APPLICATION OF THE IEA HVAC BESTEST SUITE OF TEST CASES FOR THE VALIDATION OF AN AIR-CONDITIONING MODEL

Kamel H. Haddad, Ph.D. (khaddad@nrcan.gc.ca)
CANMET Energy Technology Centre
Natural Resources Canada
Ottawa Ontario

ABSTRACT

The empirical model for split air-conditioning system with an air-cooled condensing unit, implemented in the ESP-r/HOT3000 simulation engine, accounts for the variation of the equipment part-load factor with the part-load ratio. The model also accounts for the variations of the steady-state capacity and coefficient of performance with outdoor dry-bulb temperature and indoor wet-bulb temperature. Major inputs to the model are the cooling capacity, coefficient of performance, and coil sensible heat ratio at rating conditions.

The model and its implementation in ESP-r/HOT3000 are validated using the International Energy Agency suite of test cases (HVAC BESTEST) series E300-E545 specifically designed to test the accuracy of a simulation model for a simple unitary vapor-compression cooling system.

Overall the results indicate very good agreement between the predictions of the simulation results from ESP-r/HOT3000 and those from the other five simulation programs included in the test suite. Initial simulation results for two test cases with very high outside air intake resulted in an improvement of this aspect of the ESP-r/HOT3000 simulation model. Other differences in the simulation results can be reduced by using smaller simulation time steps.

The application of the IEA HVAC BESTEST series of test cases improves the confidence in the simulation results from the ESP-r/HOT3000 model. In addition, it is found that the test cases can be an effective means of diagnosing potential problems with simulation models.

INTRODUCTION

The use of building energy analysis computer programs is becoming more and more prevalent in the field of research, and in the design and analysis of new and existing HVAC systems. The increased use of these simulation tools can be in part attributed to the major improvements in the speed of personal computers, and the availability of better user interfaces and simulation models. In addition, many of our federal and provincial energy efficiency programs rely on the use of building simulation to show compliance. This increased adoption of these simulation tools places an even greater demand on building energy simulation software developers to ensure that the simulation models that they develop are accurate, and that the implementation of these models within simulation engines is correct.

According to Judkoff and Neymark (1999), there are about 120 building simulation software tools available worldwide with thousands of users. Judkoff and Neymark indicate that several studies have shown that there are differences in the predictions of simulation programs when applied by expert users to study the performance of the same buildings. Organizations such as the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Energy Agency (IEA) have recognized the need for the development of standard methods of test for the validation of building energy simulation models.

The IEA Building and Energy Simulation Test and Diagnostic Method (IEA BESTEST) (Judkoff and Neymark 1995a) is composed of a series of test cases for the validation of building loads calculations within building energy simulation tools. This suite of test cases is based on comparing predictions from various simulation tools. The work that lead to the development of the previous IEA BESTEST was also used by Judkoff and Neymark (1995b) to develop the Home Energy Rating System (HERS BESTEST), which was used by Haddad and Beausoleil-Morrison (2001) to validate the loads calculations in the ESP-r/HOT3000 simulation engine.

Another series of test cases developed by the IEA, referred to as the HVAC BESTEST, is designed to validate simulation models for building HVAC systems. So far there are suites of test cases for the validation of forced air furnaces (Purdy and Beausoleil-Morrison 2002), radiant heating and cooling systems (Achermann 2003), and unitary air-conditioners (Neymark and Judkoff 2002 and Neymark and Judkoff 2003). All of these suites of test cases contain predictions from several simulation tools. In addition, the test cases developed by Purdy and Beausoleil-

Morrison and by Neymark and Judkoff (2002) also contain analytical solutions.

Judkoff and Neymark (2002) first developed a series of steady-state test cases, referred to as series E100-E200, for the validation of unitary air-conditioners. These test cases were used by Haddad (2004) for the validation of the air-conditioning model in ESP-r/HOT3000. The agreement, between the predictions from ESP-r/HOT3000 and those from the other simulation tools and analytical solutions in the test suite was excellent. The second test suite developed by Judkoff and Neymark (2003), referred to as series E300-E545, for the validation of unitary air-conditioners consists of a series of transient test cases.

This paper deals with the application of the IEA cooling test cases series E300-E545 for the validation of unitary air-conditioners models in the transient mode. A brief description of these test cases and the ESP-r/HOT3000 air-conditioning model is included. The results from the ESP-r/HOT3000 model are compared to those from the other simulation tools in the test suite.

DESCRIPTION OF THE ESP-r/HOT3000 AIR-CONDITIONING MODEL

A complete and detailed description of the fundamentals of the ESP-r/HOT3000 air-conditioning model is presented in Haddad (2004). The model applies to a unitary split air-conditioning system consisting of an air-cooled condensing unit and an indoor evaporator unit. Mixed air from the conditioned zones and the outdoors flows on the outside of the evaporator coil through an indoor circulation fan. This fan can be placed either upstream or downstream of the evaporator coil and it can be either operate continuously or intermittently. In the continuous mode, the circulation fan is always on. However, in the intermittent mode, the fan is on only when there is a cooling load in the conditioned spaces.

The major inputs to the model are: the total cooling capacity, coefficient of performance COP, and sensible heat ratio at rating conditions. The sensible heat ratio is the ratio of the sensible cooling capacity of the coil to the total cooling capacity. The variation of the equipment total capacity and COP with the inlet wet-bulb temperature to the evaporator coil and the outdoor dry-bulb temperature is accounted for. The effect of the coil flow rate on the total capacity and the COP is also included. The sensible heat ratio at rating conditions is used to determine the bypass factor also at rating conditions. It is assumed that the airflow at the exit of the coil is composed of two streams: one at the inlet temperature of the coil and the other at the coil surface temperature. The bypass factor is then defined as the fraction of the airflow that exists the coil at the inlet coil temperature. The model also accounts for the variation of the bypass factor with airflow rate on the evaporator coil. Every time step of the simulation, the environmental conditions within the conditioned spaces and outdoors are known and the total cooling capacity and COP can then be deduced. It is also possible to predict the sensible heat ratio at these conditions.

The sensible load of the conditioned space is passed on to the cooling model by the loads routine in ESP-r/HOT3000. The latent load on the coil is predicted using the sensible load, the sensible heat ratio, and any contribution of the fan toward the heating of the circulation air. The total load on the coil (sensible + latent), the total cooling capacity, and the fan heat input to the air stream are then used to predict the part-load ratio of the equipment for the time step.

The model is based on the use of appropriate correlations for the variation of cooling Energy-Input Ratio (EIR) with the part-load ratio. In this case EIR is the ratio of the electricity consumption of the air-conditioner at part load to that at full load. In addition, the effect of the moisture removal capacity of the coil and the introduction of outdoor air through the HVAC system on the moisture balance of the spaces served by the HVAC system are taken into account. Outside air can either be introduced at a fixed rate or it can vary based on the operation of an economizer cycle using temperature or enthalpy control. Both of these economizer types can be turned off when an upper temperature or enthalpy limit is reached.

DESCRIPTION OF THE IEA COOLING TEST CASES SERIES 300-545

All the details about the test cases can be found in the document by Neymark and Judkoff (2003). A summary of the main characteristics of the test suite is given in this section. The IEA series E300-E545 contains a total of twenty transient cases that test different aspects of the air-conditioning model. Tables 1 through 3 summarize the characteristics of each of these test cases. These tables list the name of the test case, the level of latent and sensible internal gains, cooling set point temperature, infiltration rate in air-changes per hour, and the outdoor air rate also in air-changes per hour.

Table 1: Description of preliminary test cases E300-E360[a]

Case	**Internal Gains**		**Set point °C**	**Infil (ACH)**	**OA (ACH)**
	Sensible	**Latent**			

E300 Base Case (15% OA)	mid[b]	mid	25	0	1.734
E310 High latent load	mid	high[c]	25	0	1.734
E320 Infiltration	mid	mid	25	11.56	0
E330 Outside Air	mid	mid	25	0	11.56
E340 Infil/OA interaction	mid	mid	25	5.78	5.78
E350 Thermostat setup	mid	mid	25/35	0	1.734
E360 Undersize[d]	high	mid	25	0	1.734

[a] indoor circulation fan runs continuously

[b] "mid" internal gains are high daytime and low nighttime periodically/seasonally adjusted values

[c] "high" are greater loads relative to "mid"

[d] air-conditioner does not meet the total load

Table 2: Description of economizer test cases (E400-E440)[a]

Case	Internal Gains		Set point °C	Infil (ACH)	OA (ACH)
	Sensible	Latent			
Temperature based control cases					
E400 Temp control	mid	mid	25	0	1.734
E410 Compressor lockout	mid	mid	25	0	1.734
E420 ODB[b] limit	mid	mid	25	0	1.734
Enthalpy based control cases					
E430 Enthalpy control	mid	mid	25	0	1.734
E440 Outdoor enthalpy limit	mid	mid	25	0	1.734

[a] indoor circulation fan runs continuously

[b] outdoor dry bulb temperature

Table 3: Description of test cases with no outside air (E500-E545)

Case	Internal Gains		Set point °C	Infil (ACH)	OA (ACH)
	Sensible	Latent			
Wet coil cases					
E500 Base case (0% OA)	mid2[a]	mid2	25	0	0[b]
E510 High PLR	high2[c]	high2	25	0	0
E520 Low EDB[d]= 15 °C	mid2	mid2	15	0	0
E522 Low EDB=20 °C	mid2	mid2	20	0	0
E525 High EDB	mid2	mid2	35	0	0
Dry coil cases					
E530 Dry coil	mid2	0	25	0	0
E540 Dry coil, Low EDB	mid2	0	15	0	0
E545 Dry coil, high EDB	mid2	0	35	0	0

[a] "mid2" similar to "mid" but with 0 internal gains during cooler months

[b] 0 outside air indicates that the fan cycles on and off with the compressor

[c] "high2" are greater loads relative to "mid2"

[d] entering coil dry-bulb temperature

Building geometry

All these cases use the same rectangular zone to predict the building load on the air-conditioner. The envelope of the zone is near adiabatic and the cooling load of the space are mainly driven by user-specified latent and sensible internal gains as well as by any infiltration or HVAC outdoor air load.

Temperature controller

Whenever the zone temperature goes above the specified set point, the controller is turned on and the specified controller cooling capacity is extracted from the space until the cooling set point is achieved again. There is no controller action when the zone temperature is below the cooling set point.

Mechanical system

This is a unitary vapor-compression system with an air-cooled outdoor condenser and indoor evaporator. Return air from the conditioned zone is mixed with outdoor air before entering the cooling coil. The indoor circulation fan, downstream of the coil, then supplies the conditioned air to the zone. The mechanical system can also operate in economizer mode based on temperature or enthalpy control.

Equipment performance data

The test suite comes with manufacturers data that is to be used to generate the simulation results. The data consists of values for the total cooling load, sensible load, and the power input to the compressor of the air-conditioner. This data is given for different outdoor dry-bulb temperature and inlet wet-bulb and dry-bulb temperatures to the coil.

MODELLING OF THE TEST CASES IN ESP-r/HOT3000

Weather Data

The TMY2 weather files provided with the test suite are used to generate binary weather files for ESP-r/HOT3000. Hourly weather data required for ESP-r/HOT3000 is:

- Outdoor dry-bulb temperature
- Direct normal radiation
- Diffuse solar radiation on horizontal surface
- Wind speed
- Wind direction
- Relative humidity

All of these variables are given directly in the TMY2 weather files.

Building Zone Description

The building zone description used in the simulation is as specified in the test suite manual except for the material specifications. Initially the material specifications for the building envelope given in the test manual is used, but this results in a convergence problem due to the very low specific heat, density, and conductivity specified when the envelope elements are declared as exposed to ambient conditions. To resolve the convergence problems, an adiabatic boundary condition for the envelope is then used instead. With the adiabatic boundary condition, it is possible to specify a very low material density and specific heat to eliminate any thermal mass effects.

This deviation from the test specifications will impact the predicted values of temperature, relative humidity, and humidity ratio when the cooling load within the zone is zero (absence of internal gains, infiltration, and HVAC outdoor air) for an extended period of time as is the case for test cases E500 - E545. For these cases, an adiabatic boundary condition will result in constant zone air conditions in the absence of sensible and latent gains to the space. It is to be noted that the thermal resistance of the building enveloped specified in the test specifications is very high but does not correspond to a completely adiabatic condition.

Equipment Performance Curves

The ESP-r/HOT3000 cooling model uses correlations for the gross equipment capacity and the power input to the compressor. The equipment data given in the test specification is used to develop the correlations used.

The gross cooling capacity of the air-conditioner under wet conditions is correlated to the outdoor dry-bulb temperature and the coil entering wet-bulb temperature:

$$\begin{aligned}&Total\ Cooling\ Capacity\ (kW) = a1 + a2 \times Todb + \\ &a3 \times Todb^2 + a4 \times Tewb + a5 \times Tewb^2 + \\ &a6 \times Todb \times Tewb\end{aligned} \qquad (1)$$

where:
a1 = 23.49707981
a2 = -0.1076915531
a3 = -0.001612289548
a4 = 0.8052200912
a5 = 0.008864708391
a6 = -0.004824135037

The power input to the compressor under wet conditions is also correlated to the outdoor dry-bulb temperature and the coil inlet wet-bulb temperature:

$$\begin{aligned}&Compressor\ Power\ (kW) = b1 + b2 \times Todb + \\ &b3 \times Todb^2 + b4 \times Tewb + b5 \times Tewb^2 + \\ &b6 \times Todb \times Tewb\end{aligned} \qquad (2)$$

where:
b1 = 4.157768999
b2 = 0.1136096948
b3 = -0.0003236709368
b4 = 0.01115838853
b5 = 0.002180347593
b6 = 0.001799048516

The ESP-r/HOT3000 cooling model includes a method for calculating the coil sensible heat ratio under wet conditions. Therefore the sensible capacity equipment data in the test suite is not used to generate the simulation results.

Ideal Controller

An ideal controller with no throttling range is used. The controller cools the space back to the set point temperature when air temperature inside the space rises above the desired set point. For cases E300 - E360, the maximum sensible cooling capacity of the controller for a given time step is set equal to the gross sensible cooling capacity of the equipment for the previous time step. In this case the fan power is included as part of the sensible internal gains to the space.

For cases E400 - E440, when the air-conditioner and the economizer can operate together to meet the load, the maximum controller capacity for a given time step is set equal to the gross sensible cooling capacity for the previous time step plus any sensible cooling capacity associated with the operation of the economizer. If the air-conditioner and the economizer can not operate together to meet the load, then the controller maximum sensible cooling capacity is set to the gross equipment sensible cooling capacity for the previous time step. In this case, the fan power is included as part of the sensible internal gains to the space.

For cases E500 - E545, with a circulation fan in the intermittent mode, the maximum sensible capacity of the controller for a given time step is set equal to the sensible gross cooling capacity of the equipment for the previous time step minus the fan power. In this case the fan power is not included as an internal gain to the space. The net cooling capacity used for the evaluation of the part-load ratio is the gross capacity less the fan power.

Effect of Indoor Circulation Fan

When the indoor circulation fan is in continuous mode, it is specified as a sensible internal gain to the space. Its effect is then accounted for through its effect on the sensible cooling load of the space and an increased part-load ratio of the air-conditioner. When the indoor circulation fan is in auto mode, the capacity of the equipment used for the calculation of the part-load ratio is degraded by the fan power. In this case the fan power is not included as internal gain to the space.

Simulation of Infiltration

The infiltration rates for cases E320 and E340 are specified in the test suite using three day types with each day type valid over a given period of the year. Given that the infiltration day types in ESP-r/HOT3000 are valid for the whole year, the conductance associated with infiltration for cases E320 and E340 is then read from an ASCII file. For each time step, this conductance is set equal to the product of the outdoor air density, volume flow rate, and specific heat:

$$C_{\inf} = \rho_{oa}\dot{V}_{oa}Cp_{oa} \tag{3}$$

This conductance is then automatically used in ESP-r/HOT3000 as part of the air-point energy balance.

Simulation of Outdoor Air Effect

The sensible heat gain/loss from the introduction of outdoor air through the HVAC system is accounted for in the ESP-r/HOT3000 model as part of the sensible internal gains of the space. In this case sensible effect of outdoor air for the time step is treated in the model as sensible heat from lights or any other source of internal gain. If the outdoor air temperature is less than the space temperature, the sensible heat term associated with the introduction of outdoor air through the HVAC system has a negative sign for it helps cool the space. This sign is set to positive when the temperature of outdoor air is greater than that inside the conditioned space.

The space air-point moisture balance is modified to include an extra moist air supply term at the actual exit air conditions from the cooling coil. The model accounts for the effect of outdoor air on the inlet conditions to the coil. These inlet conditions are needed to predict the correct steady-state total capacity and COP of the air-conditioner.

COMPARISON OF RESULTS FROM ESP-r/HOT3000 AND FROM OTHER SIMULATION PROGRAMS

The test suite contains simulation results for the twenty test cases from five other simulation programs: TRNSYS, DOE2.1E-J (James Hirsch and Associates), DOE2.1E-E (Energy Science and Technology Transfer Center at Oak Ridge National Laboratory), ENERGYPLUS, and CODYRUN. The results from these simulation programs are contained in an Excel spreadsheet that accompanies the test suite.

The figures contained in this spreadsheet are modified to include the results from ESP-r/HOT3000. Only some of these modified figures are presented in the following section of the paper due to space limitations. In addition, due to space limitations also, the figures presented in this paper do not contain results from all the test cases. It is to be noted also that there are no results reported for cases E410 using ENERGYPLUS and E400, E410, E420, E430, and E440 using CODYRUN.

Outdoor Air Effect

The approach described previously for the simulation of the outdoor air effect in ESP-r/HOT3000 is used first to generate simulation results for cases E330 and E340 and the results are shown in Table 4 and 5.

Table 4: ESP-r/HOT3000 predictions of annual electricity consumptions for cases E320 – E340 with original modeling approach of outdoor air effects

Cases	Electricity Consumption (kWh)		
	Total	Compressor	Compressor Fan
E320	39475	25928	2683
E330	38770	25338	2568
E340	39892	26349	2680

Table 5: ESP-r/HOT3000 predictions of annual coil loads for cases E320 – E340 with original modeling approach of outdoor air effects

Cases	Coil Loads (kWh)			
	Indoor Fan	Total	Sensible Load	Latent Load
E320	10880	97036	62720	34315
E330	10880	94992	58428	36562
E340	10880	99404	61509	37895

These results indicate a decrease in the total and sensible evaporator coil loads for case E330 relative to cases E320 and E340. This is different from all the results from the other simulation programs, which predict an increase in the total and sensible coil loads for case E330 relative to E320 and E340. It can therefore be concluded that the original modeling approach in ESP-r/HOT3000 does not effectively predict the relative differences between simulation results when there is both outdoor air and infiltration present.

The initial approach for modelling outdoor air intake through the HVAC system has since been modified. Its effect on the air-point energy and moisture balance is now accounted for in the same way infiltration is accounted for within the ESP-r/HOT3000 loads module. Outside air is included as another airflow into the conditioned space within the ESP-r/HOT3000 numerical solution scheme, and the moisture removal at the cooling coil is still accounted for in the space moisture balance. The effect of the outside air on the inlet air conditions to the coil is also still accounted for properly. With this modification, the results for case E330 show the same kind of relative differences with cases E320 and E340 as that predicted by the other simulation programs as shown in Tables 6 and 7. This approach for treating outdoor air is then used to generate the results for all the test cases involving the introduction of outdoor air through the HVAC system.

Table 6: ESP-r/HOT3000 predictions of annual electricity consumptions for cases E320 – E340 with modified modeling approach of outdoor air effect

Cases	Electricity Consumption (kWh)		
	Total	Compressor	Compressor Fan
E320	39457	25912	2681
E330	40330	26775	2693
E340	39947	26400	2684

Table 7: ESP-r/HOT3000 predictions of annual coil loads for cases E320 – E340 with modified modeling approach of outdoor air effect

Cases	Coil Loads (kWh)			
	Indoor Fan	Total	Sensible Load	Latent Load
E320	10880	96957	62734	34224
E330	10880	102008	61822	40186
E340	10880	99753	61406	38346

Electricity Consumption

Figure 1 shows the sum of the electricity consumption by the compressor, indoor circulation fan, and outdoor condenser fan. Figure 2 shows the electricity for only the compressor. The results from ESP-r/HOT3000 agree very well with those from the other programs for all the test cases.

Figure 3 shows the peak sum of electricity consumption by the compressor, and indoor and outdoor fan. Again the agreement between results from ESP-r/HOT3000 and from the other programs is good. However, for cases E310 and E520 we notice that the ESP-r/HOT3000 peaks are consistently lower than those predicted from the other programs. For these two cases, there are instances when the total space sensible + latent loads for the time step are very close to the total equipment capacity.

The ESP-r/HOT3000 model sets the maximum controller capacity for the time step equal to the sensible equipment capacity from the previous time step. At this time, the model does not include an iterative process within the time step to update the controller capacity once new space conditions are found for the time step. With the current model, it is therefore possible to have an actual sensible space load for the time step that is slightly higher than the present sensible equipment capacity. When this happens, the model reduces the sensible load and sets it equal to the equipment sensible capacity for the time step, set equal to the capacity from the previous time step, which explains the lower peak consumptions observed in these cases. The effect of this modeling approach, on the results, can be reduced by using a smaller simulation time step in ESP-r/HOT3000 than the 15-minute time step used to generate the results in this paper.

Figure 4 shows the hourly variation of the total electricity for June 28 predicted by all the simulation tools.

Coil Loads

Figures 5 and 6 show the total coil load and the sensible coil load. Again, the agreement between ESP-r/HOT3000 and the other programs is very good. Figure 7 shows the variation of the coil total load on June 28th.

Space Conditions

The test suite also contains results for minimum, maximum, and average values for the space temperature, humidity ratio, and relative humidity. In this case the agreement between ESP-r/HOT3000 and the other programs is good with few exceptions. Most of the remaining disagreements for these cases are related to the results for E500 to E545. For these cases, the zone average and minimum dry bulb temperature predicted by ESP-r/HOT3000 are higher than those from the other programs. This can be attributed to the fact that the building shell is specified as adiabatic in the ESP-r/HOT3000 models for the test cases instead of having a large thermal resistance as is the case for the other simulation programs. This assumption is expected to have an effect on the predicted zone conditions for test cases E500 to E545 because they have no internal gains during the colder months of the year. It is also found that the maximum zone temperature for case E520 predicted by ESP-r/HOT3000 is higher than in the case of the other programs. It is very possible that this is also due to the fact that the sensible capacity of the controller for a certain time step is taken equal to the sensible equipment capacity calculated at the conditions from the previous time step. The effect of this can also be reduced through the use of a smaller time step.

CONCLUSIONS

The unitary air-conditioning model in ESP-r/HOT3000 is validated using the IEA cooling test cases E300-E545. The simulation results of ESP-r/HOT3000 are compared to those from four other programs. It is found that the results from ESP-r/HOT3000 agree very well with those from the other tools. The remaining disagreement can be attributed to: the fact that the model created in ESP-r/HOT3000 assumes that the building shell is adiabatic instead of having a large thermal resistance as specified in the test specifications; as well as the fact that the temperature controller sensible capacity for a given time step is set in ESP-r/HOT3000 equal to the sensible equipment capacity from the previous time step. The effect of this latter modeling approach can be further reduced by using a smaller simulation time step than that used in this study.

Initial results for cases with outdoor air and infiltration revealed that the original implementation of the model in ESP-r/HOT3000 did not properly account for the effect of outdoor air. This implementation was modified and the new predicted results agree much better with those from the other simulation tools. The application of the IEA test suite to the ESP-r/HOT3000 model helps to increase the confidence in the fundamental basis and the implementation of this model. In addition, these tests can be a very effective tool for identifying potential problems with simulation models. However, more work still needs to be done to expand the suite of test cases for the validation of cooling models. Other test cases can be used to validate models for moisture evaporation from the cooling coil back into the air stream when the compressor is off and the circulation fan is in continuous mode. In addition, test cases are needed for the validation of models for multi-speed air-conditioners, and the interaction of the air-conditioner with the air-delivery system for a multi-zone building.

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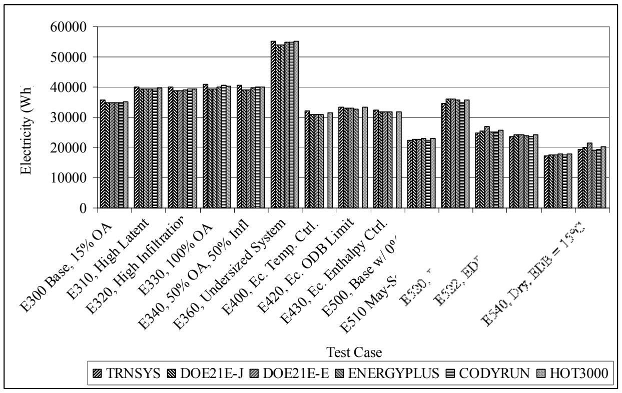

Figure 1: Total electricity consumption

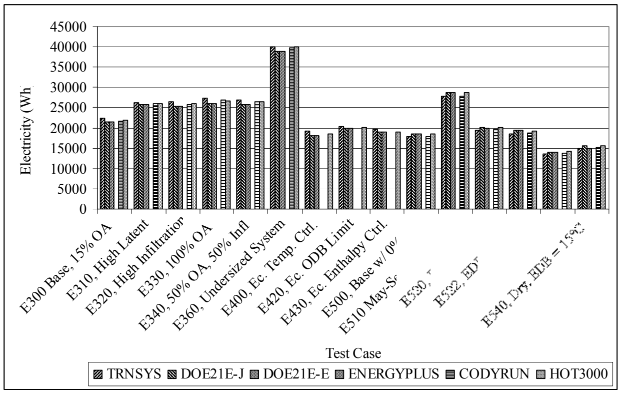

Figure 2: Total compressor electricity consumption

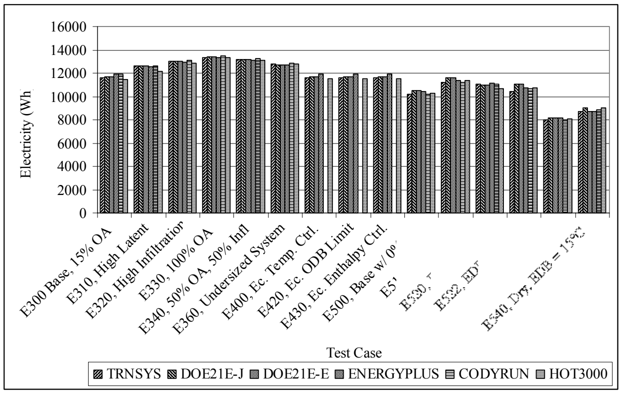

Figure 3: Peak total electricity consumption

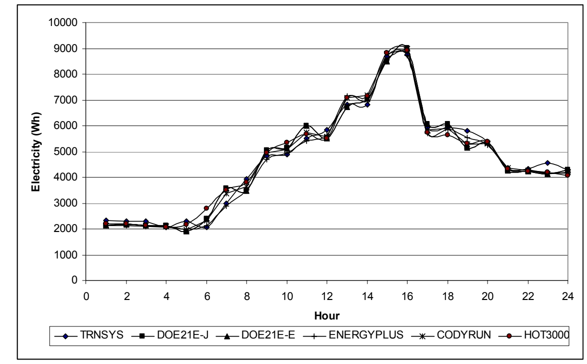

Figure 4: Hourly variation of total electricity consumption for June 28th

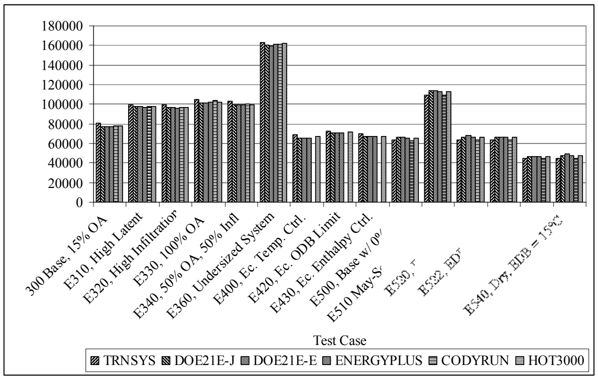

Figure 5: Total coil load (sensible + latent)

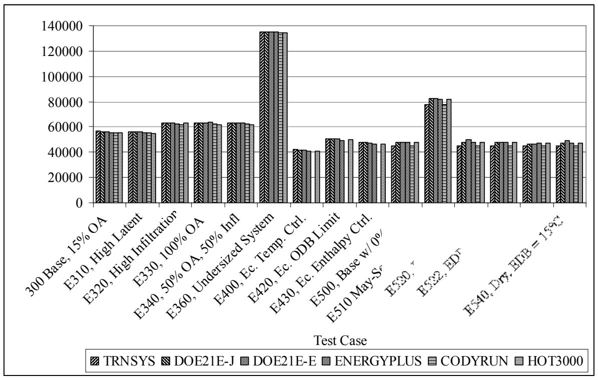

Figure 6: Total sensible coil load

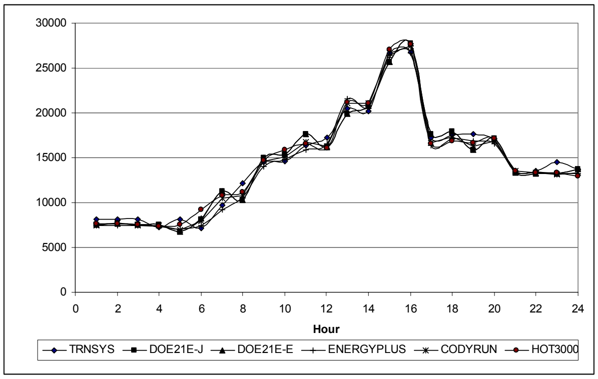

Figure 7: Hourly Variation of the total coil load for June 28th