THE DEVELOPMENT AND VALIDATION OF A FURNACE MODEL FOR ESP-r/HOT3000

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ABSTRACT

With so many reliable building simulation software programs available, it is often not feasible or desirable to develop a new simulator from scratch. As many existing programs have extensible structures, new models and algorithms can be easily incorporated.

This paper sets out to contribute to the body of knowledge on the appropriate development and validation approaches of HVAC algorithms. It provides an account from a recent on-going software development project and examines the specific case of incorporating a furnace model into a commercially available simulation engine.

In addition, it describes an HVAC BESTEST series of test cases developed for fuel-fired furnaces. These test cases were used to validate the fuel-fired furnace algorithm incorporated into three simulation programs, with very good agreement.

INTRODUCTION

The CANMET Energy Technology Centre's (CETC) next generation HOT2000 simulation project - coined HOT3000 - is based upon the comprehensive and extensively validated simulation program ESP-r (ESRU 2000). This simulation environment is referred to as ESP-r/HOT3000 throughout the paper.

The choice of simulation engine for the ESP-r/HOT3000 project followed an extensive investigation of building-side processes, HVAC-side processes, as well as a survey of 30 existing building simulation tools (Haltrecht et al. 1999).

ESP-r applies a finite-difference formulation based on a control-volume heat-balance to represent all relevant energy flows within the building. Finite-difference nodes are used to represent: air volumes (rooms), solid-fluid interfaces (the internal and external surfaces of walls and windows), and plant components (boilers and ducts). In addition, numerous nodes are placed through each fabric element (walls and windows) to represent these multi-layered constructions.

A heat balance is written for each node in algebraic form, approximating the governing partial differential equations and linking all inter-node heat flows over time and space. A simultaneous solution is then performed to determine the state of each node and the inter-nodal heat flows. The equation set is reformed and resolved for each subsequent time step of the simulation. The interested reader is referred to Clarke (1985) for a comprehensive review of this approach.

Numerous modelling capabilities have been added to ESP-r's extensible structure to support the HOT3000 development. These include the BASESIMP ground heat transfer algorithm (Beausoleil-Morrison and Mitalas 1997), the AIM-2 air infiltration model (Walker and Wilson 1990), and models to predict the performance of residential HVAC equipment.

When new algorithms are developed and incorporated into the ESP-r/HOT3000 core, they must be extensively validated. In addition to testing the code, the algorithm itself requires testing. The code may be bug-free, but an error in the algorithm will lead to unreliable results.

A furnace model was recently incorporated into the ESP-r/HOT3000 simulation program. CETC has also initiated the development of a series of test cases for validating fuel-fired furnace algorithms incorporated in building simulation software. This exercise provided an excellent opportunity to develop the HVAC BESTEST series, as well as to test the furnace algorithm incorporated in HOT3000/ESP-r.

DEVELOPMENT OF NEW ALGORITHMS FOR A FUEL-FIRED FURNACE MODEL

The furnace model implemented into the ESP-r /HOT3000 engine is an empirical-based-model. In this case, the performance of a certain type of furnace is measured in a laboratory setting and a correlation is developed that gives the furnace part-load efficiency as a function of the part-load ratio.

The following sections detail the model algorithm and its implementation into the ESP-r/HOT3000 core.

Fuel-Fired Furnace Algorithm

Furnace Energy Consumption

The power consumption of the furnace, during a time step, is based on the following equation:

$$\text{Furnace Power Input} = \frac{\text{furnace steady state capacity}}{\text{furnace steady state efficiency}} \cdot \frac{PLR}{PLF} \tag{1}$$

where PLR is the part-load ratio, equal to the ratio of the sum of the heating loads of the zones being served by the furnace to the steady-state capacity of the equipment:

$$PLR = \frac{\text{heating load}}{\text{furnace steady state capacity}} \tag{2}$$

In cases where the PLR is greater than 1, the furnace does not have enough capacity to meet the heating load and the heating set point of the conditioned space can not be maintained.[1]

When there is a circulation fan, the definition of PLR depends on the operation mode of the fan as discussed later in the paper.

The part-load factor, PLF, in Equation 1 is used to account for the degradation of the furnace efficiency at part-load conditions. PLF is then the ratio of the part-load efficiency to the steady-state efficiency:

$$PLF = \frac{\text{furnace part load efficiency}}{\text{furnace steady state efficiency}} \tag{3}$$

The energy consumption of the furnace during the time step, Δt, in seconds, is therefore:

$$\text{furnace energy} = \Delta t \cdot \text{furnace power input} \tag{4}$$

Part-Load Performance

The part-load performance curves used in ESP-r/HOT3000 are based on Barringer (1991) and Henderson (1998), and these part-load performance correlations account for the furnace off-cycle flue losses.

From the Barringer report, the PLF of the furnace, defined in Equation 3, becomes:

$$PLF = \frac{af \cdot PLR}{PLR + bf} \tag{5}$$

Table 1 lists the correlating coefficients, af and bf, proposed by Barringer for the different furnaces.

The Barringer performance curves, and their associated variations in PLF as a function of PLR, are shown in Figure 1. The curve for mid-efficiency oil represents all oil furnaces except condensing types. The curve for continuous pilot gas types represents all wood, natural gas, and propane furnaces except condensing and induced draft types.

Fuel	**Furnace Type**	*af*	*bf*
Electricity	---	1.	0.
Natural Gas[2]	Spark ignition Spark ignition and vent damper Continuous pilot	1.008	0.0166
	Condensing Induced draft	1.0	0.
Oil	Flame retention head Flue vent damper Direct vent non-condensing Mid-efficiency Oil furnace	1.005	0.0093
	Condensing	1.	0.
Wood	Advanced air tight Advanced air tight with catalytic converter Wood furnace	1.008	0.0166

Table 1: Correlation coefficients *af* and *bf* proposed by Barringer (1991).

In contrast, the Henderson correlation equation is based on the following expression for PLF:

$$PLF = \frac{PLR}{HIR} \tag{6}$$

where HIR is the heat-input ratio given by:

$$\begin{aligned} HIR &= \frac{\text{furnace power input}}{\text{furnace steady state power input}} \\ &= a + b \cdot PLR + c \cdot PLR^2 + d \cdot PLR^3 \end{aligned} \tag{7}$$

Henderson defines two sets of correlating coefficients: one that is applicable for all atmospheric furnaces and a separate set for induced draft furnaces, as shown in Table 2.

Furnace Type	*a*	*b*	*c*	*d*
Atmospheric	0.0117	0.9806	0.1178	-0.1103
Induced Draft	0.0080	0.8756	0.2925	-0.1762

Table 2: Correlation coefficients *a*, *b*, *c*, and *d*, proposed by Henderson (1987).

Figure 1 provides a comparison of the resulting curves, and shows good agreement between the Henderson

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[1] Should this occur, the *PLR* is set 1, and a warning message is issued to the ESP-r/HOT3000 user indicating that the heating load will not be met for a certain number of hours.

[2] The coefficients *af* and *bf* for natural gas furnaces are used to represent propane furnaces.

correlation for atmospheric furnaces and the Barringer correlations for continuous pilot and mid-efficiency furnaces. The difference is larger, however, for induced draft furnaces especially at low *PLR* values.

One interesting aspect of the part-load performance curve, shown in Figure 1, is that for condensing furnaces, the *PLF* can be greater than 1 at low *PLR* values. According to Henderson (1998), this is due to the relatively oversized heat exchanger at part-load conditions.

For implementation into ESP-r/HOT3000, the part-load performance curves proposed by Barringer were used for all furnace types except condensing and induced draft, for which the Henderson correlations were used.

Additional HVAC Components

In addition to the furnace operation, the operation and energy consumption of circulation fans, draft fans, and pilot lights have been incorporated into the model. The following sections describe these algorithms.

Circulation Fan Energy Consumption

The capacity of the circulation fan can be estimated based on the following correlation (Barringer 1991):

$$\text{fan power} = 0.0194 \cdot \text{furnace steady state capacity} \qquad (8)$$

When the circulation fan energy is modeled, the definition of the part-load ratio is altered depending on the circulation fan mode of operation.

For continuous mode; the fan operates continuously, for auto mode; the fan operates only when the furnace operates.

Fan in Continuous Mode

For this case, the *PLR* of the furnace is calculated with Equation 2 and the fan power is included as an extra internal heat gain to the conditioned space. The energy consumption of the fan during a time step is:

$$\text{fan energy} = \text{fan power} \cdot \Delta t \qquad (9)$$

Fan in Auto Mode

For this case, the fan capacity is added to the capacity of the furnace and the modified *PLR* is:

$$PLR_{fan\ auto} = \frac{\text{heating load}}{\text{furnace steady state capacity} + \text{fan power}} \qquad (10)$$

The circulation fan energy consumption during a simulation time step is:

$$\text{fan energy} = \text{fan power} \cdot PLR_{fan\ auto} \cdot \Delta t \qquad (11)$$

Draft Fan Energy Consumption

For induced draft and condensing furnaces, a draft fan exhausts the combustion products to the outdoors. This draft fan is only on when the burner of the furnace is on. Therefore, the energy consumption of the draft fan during a specific time step is:

$$\text{draft fan energy} = \text{draft fan power} \cdot PLR \cdot \Delta t \qquad (12)$$

In this equation, *PLR* is based on either Equation 2 or 10 depending on the circulation fan mode of operation.

Pilot Energy Consumption

Furnace pilot lights are on only when the burner of the furnace is not in operation. The pilot energy consumption during a particular time step is:

$$\text{pilot energy} = \text{pilot power} \cdot (1 - PLR) \cdot \Delta t \qquad (13)$$

Again, *PLR* is based on either Equation 2 or 10,

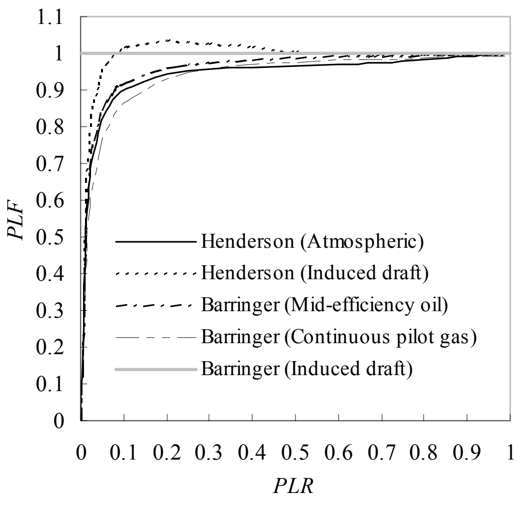

Figure 1: Comparison of the Henderson and Barringer performance correlations.

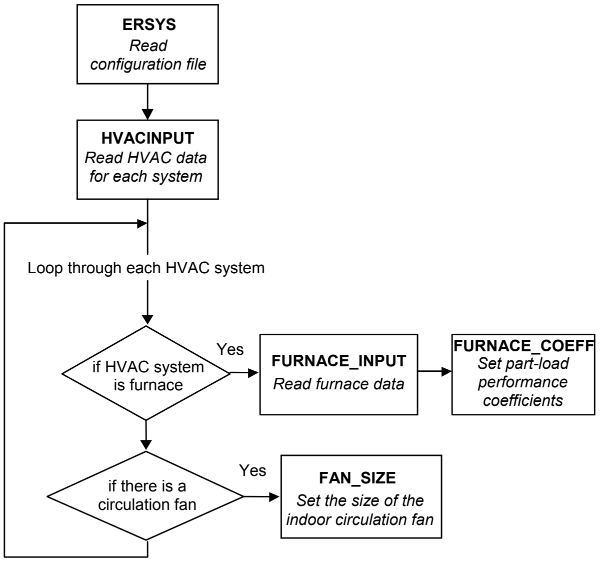

Figure 2: Flowchart of furnace input data reading.

depending on the circulation fan mode of operation.

Incorporation of Furnace Model into ESP-r/ HOT3000

Figure 2 shows a flowchart of the section of ESP-r/HOT3000 code where the furnace input data is read. Subroutine ERSYS reads a configuration file for a specific model. The configuration file contains information relating to the simulation (databases, zone construction, operation, and geometry files, etc…).

When the configuration file contains a reference to an HVAC file, the subroutine HVACINPUT is called. HVACINPUT calls the appropriate subroutine for reading the input information for each of the HVAC systems listed in the HVAC file.

If a furnace is one of the HVAC systems defined in the HVAC file, then the HVACINPUT subroutine calls FURNACE_INPUT to read the appropriate furnace input data. The circulation fan size is determined in the subroutine HVACINPUT, unless it was user-specified.

Figure 3 shows the section of code where the energy consumptions of the furnace, circulation and draft fans and pilot are calculated. The MZNUMA subroutine loops through each day of the simulation period, then each hour of the day, and then each time step in the hour. At the end of every time step iteration, the heating and cooling loads for each of the zones considered in the simulation are determined. At this point, the HVACSIM subroutine is called to simulate the performance of the HVAC system - if one has been defined in the configuration file.

The HVACSIM subroutine loops through all the HVAC systems defined in the HVAC data file. If one of these systems is a furnace, then its performance is simulated in FURNACE - where the furnace and, if applicable, pilot energy consumptions are set. In cases with a circulation and/or draft fan, their energy consumptions (during the time step) are determined.

VALIDATION

There are many ways to determine the validity of a particular piece of code, including: software testing and verification to ensure that it is error and bug free, performing code walkthroughs with other developers to allow an objective examination of coding decisions, as well as adopting coding standards to ensure uniform coding practices within a particular program.

The importance, and the resultant improvement in quality and reliability, of adopting good procedures and standards in the software development process are examined in Mombourquette (2002).

Code Validation

Model Implementation

During code development for a certain algorithm, there is always the possibility of introducing errors or bugs in the code. At the end of the code implementation phase,

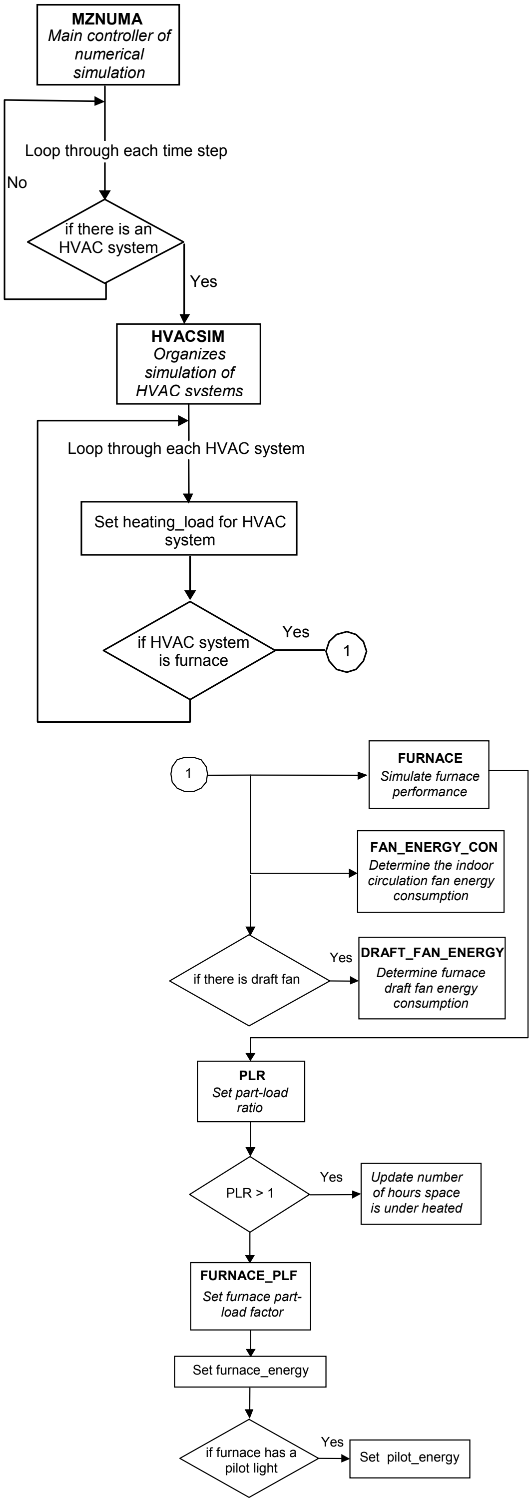

Figure 3: Flowchart of furnace model implementation into HOT3000/ESP-r.

it is therefore very important to test the code thoroughly to ensure that it is performing as intended.

The first sections tested for implementation in ESP-r/HOT3000 were the furnace data read in sections (subroutines HVACINPUT and FURNACE_INPUT). In this case, *write* statements were placed throughout the code to ensure that all furnace input variables in the HVAC file were being properly read.

The sections of code where the calculations of various energy consumptions were performed were tested using a sample ESP-r/HOT3000 input file. First, spot checks were performed on each of the subroutines called to calculate the furnace energy consumption. The part-load ratio calculated in PLR and the part-load factor calculated in FURNACE_PLF were then compared to spreadsheet calculations for a few scenarios.

Finally, ESP-r/HOT3000 simulations were run for all combinations of fuel types and furnace types. The simulated energy consumptions of the furnace, pilot, circulation fan, and draft fan were compared to spreadsheet calculations for several time steps.

Code Walkthrough

One of the final steps in the code development process, before the new code is incorporated into the master version of the engine, is to perform a code walkthrough. The code walkthrough provides team members with the opportunity to comment and make suggestions on the syntax and form of the new code. It is also the time when the rest of the team can ensure that the programmer has properly followed the coding standard.

Suggestions made during the code walkthrough are incorporated into the code before it becomes part of the master version.

Algorithm Validation

One important issue that has not yet been discussed is the validity of the algorithms used in the development. Adopting good procedures and standards will ensure that your code is error and bug-free, but are the underlying algorithms correct?

As part of IEA Task 22, fuel-fired furnace algorithm validation test cases have been developed. This exercise provided an excellent opportunity to develop a BESTEST series, as well as test the fuel-fired furnace algorithm, described in the previous sections.

The following sections describe the intention of these test cases, the process for developing the test cases, and provide results from an inter-program comparison.

IEA HVAC BESTEST

The Heating Ventilating and Air-Conditioning (HVAC) BESTEST was developed to provide practical diagnostic procedures and data for testing the ability of whole building simulation programs to model the performance of various HVAC systems.

The BESTEST procedure is intended to isolate a single facet of an HVAC system in each test case, starting with the simplest case and progressively adding complexity. The test cases use a carefully specified HVAC system with a highly simplified near-adiabatic building envelope.

The tests are developed so that many different building simulation programs, representing different degrees of modelling complexity, can be tested.

The HVAC test cases are similar in principle to the test cases developed by Judkoff and Neymark (1995) assessing the accuracy of building loads algorithms. These cases test various aspects of building loads calculations such as solar gains, thermal mass, transmission losses/gains, and solar shading. When applied to various building simulation programs, these loads test cases helped diagnose several bugs.

Similarly, the IEA HVAC BESTEST will eventually be useful in uncovering deficiencies in some of the HVAC modeling algorithms used in simulation engines. As a result, the users of these building simulation programs will have more confidence in the simulation results generated using a program that has undergone testing using the HVAC BESTEST.

Neymark and Judkoff (2000) have developed a series of test cases focusing on the modelling of unitary vapour compression cooling equipment. The test cases described below (Purdy and Beausoleil-Morrison 2001) will join the HVAC BESTEST series.

Fuel-Fired Furnace Test Cases

A total of fourteen cases have been proposed for testing the performance of fuel-fired furnace models. These tests are divided into two tiers. The first tier employs simplified boundary conditions and tests the basic functionality of furnace models. More realistic boundary conditions are used in the second tier, where specific and detailed aspects of furnace models are examined. This paper discusses the eight tier 1 cases, whereas the tier 2 cases will be developed in the future.

Specific cases are designed to test a building energy simulation program's fuel-fired furnace algorithm with respect to the effect of:

- Furnace steady-state efficiency
- Furnace part load ratio
- Outdoor temperature
- Circulating fan operation
- Draft fan operation

The base case building (Case *1a*) is a single near-adiabatic rectangular zone with energy transfer through a single surface to drive the heating loads. The geometric and material specifications are purposely kept as simple as possible to minimize the opportunity for user input errors. The mechanical equipment represents a simple sealed combustion gas furnace.

The additional test cases, Cases *1b-1h*, are organized as modifications to the base case and ordered in a manner that will facilitate implementing the tests - they are progressively more complex.

Table 3 details the test cases as well as the furnace and fan equipment operating points and the associated weather files. These test cases are further explored in the following sections.

Case	**η[3](%)**	***PLR***	**DBT[4] (°C)**	**Circulating Fan (W)**	**Draft Fan (W)**
1a	100	1	-30	0	0
1b	80	1	-30	0	0
1c	80	0.4	0	0	0
1d	80	0.0	20	0	0
1e	80	0.0-0.8	-20 to 20	0	0
1f	80	0.0-0.8	-20 to 20	200-cont.	0
1g	80	0.0-0.8	-20 to 20	200-cyclic	0
1h	80	0.0-0.8	-20 to 20	200-cyclic	50-cyclic

Table 3: Test Case Specifications.

Analytical/Calculated Solution

The test case configurations (*1a-1h*) are well posed for an analytical or calculated solution that can be used for comparison with the software being tested.

Case *1a*: Base Case Building and Mechanical System

The base case building is a 48 m^2 floor area, single story, low mass building with rectangular prism geometry and internal measurements as shown in Figure 4. The zone air volume is 129.6 m^3.

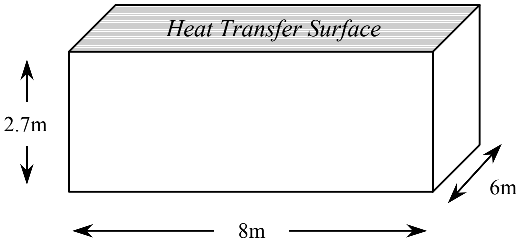

Figure 4: Base case building with heat transfer surface.

The base case building is designed as a near-adiabatic test cell. Energy is transferred to the outdoors through the heat transfer surface, with the furnace used to maintain the interior set-point temperature.

Material properties for the exterior wall, floor, and roof are listed in Table 5. The roof will be modelled as the heat transfer surface, and the insulation in the walls and floors has been made very thick and resistant to heat transfer to effectively thermally decouple the zone from ambient conditions.

Element	**Area (m²)**	**k (W/mK)**	**t (m)**	**U[5] (W/m²K)**
Wall	75.6	0.01	1.00	0.01
Floor	48.0	0.01	1.00	0.01
Roof (Heat Transfer Surface)	48.0	0.0714	0.01	7.14

Table 4: Building Material Properties.

Surface Convective and Radiative Heat Transfer Coefficients

Solar absorptivity, longwave emissivity and surface convection coefficients will approach zero for all interior and exterior opaque surfaces. The only exception to this is the heat transfer surface, with a constant non-zero surface convection coefficient.

The following surface convection coefficients (h_c), longwave emissivity (λ), and solar absorptivity (α) will be defined for all internal and external surfaces:

- h_c = 20W/m²K for heat transfer surface;
- $h_c \rightarrow 0$ for all other surfaces;
- longwave emissivity, λ, $\rightarrow 0$ at all surfaces; and
- solar absorptivity, α,$\rightarrow 0$ at all surfaces.

The floor will have the same exterior film coefficient as the other walls, as if the entire zone were suspended above the ground.

If the software does not allow a definition of zero for h_c, λ, or α, the software tester is encouraged to set these values to as small a number as possible.

HVAC Equipment

Mechanical equipment specifications represent a simple sealed combustion gas furnace. The equipment full-load capacity and full-load performance data for the

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[3] Steady-state furnace efficiency.

[4] Outdoor dry-bulb temperature.

[5] This U-value is defined between internal and external surfaces of envelope components, and as such does not include the resistance offered by surface convection and longwave radiation.

natural gas furnace are as follows:

Furnace capacity = 10 kW
Furnace full-load efficiency = 100%
Circulating fan power draw = 0 W, runs continuously.
Draft fan power draw = 0 W, cycles with burner operation

The following assumptions are made regarding the furnace and zone operation.

- The furnace injects heat directly to the zone air, i.e., a convective heating system.
- The zone air is fully mixed.
- The furnace draws its combustion air from outdoors.
- The furnace flue does not extract air from the zone.
- There is no pilot light.
- There are no air or thermal losses from the ducts.

Case *1b*: Efficiency Test

Case *1b* is the same as Case *1a*, except that the furnace will run continuously at 80% efficiency at full-load capacity (10kW). This case is designed to ensure the furnace efficiency is accurately represented in the fuel consumption calculation.

Case *1c*: Steady-State Part Load Test

For Case *1c*, the furnace will not run at full-load capacity. This case is designed to ensure that the part-load curves have been properly implemented.

In this case, the outdoor temperature has been increased from a constant -30°C to a constant 0°C. The indoor-outdoor temperature difference was reduced from a 50°C in Cases *1a* and *1b* to 20°C. For this reason, the furnace will run continuously at 40% full-load capacity and part-load operation will be examined.

Case *1d*: No Load Test

The objective of this test case is to test a program's ability to accurately respond to a zero heating load on the heating equipment.

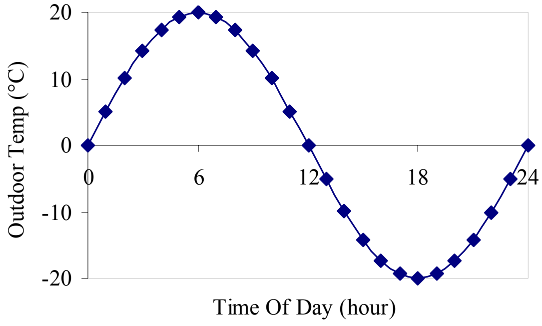

Figure 5: Outdoor temperature varying sinusoidally from 20°C to -20°C over 24 hour period.

The weather file has a constant outdoor temperature equal to the indoor setpoint of 20°C.

Case *1e*: Dynamic Part Load Test

The objective of this test case is to examine a program's ability to accurately respond to variations in load.

The weather file has a daily-sinusoidally-varying outdoor temperature, as shown in Figure 5.

This case is designed to ensure that the model operates over the full range of the part-load curve and represents a more stringent test on whether the part-load factor correlation was implemented properly.

Case *1f*: Circulating Fan Test

The objective of this case is to test a program's ability to model circulating fan operation.

Case *1f* is the same as Case *1e*, except that the circulating fan runs continuously and draws 200W. This case is designed to ensure that the fan electrical consumption is calculated properly and that the heat output of the circulating fan is correctly reflected in the zone energy balance.

The modified mechanical equipment specifications are:

Circulating fan power draw = 200W, runs continuously.[6]

Case *1g*: Cycling Circulating Fan Test

The objective of this test case is to test a program's ability to model a cyclic fan operation.

Case *1g* is the same as Case *1f*, except that the circulating fan cycles with burner operation instead of running continuously. This case is designed to ensure that the impact of fan cycling is properly considered in calculation of circulation fan electrical consumption.

The modified mechanical equipment specifications are:

Circulating fan power draw = 200W, cycles with burner operation.[6]

Case *1h*: Draft Fan Test

The objective of this test case is to test a program's ability to model a draft fan operation.

Case *1h* is the same as Case *1f*, except that the draft fan electrical consumption is incorporated. This case is designed to ensure that the impact of the draft fan is properly considered in the electrical consumption calculation, but not accounted for in the fuel consumption. The heat output of the draft fan should not be added to zone energy balance.

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[6] The draft fan power draw remains 0 W and cycles with the burner operation.

The modified mechanical equipment specifications are:

Circulating fan power draw = 200W, runs continuously. Draft fan power draw = 50W, cycles with burner operation.

Results from Inter-Program Comparison

The Tier 1 test cases were implemented and run with three software programs: ESP-r/HOT3000, EnergyPlus, and DOE2.1E. The results from these simulations were compared to the calculated/analytical solution, as shown in Figure 6.

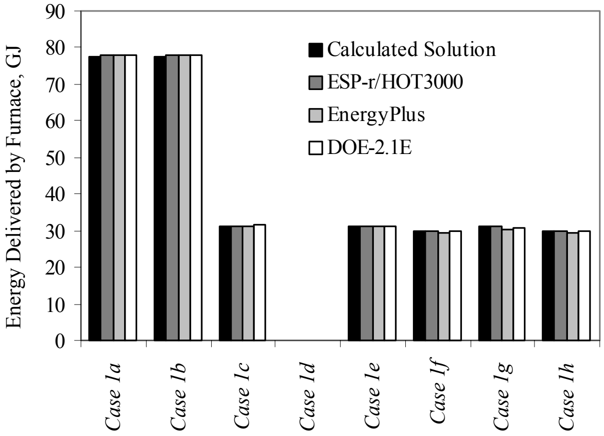

Figure 6: Energy Delivered By Fuel-Fired Furnace, in GJ.

It can be seen that the simulated energy delivered to the zone results of the three building simulation programs agree very well with the calculated/analytical solution.

CONCLUSIONS

This paper describes a project to incorporate a fuel-fired furnace model into the ESP-r/HOT3000 core. The development process involved selecting an appropriate algorithm, incorporating the new algorithm into the HOT3000/ESP-r structure, adhering to coding standards, performing code walkthroughs, and finally validating both the code and the algorithm.

A series of IEA BESTEST fuel-fired furnace validation test cases were developed. These test cases were used to validate the fuel-fired furnace algorithm incorporated into three whole-building simulation programs. The agreement between the calculated/analytical solution and simulated results was shown to be very good.

The procedure developed for testing furnace algorithms can easily be applied to other HVAC system models such as air-source heat pumps. It is expected that the test procedure will uncover more differences between simulation engines as the complexity of the HVAC simulation model or algorithm increases.

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