW (2 - WCW): Water flowrate thru the coil
- TEMPERATURE (7 - TICW): Coil inlet water temp.

**OUTPUTS:**
- TEMPERATURE (8 - TOCW): Coil outlet water temperature
- POWER (1 - QCW): Heat flowrate to the coil water

**PARAMETERS:**
- DCOIL (0.193000E-01): Diameter of the coil (m)
- LCOIL (4.206000): Length of the coil (m)

**UNIT 3**
**BOILER BURNER AND WATER PUMP CONTROL**

**INPUTS:**
- TEMPERATURE (10 - TBURN): Burner control temperature
- TEMPERATURE (4 - TBLW): Boiler water temperature
- TEMPERATURE (9 - TLOAD): Load temperature
- CONTROL (2 - CHERM): Thermostat control indicator 1/0 for auto/
- FLOW (2 - WCW): Water flowrate thru the coil

**OUTPUTS:**
- CONTROL (1 - SWCH): Burner control on/off signal
- FLOW (1 - WSW): Boiler circulating water flowrate

**PARAMETERS:**
- TBURON (85.0000): Boiler burner-on temp. (C)
- TBUROF (98.9000): Boiler burner-off temp. (C)
- TPMON (70.0000): Boiler water pump-on temperature (C)
- TPMPOF (80.0000): Boiler water pump-off temperature (C)
- WPUMP (0.286100): Circulating water flowrate (kg/s)
- RATEOF (0.100000E-03): Minimum water flow rate ratio when pump off

---

Initial Variable Values:
PRESSURE 1 -> 0.000000 (kPa)
FLOW 1 -> 0.000000 (kg/s)
FLOW 2 -> 0.000000 (kg/s)
TEMPERATURE 1 -> 315.000 (C)
TEMPERATURE 2 -> 26.5000 (C)
TEMPERATURE 3 -> 17.0000 (C)
TEMPERATURE 4 -> 30.0000 (C)
TEMPERATURE 5 -> 57.3800 (C)
TEMPERATURE 6 -> 14.0000 (C)
TEMPERATURE 7 -> 28.0000 (C)
TEMPERATURE 8 -> 25.0000 (C)
TEMPERATURE 9 -> 28.0000 (C)
TEMPERATURE 10 -> 80.0000 (C)
CONTROL 1 -> 1.000000 (-)
CONTROL 2 -> 0.000000 (-)
POWER 1 -> 0.000000 (kW)
POWER 2 -> 0.000000 (kW)
POWER 3 -> 0.000000 (kW)
POWER 4 -> 0.000000 (kW)
POWER 5 -> 0.000000 (kW)
POWER 6 -> 0.000000 (kW)
POWER 7 -> 0.000000 (kW)

Simulation Error Tolerances:

1  RTOLX= 0.100000E-03  ATOLX= 0.100000E-04
   XTO= 0.200000E-03  TTIME= 1.00000

SUPERBLOCK 1
2  FREEZE OPTION 0  SCAN OPTION 0

The following are Boundary Variables in the simulation:

FLOW 2
TEMPERATURE 9
TEMPERATURE 10
CONTROL 2

The following are the reported variables:

SUPERBLOCK 1  REPORTING INTERVAL  120.000
TEMPERATURE 1
TEMPERATURE 4
TEMPERATURE 8
CONTROL 1
POWER 1
POWER 2
POWER 4
APPENDIX C  Boundary Data File Generation Program - CRBND

CRBND3: Generation of boundary data file for the boiler model when domestic hot water is drawn with space heating.

This program generates a set of data files or a file for space loads at a given domestic hot water draw.

August 5, 1988 Cheol Pook

PROGRAM CRBND3
PARAMETER (MAXN=15)
REAL XPUMP(MAXN), CYCLERT(MAXN), NCYCLE
INTEGER TSTOP, TPS, T Pon(MAXN), TPOFF(MAXN), NCYPMP(MAXN)
CHARACTER BDNEFILE*12, FILEXT(MAXN)*3, STEPMP+11, ERRFILE*12
CHARACTER STEPOUT*12, ANSWER*1
DATA XPUMP/0.02, 0.05, 0.10, 0.15, 0.20, 0.225, 0.30,
& 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95, 0.975/
& CYCLERT/0.4, 0.6, 1.20, 1.40, 1.70, 1.80, 2.20,
& 2.45, 2.5, 2.35, 2.20, 1.70, 0.90, 0.50, 0.40/
& TPS/12/
& FILEXT/'002', '005', '010', '015', '020', '023', '030',
& '040', '050', '060', '070', '080', '090', '095', '098'/
PRINT *. 'Is this run STEP 1 or STEP 2 ?'
READ *, ISTEP
PRINT *, 'ISTEP = ', ISTEP

Determine the pump on/off-times and the number of cycles per the period.

PRINT 1000
TSTOP=5000+Tps+3600
DO 10 1=1, MAXN
NCYCLE=CYCLERT(I)+TPS
TPON(I)=3600+X PUMP(I)/CYCLERT(I)
TPOFF(I)=3600+TPS/NCYCLE-TPON(I)
IF(NCYCLE-INT(NCYCLE) .GT. 0.0) THEN
 NCYPMP(I)=INT(NCYCLE+1.0)
ELSE
 NCYPMP(I)=NCYCLE
ENDIF
PRINT 2000, I, XPUMP(I), CYCLERT(I), NCYPMP(I), TPON(I), TPOFF(I),
& TSTOP
10 CONTINUE

Create a boundary data files with different file extension

IF(Istep .EQ. 1) THEN
 CALL STEP1NA
ENDIF

PRINT *, 'Are you processing a single file ? (N)'
READ *(FMT='(A1)') ANSWER
IF(ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') THEN
 PRINT *, 'What is the index number?'
 READ *, INDEX
 I=INDEX
STEPMP='STEPMP.'//FILEXT(I)
STEPOUT='STEPOUT.'//FILEXT(I)
BDNEFILE='BDNE000.'//FILEXT(I)
ERRFILE='ERR000.'//FILEXT(I)
IF(ISTEP .EQ. 1) THEN
  CALL STEPIN(TPON(I),TPOFF(I),NCYMP(I),STEPPMP)
  CALL STEPCOM(STEPOUT)
  PRINT *, 'Edit STEPOUT:',FILEXT(I), and perform STEP 2
ELSEIF(ISTEP .EQ.2) THEN
  CALL STEPBDN(BNDFILE,STEPOUT,NUMCOL)
  CALL CHEKBDN(BNDFILE,ERRFILE,NUMCOL)
  PRINT *, 'Edit BNDE000.',FILEXT(I)
  PRINT *, ' based on ERRE000.',FILEXT(I)
  PRINT *
  ENDIF
ELSE
  PRINT *, ' NOTE: Excluded are Index 1 and 15. '
DO 20 I=2,MAXN-1
  DO 20 I=1,MAXN
  STEPPMP='STEPPMP://FILEXT(I)
  STEPOUT='STEPOT://FILEXT(I)
  BNDFILE='BNDE000://FILEXT(I)
  ERRFILE='ERRE000://FILEXT(I)
  IF(ISTEP .EQ. 1) THEN
    CALL STEPIN(TPON(I),TPOFF(I),NCYMP(I),STEPPMP)
    CALL STEPCOM(STEPOUT)
    PRINT *, 'Edit STEPOUT:',FILEXT(I), and perform STEP 2
  ELSEIF(ISTEP .EQ.2) THEN
    CALL STEPBDN(BNDFILE,STEPOUT,NUMCOL)
    CALL CHEKBDN(BNDFILE,ERRFILE,NUMCOL)
    PRINT *, 'Edit BNDE000.',FILEXT(I)
    PRINT *, ' based on ERRE000.',FILEXT(I)
    PRINT *
  ENDIF
20 CONTINUE
ENDIF
1000 FORMAT(/79C*')/T3.TB.'Xpump'.T10.'Cycle Rate'.T30.
 & ' # cycles'.T42.'Tp.on'.T52.'Tp.off'.T62.'Tstop'/79('.'//'))
2000 FORMAT(15,2F10.3,4I10)
STOP
END
C
SUBROUTINE STEPINA
C
STEPINA : Generation of input data to STEPBDN.FTN when domestic hot water is drawn.
C
C
IMPLICIT INTEGER(A-Z)
CHARACTER*1 YESNO
REAL WCWON,WCWOFF,US
DATA TBURN/100/.CTHERM/1/
DATA YESNO/'y'/.TLDON.TLDFF/68,85/
OPEN(8,FILE='STEPINA2.DAT')
PRINT *, ' Enter the total amount of water drawn in Gal'
READ *, US
PRINT *, ' How many cycles in 6-hour period?'
READ *, NCYCLE
PRINT *, ' Start time of draw?'
READ *, TSTART

73
WCWON=0.1892
WCWOFF=0.0
DURATN=US*3.7854/(WCWON*NCYCLE)
PRINT *; " DURATION OF DRAW =", DURATN
PRINT *; " DRAW RATE (KG/S) =", WCWON

DO 10 I=1,NCYCLE

TIMEON=TSTART+(I-1)*3600*6/NCYCLE
TIMEOF=TIMEON+DURATN

WRITE(8,1000) YESNO
WRITE(8,1100) TIMEON, WCWOFF, TLDOFF, TBURN, CTERM
WRITE(8,1100) TIMEOF, WCWON, TLDOFF, TBURN, CTERM
WRITE(8,1100) YESNO
WRITE(8,1100) TIMEOF, WCWON, TLDOFF, TBURN, CTERM
WRITE(8,1100) TIMEOF, WCWOFF, TLDOFF, TBURN, CTERM

10 CONTINUE

YESNO='n'
WRITE(8,1000) YESNO

1000 FORMAT(A1)
1100 FORMAT(I10,F10.4,3I5)
RETURN
END

C SUBROUTINE STEPIN(TPON,TPOFF,NCYPMP,STEPPMP)

C STEPIN : Generation of input data to STEPBND.FTN
when the water pump is cycled.

C

IMPLICIT INTEGER(A-Z)
CHARACTER STEPPMP*11
CHARACTER*1 YESNO

DATA TSTART/5000/, WCW/0/, TBURN/100/, CTERM/1/
DATA TLDOFF/68.85/

NAMELIST /NAM2/ TPON, TPOFF, NCYPMP

OPEN(7,FILE=STEPPMP)

C

PRINT NAM2
DO 10 I=1,NCYPMP

YESNO='y'
TIMEON=TSTART+(I-1)*(TPON+TPOFF)
TIMEOF=TIMEON+I*TPON+(I-1)*TPOFF

WRITE(7,1000) YESNO
WRITE(7,1100) TIMEON, WCW, TLDOFF, TBURN, CTERM
WRITE(7,1100) TIMEON, WCW, TLDOFF, TBURN, CTERM
WRITE(7,1100) YESNO
WRITE(7,1100) TIMEOF, WCW, TLDOFF, TBURN, CTERM
WRITE(7,1100) TIMEOF, WCW, TLDOFF, TBURN, CTERM

10 CONTINUE

YESNO='n'
TSTOP=TIMEOF+TPOFF
WRITE(7,1000) YESNO
WRITE(7,1100) TSTOP

1000 FORMAT(A1)
1100 FORMAT(I10,4I5)
SUBROUTINE STEPCOM(STEPOUT)

STEPCOM: Combining outputs of STEPIN.FTN for space heating and domestic hot water draw

PARAMETER (MAXDAT=500)
CHARACTER*1 YESNO
CHARACTER*80 HEAD
CHARACTER*1 STEPPMP, STEPOUT, FILEXT
REAL WCWS(MAXDAT,3), WCWD(MAXDAT,3)
INTEGER TIMES(MAXDAT), TLDS(MAXDAT,3), TLDD(MAXDAT,3)
INTEGER TBURN, COTHERM, TIMED(MAXDAT), TIME(MAXDAT), TSTOP

OPEN(9, FILE=STEPOUT)
OPEN(10, FILE='STEPLEAD.DAT')
REWIND 7
REWIND 8
REWIND 10

* Read File 10 and write on File 9 (Initialization heading)

L=1
5 READ(10,1100,END=7) HEAD
WRITE(9,1100) HEAD
GOTO 5

* Read File 7 (Output for space heating)

7 1=1
10 READ(7,1000) YESNO
IF(YESNO.EQ. 'y') THEN
READ(7,*) TIMES(I), WCWS(I,1), TLDS(I,1), TBURN, COTHERM
READ(7,*) TIMES(I), WCWS(I,2), TLDS(I,2), TBURN, COTHERM
I=I+1
GOTO 10
ENDIF
READ(7,*) TSTOP
NUMDAT7=I-1
PRINT *, Total number of time changes of file 7 = ', NUMDAT7

* Read File 8 (Output for domestic hot water draw)

J=1
20 READ(8,1000) YESNO
IF(YESNO.EQ. 'y') THEN
READ(8,*) TIMED(J), WCWD(J,1), TLDD(J,1), TBURN, COTHERM
READ(8,*) TIMED(J), WCWD(J,2), TLDD(J,2), TBURN, COTHERM
J=J+1
GOTO 20
ENDIF
NUMDAT8=J-1
PRINT *, Total number of time changes of file 8 = ', NUMDAT8

* Combining two files with a kind of sorting

TIMEMK=TIMED(1)
ISTART=1
JJ=1
KK=0
YESNO='y'
25 DO 40 I=ISTART, NUMDAT7
IF(TIMES(I) .LT. TIMEMK) THEN
K1=KK+I-ISTART+1
TIME(K1)=TIMES(I)
40 CONTINUE

75
SUBROUTINE STEPBD(BNDFIL,STPENUT,NUMCOL)

STEPBD : Stepwise changes in Boundary variables

| t0 t1 t2 t3 t4 t5 t6 t7 t8 t9 |
|---|---|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |   |   |

The step change occurs at t1.
NUMSUB : Number of subintervals in an interval (=5)
NUMINT : Number of intervals chosen (=9)
DELSUB : Size of each subinterval in seconds
DELT : Size of each interval in seconds
NUMCOL : Number of columns of Y-variables

In the figure shown above, there are 9 intervals, of which size is DELT seconds, DELT = NUMSUB*DELTB.

PARAMETER (MAXCOL=30,MAXINT=20,MAXSUB=10)
CHARACTER ANSWER*1, BNDFILE*12, FILEXT*3,STEPOUT*12
REAL Y1(MAXCOL),Y2(MAXCOL), DELY(MAXCOL), YY(MAXCOL)
REAL TIME(0:MAXINT), TIME1(0:MAXINT,0:MAXSUB)
REAL Y(0:MAXINT,MAXCOL)
INTEGER TIME2

OPEN(9,FILE=STEPOUT)
OPEN(11,FILE=BNDFILE)
CLOSE(11,STATUS='DELETE')

OPEN(11,FILE=BNDFILE)
REWIND 9

C* PRINT *, '—— A boundary data is being generated ——'
C* PRINT *, 'What is the number of columns for Y-values ?'
READ(9,*) NUMCOL
C* PRINT *, 'Enter Subinterval size in seconds'
C* PRINT *, 'Number of Intervals?, and Number of Subintervals'
READ(9,*) DELTSB, NUMINT, NUMSUB
IF(NUMSUB .LT. 4) THEN
   PRINT *, '—— NUMBER OF SUBINTERVOLS MUST BE MORE THAN 4——'
   STOP ' MODIFY YOUR INPUT DATA AND TRY AGAIN '
ENDIF
C* CONTINUE
READ(9,*) TSTEP, (Y1(I), I=1, NUMCOL)
C* PRINT *, 'Enter Step change time, and Y-values before change'
READ(9,*) TSTEP, (Y2(I), I=1, NUMCOL)

DELT=NUMSUB*DELTB
TIME(0)=TSTEP-DELT

DO 20 J=0, NUMINT
   TIME(J)=TIME(0)+REAL(J)*DELT
DO 20 K=0, NUMSUB
   TIME1(J,K)=TIME(J)+REAL(K)*DELTB
20 CONTINUE

DO 30 I=1, NUMCOL
   DELY(I)=(Y2(I)-Y1(I))/(NUMINT-1)
   Y(0,I)=Y1(I)
30 CONTINUE

DO 30 J=0, NUMINT-1
   Y(J,1)=Y(0,1)+REAL(J)*DELY(I)
30 CONTINUE

DO 40 J=0, NUMINT-1
   YY(I)=Y(J,1)+1.0E-10
40 CONTINUE

DO 50 K=0, NUMSUB
   TIME2=TIME1(J,K)+1.0E-10
   WRITE(11,1000) TIME2,(YY(L), L=1, NUMCOL)
50 CONTINUE

C* PRINT *, 'Continue?'
READ (9, FMT='(A1)') ANSWER
IF(ANSWER .EQ. 'Y'.OR. ANSWER .EQ. 'y') GOTO 10

1000 FORMAT(1X, 17, F10.4, 6F10.2)
SUBROUTINE CHEKBND(BNDFILE, ERRFILE, NUMCOL)

CHEKBND : Check the boundary data file for proper sequence of the time data

PARAMETER (MAXCOL=30)
CHARACTER ERRFILE*12, BNDFILE*12
REAL YY(MAXCOL)
INTEGER TIMENEW, TIMEOLD, TIME2

OPEN(12, FILE=ERRFILE)
CLOSE(12, STATUS='DELETE')
OPEN(12, FILE=ERRFILE)

OPEN(11, FILE=BNDFILE)
REWIND 11

TIMEOLD=0
10 READ(11,1000, END=20) TIME2, (YY(L), L=1, NUMCOL)
TIMENEW=TIME2
IF (TIMENEW .LT. TIMEOLD) THEN
  PRINT *, ' Time is less than the previous value'
  PRINT *, ' ERROR: ', TIMENEW, TIMEOLD
  WRITE(12, 2000) TIMENEW, TIMEOLD
ELSE
  TIMEOLD=TIMENEW
ENDIF
GOTO 10
20 CONTINUE

1000 FORMAT(1X, I7, F10.4, 6F10.2)
2000 FORMAT(2X, 2I12)

RETURN
END
APPENDIX D Integration Routine for Energy Values - ENERGY

-------------------------------------------------------------------------------------

| C | ENERGY : Integration by using trapezoidal method |
| C | Step change is considered for the SB*.DAT files |
| C | May 10, 1988  C. P. |
| C | Revised :  July 15, 1988 |
| C | NCOL : Number of data columns per a record |
| C | NROW : Number of data rows in a whole file |
| C | ISEL : Index number of column of selected data |
| C | NRPR : Number of rows per a record |
| C | TBEGIN : Beginning time of integration (s) |
| C | TEND : Ending time of integration (s) |

-------------------------------------------------------------------------------------

PROGRAM ENERGY

PARAMETER (MAXCOL=30,MAXROW=15000)
REAL X(MAXCOL),Y(MAXROW),T(M<ROW)
CHARACTER INPFIL*20,XX*80

C* DATA NRPR/4/
DATA DTMIN/8.1/

C* PRINT *, ' Data File Name ?'
C* READ(*,FMT=('A20')) INPFIL
C* PRINT 1000, INPFIL
C*1000 FORMAT(10C*').A20.5X.10C*'))
C* OPEN(7,FILE=INPFIL)

5 OPEN(8,FILE='ENERGY8.OUT')
READ(8,FMT=('A80'),END=7) XX
GOTO 5

7 PRINT *, ' Total number of columns and rows ?'
READ *, NCOL, NROW
PRINT *, ' Number of rows per a record in the file ?'
READ *, NRPR
WRITE(8,1000)

10 REWIND 7
PRINT *, ' Selected channel number ?'
READ(*,END=50) ISEL
PRINT *, ' Selected channel number ' , ISEL
PRINT *, ' Beginning time, Ending time (s) ?'
READ *, TBEGIN, TEND
PRINT *, ' TBEGIN = ',TBEGIN, ' TEND = ',TEND
PRINT *, ' Maximum time interval and change in value '
READ *, DTREF, DYREF
PRINT *, DTREF = ',DTREF, ' DYREF = ',DYREF

ICOUNT=1
20 READ(7,*),END=30 (X(J),J=1,NCOL)
TIME = X(1)
IF(TIME.GE.TBEGIN .AND. TIME.LE.TEND) THEN
  T(ICOUNT)=X(1)
  Y(ICOUNT)=X(ISEL)
  ICOUNT=ICOUNT+1
ELSEIF(TIME.GT.TEND) THEN
  GOTO 30
ENDDIF

IF(ICOUNT-1.LT.NROW/NRPR) THEN
  GOTO 20
ENDDIF

30 NCOUNT=ICOUNT-1

IF(NCOUNT .GE. MAXROW) THEN
  STOP ' MAXROW IS greater than 15000 '
END IF

79
ENDIF
SUM=0.0
DO 40 I=1,NCOUNT
C Tropezoidal integration
IF(I.GT.1) THEN
C Step change
   IF(((T(I)-T(I-1)).GE. DTREF .AND. 
     (Y(I)-Y(I-1)).GE. DYREF) THEN
      TR=T(I)-DTMIN
      S=Y(I-1)*(TR-T(I-1))
   ELSEIF((T(I)-T(I-1)).GE. DTREF .AND. 
     (Y(I)-Y(I-1)).GE. DYREF) THEN
      TR=T(I-1)+DTMIN
      S=Y(I)*(T(I)-TR)
   ELSE
      S=(Y(I)+Y(I-1))*(T(I)-T(I-1))/2.0
   ENDIF
ELSE
   S=0.0
ENDIF
C PRINT ' I = ',I,'S=',S
SUM=SUM+S
40 CONTINUE
AVE=SUM/(TEND-TBEGIN)
PRINT ' TOTAL = ',SUM
PRINT ' AVERAGE = ',AVE
PRINT ' ' WRITE(8,2000) ISEL,TBEGIN,TEND,SUM,AVE,DTREF,DYREF
IF(ISEL.EQ.5) THEN
   TBON=SUM
   TBOFF=TEND-TBEGIN-TBON
ELSEIF(ISEL.EQ.7) THEN
   QHWT=SUM
ELSEIF(ISEL.EQ.8) THEN
   QINP=SUM
ELSEIF(ISEL.EQ.6) THEN
   QCW=SUM
ENDIF
GOTO 10
50 XBURN= TBON/(TBON+TBOFF)
EF= QCW/QINP*100.
PRINT ' TBON =',TBON,' TBOFF =',TBOFF
PRINT ' XBURN =',XBURN,' EF =',EF
EFFU= QHWT/QINP*100.
P RINT ' XBURN =',XBURN,' EFFU =',EFFU
1000 FORMAT(79('='))
2000 FORMAT(15,2F7.0,F12.1,3F10.4)
CLOSE(8)
STOP '---- END OF JOB ----'
END
SPL : Interpolate the data points using B-spline method

August 22, 1988 Cheol Park

PROGRAM SPL
PARMETER (NDATA=100,NSETMAX=10)
CHARACTER TITLE(2)=80
DIMENSION X(NDATA),Y(NDATA),FDP(NDATA),XX(NDATA),YY(NDATA)
DIMENSION YNEW(NDATA,NSETMAX)
DATA N/12/,NSET/6/
OPEN(7,FILE='SPL.INP')
OPEN(8,FILE='SPL.X')
OPEN(9,FILE='SPL.OUT')
CLOSE(9,STATUS='DELETE')
OPEN(9,FILE='SPL.OUT')
REWIND 7
REWIND 8
REWIND 9

C Read the reference data file.
DO 60 KK=1,NSET
READ(7,2000,END=999) TITLE(1)
READ(7,2000) TITLE(2)
DO 10 I=1,N
READ(7,*) IXPUMP,XBURNER, X(I),Y(I)
10 CONTINUE

C Calculate the derivatives at each of point (x,y)
CALL SPLINE(N,X,Y,FDP)

C Read the input file of XX.
DO 30 J=1,NDATA
READ(8,*,END=40) XX(J)
30 CONTINUE
40 NN=J-1
REWIND 8
DO 50 K=1,NN

C Interpolate for given data.
CALL SPEVAL(N,X,Y,FDP,XX(K),YY(K))
PRINT *, K, XX(K), YY(K)
YNEW(K,KK)=YY(K)
50 CONTINUE
60 CONTINUE
DO 70 K=1,NN
WRITE(9,1000) XX(K),(YNEW(K,KK),KK=1,NSET)
70 CONTINUE
1000 FORMAT(8F10.2)
2000 FORMAT(AB6)
999 STOP
SUBROUTINE SPLINE(N,X,Y,FDP)

SPLINE : computes the second derivatives needed in cubic spline interpolation. The original program was written by J. H. Ferziger Ref.[1]. A little modification is made.

July 18, 1984 C.P.

N: Number of data points
X: Array containing the values of the independent variable (Assume to be in ascending order)
Y: Array containing the values of the function at the data points given in the X array
FDP: Output array which contains the second derivatives of the interpolating cubic spline.

REFERENCE:

REAL LAMDA
PARAMETER (NMAX=100)
DIMENSION X(NMAX),Y(NMAX),A(NMAX),B(NMAX),C(NMAX),R(NMAX),& FDP(NMAX)

Compute the coefficients and the RHS of the equations. This routine uses the cantilever condition. The parameter LAMDA is set to 1. But this can be user-modified.

A,B,C are the three diagonals of the tridiagonal system, and R is the right hand side.

LAMDA = 1.
C(1)=X(2)-X(1)
DO 10 I=2,N-1
C(I)=X(I+1)-X(I)
A(I)=C(I-1)
B(I)=2.*(A(I)+C(I))
R(I)=6.*((Y(I+1)-Y(I))/C(I)-(Y(I)-Y(I-1))/C(I-1))
10 CONTINUE
B(2)=B(2)+LAMDA*C(1)
B(N-1)=B(N-1)+LAMDA*C(N-1)

Tridiagonal solver subroutine.
But the notation is clumsy so we will solve directly.

DO 20 I=3,N-1
T=A(I)/B(I-1)
B(I)=B(I)-T*C(I-1)
R(I)=R(I)-T*R(I-1)
20 CONTINUE
FDP(N-1)=R(N-1)/B(N-1)
DO 30 I=2,N-2
FDP(N-I)=(R(N-I)-C(N-I)*FDP(N-I+1))/B(N-I)
30 CONTINUE
FDP(1)=LAMDA*FDP(2)
FDP(N)=LAMDA*FDP(N-1)
RETURN
END

SUBROUTINE SPEVAL(N,X,Y,FDP,XX,F)

END
SPEVAL : evaluates the cubic spline for given the derivatives computed by subroutine SPLINE.

XX: Value of independent variable for which an interpolated value is requested
F: The interpolated result

PARAMETER (NMAX=100)
DIMENSION X(NMAX),Y(NMAX),FDP(NMAX)

Find the proper interval.

DO 10 I=1,N-1
   IF(XX.LE.X(I+1)) GOTO 20
   CONTINUE

Evaluate the cubic.

DXM=XX-X(I)
DXP=X(I+1)-XX
DEL=X(I+1)-X(I)
F=FDP(I)*DXP*(DXP*DXP/DEL-DEL)/6.
& +FDP(I+1)*DXM*(DXM*DXM/DEL-DEL)/6.
& +Y(I)*DXP/DEL+Y(I+1)*DXM/DEL

RETURN
END
APPENDIX F  Equation for Combined Seasonal Efficiency  -  EFFSPWT

EFFSPWT :  Efficiency equation

\[ \eta = \alpha x/(x+b) + c \]

September 22, 1988 Cheol Park
Rev: September 26, 1988

PROGRAM EFFSPWT

REAL EF,EFMULT,ETA225,ETA225N,ETANEW,ETASS,ETAZERO,U,XDHW,
& XLOAD,XSPWT
REAL ETA
INTEGER I,IMAX,J,JMAX,NCASE,NDATA

PARAMETER (IMAX=50,JMAX=20)

DIMENSION XLOAD(IMAX),ETANEW(IMAX,JMAX),XDHW(JMAX)
DIMENSION U(JMAX),EF(JMAX),ETA225N(JMAX)

OPEN(7,FILE='EFFSPWT.INP')
OPEN(8,FILE='EFFSPWT.OUT')
CLOSE(8,STATUS='DELETE')
OPEN(8,FILE='EFFSPWT.OUT')

REWIND 7

C Read the input data for zero-water-load.
READ(7,*) ETAZERO,ETA225,ETASS,EFMULT

C Read the number of cases, the water drawn per day in gallon, and the energy factors(%), and the load factor due to domestic hot water draw(-).

READ(7,*) NCASE
DO 10 J=1,NCASE
READ(7,*) U(J),EF(J),XDHW(J)
EF(J)=EFMULT+EF(J)/100
10 CONTINUE

DO 20 J=1,NCASE
XSPWT=0.225+XDHW(J)
ETA225N(J)=ETA(ETAZERO,ETA225,ETASS,XSPWT)
20 CONTINUE

C Read the loads where the efficiencies are calculated.

READ(7,*) NDATA
DO 30 I=1,NDATA
READ(7,*) XLOAD(I)
XLOAD(I)=XLOAD(I)/100
30 CONTINUE

DO 40 J=1,NCASE
DO 40 I=1,NDATA
ETANEW(I,J)=ETA(EF(J),ETA225N(J),ETASS,XLOAD(I))
40 CONTINUE

DO 50 J=1,NCASE
WRITE(8,1000) XLOAD(I),(ETANEW(I,J),J=1,NCASE)
50 CONTINUE
1000 FORMAT(8F10.4)
STOP
END

FUNCTION ETA(ETAZERO, ETA225, ETASS, XLOAD)

REAL A, B, C, ETA, ETA225, ETASS, ETAZERO, XLOAD

C A curve-fit equation

C ETAZERO
B=0.225*(ETASS-ETA225)
&
A=(ETASS-C)*(1+B)
ET=ETA225+0.775*ETAZERO

RETURN
END
C **********************************************************************************************************
C EQTBIN: Efficiency equation and bin analysis
C
C Eta = ax/(x+b) + c
C
C September 22, 1988 Cheol Park
C Rev: January 27, 1989
C
C **********************************************************************************************************
C
PROGRAM EQTBIN
REAL EF, ETA225, ETA225N, ETANEW, ETASS, ETAZERO, U, &
XDHW, XLOAD, XPW, ETAU, ETASBIN
REAL ETA
INTEGER I, IMAX, J, JMAX, NCASE, NDATA
CHARACTER TITLE*80

PARAMETER (IMAX=50, JMAX=20)

DIMENSION XLOAD(IMAX), ETANEW(IMAX, JMAX), XDHW(JMAX)
DIMENSION U(JMAX), EF(JMAX), ETA225(JMAX), ETA225N(JMAX)
DIMENSION ETAU(IMAX), ETASBIN(JMAX)

OPEN(7, FILE='EQTBIN.INP')
OPEN(8, FILE='EQTBIN.OUT')
CLOSE(8, STATUS='DELETE')
OPEN(8, FILE='EQTBIN.OUT')

REWIND 7

C Read the input data for zero-water-load.
READ(7,*) ETAZERO, ETASS

C Read the number of cases, the water drawn per day in gallon, and
C the energy factors(%), and the load factor due to domestic hot water
draw(-).
READ(7,*) NCASE
DO 10 J=1, NCASE
READ(7,*) U(J), EF(J), XDHW(J), ETA225(J)
EF(J)=EF(J)/100.
10 CONTINUE

C Find a new combined efficiency at the point where the space load
C is 22.5 percent.
DO 20 J=1, NCASE
XPW=0.225+XDHW(J)
20 CONTINUE
ETA225N(J) = ETA(ETAZERO, ETA225(J), ETASS, XSPWT)

CONTINUE

C Read the loads where the efficiencies are calculated.

READ(7,*) NDATA
DO 30 I = 1, NDATA
READ(7,*) XLOAD(I)
XLOAD(I) = XLOAD(I)/100
CONTINUE

DO 50 J = 1, NCASE
DO 40 I = 1, NDATA
ETANEW(I, J) = ETA(EF(J), ETA225N(J), ETASS, XLOAD(I))
IF(I .GT. 1) THEN
   ETAU(I - 1) = ETANEW(I, J)
ENDIF
CONTINUE

CALL ESEASON( ETAU, ETAS)
ETASBIN(J) = ETAS

CONTINUE

TITLE = '****** OUTPUT OF EQTBin.FTN ******'
WRITE(8, 2000) TITLE
WRITE(8, 3000) (U(J), J = 1, NCASE)
WRITE(8, 4000)
DO 60 I = 1, NDATA
WRITE(8, 5000) (ETASBIN(J), J = 1, NCASE)
CONTINUE

1000 FORMAT(12F10.4)
2000 FORMAT(A80)
3000 FORMAT( ' XLOAD U = ', 12F10.1)
4000 FORMAT( )
5000 FORMAT( '/' Eta,bin = ':', 12F10.4)

STOP
END

C *****************************************************
C
C FUNCTION ETA(ETAZERO, ETA225, ETASS, XLOAD)
C
C *****************************************************
C
REAL A, B, C, ETA, ETA225, ETASS, ETAZERO, XLOAD

C A curve-fit equation
C=ETAZERO
B=-0.225*(ETASS-ETA225)
&
A=(ETASS-C)*(1.+B)
 ETA=A*XLOAD/(XLOAD+B)+C

RETURN
END

C*******************************************************************************
C ESEASON : seasonal efficiency for combined space and water loads
C January 26, 1989 Cheol Park
C*******************************************************************************

subroutine eseason(etau, etas)
real sum1, sum2, xspace, etau, etas, temp
real n
integer i, imax
parameter ( imax= 15 )
dimension xspace(imax), etau(imax), temp(imax),
& n(imax)

C bin data for region IV

data n/0.132, 0.111, 0.103, 0.093, 0.100, 0.109, 0.126,
& 0.087, 0.055, 0.036, 0.026, 0.013, 0.006, 0.002,
& 0.001/

data temp/ 62., 57., 52., 47., 42., 37., 32., 27., 22.,
& 17., 12., 7., 2., -3., -8./

C design condition

data tref/65.0/, tdesign/5.0/, oversize/0.7/

sum1 = 0.0
sum2 = 0.0

do 10 i=1,imax

xspace(i) = (tref-temp(i))/((tref-tdesign)*(1.+oversize))

sum1 = sum1 + n(i)*xspace(i)
sum2 = sum2 + n(i)*xspace(i)/etau(i)
if (i .eq. imax) then
print *, 'i, xspace, sum1, sum2, etau =', i, xspace(i), sum1, & sum2, etau(i).
endif

continue

etas = sum1/sum2
print *
print *, 'Seasonal Efficiency = ', etas

return
end
1. **Publication OR Report No.**
   - NISTIR 89-4104

2. **Performing Organ. Report No.**

3. **Publication Date**
   - JUNE 1989

4. **Title and Subtitle**
   - A Study on the Performance of Residential Boilers for Space and Domestic Hot Water Heating

5. **Author(s)**
   - Cheol Park and George E. Kelly

6. **Performing Organization (If joint or other than NBS, see instructions)**
   - NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
   - U.S. DEPARTMENT OF COMMERCE
   - GAITHERSBURG, MD 20899

7. **Contract/Grant No.**

8. **Type of Report & Period Covered**

9. **Sponsoring Organization Name and Complete Address (Street, City, State, ZIP)**
   - U.S. Department of Energy
   - Office of Conservation and Renewable Energy
   - Washington, DC 20585

10. **Supplementary Notes**
   - □ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. **Abstract** (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A residential boiler for space heating and domestic hot water heating was studied by conducting laboratory tests and computer simulations. A clam-shell, wet-base, oil-fired, residential boiler with a tankless coil for heating domestic water was selected for this research project.

The purpose of this study was to develop a method for evaluating the performance of an integrated space and water heating appliance. Based upon laboratory tests, a computer model was developed and used with the HVACSIM® building system simulation program to simulate the operation of the integrated appliance.

The model was verified for heat-up, cool-down, cyclic, and standby modes of operation, along with various domestic hot water draw cycles. Using the verified model, computer simulations were carried out for both summer and winter operations of the appliance. As a result of these simulation studies, a simple method for determining the combined, seasonal efficiency of Type I appliance, whose primary design function is space heating and secondary function is domestic water heating, is presented.

12. **Key Words** (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
   - computer simulation; domestic hot water heating; integrated appliance; performance test procedure; residential boiler, space heating.

13. **Availability**
   - □ Unlimited
   - □ For Official Distribution. Do Not Release to NTIS
   - □ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. **No. of Printed Pages**
   - 102

15. **Price**
   - $19.95