BETSRG Report 2002-1

September 2002

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Executive Summary

Two separate parts have been included in this report. The first part covers the documentation of three analytical verification tests developed for multi-zone control models in whole building energy simulation programs. These three tests are: the master-slave ideal control test; the master-slave VAV control test; the master-slave on-off control test. (The master-slave zone control refers to any situation where a thermostat in one zone controls the heating or cooling provided to other zones. The zone containing the central thermostat is the "master" zone, and the other zones are called "slave" zones. This situation is of particular interest for residential building simulation.)

The second part of this report covers our analytical testing results of ESP-r and EnergyPlus program. The tests consist of single zone tests and multi-zone tests. The single zone tests include most of the analytical tests in the ASHRAE 1052-RP test suite (Spitler, et al. 2001). The multi-zone tests include six tests extended from the 1052-RP single zone tests to cover inter-zone heat transfer and inter-zone airflow, and the three master-slave zone control tests for which the documentation is given in the first part of this report.

References

Spitler, J.D., S.J. Rees, D. Xiao. 2001. *Development of an analytical verification test suite for whole building energy simulation programs – building fabric (1052-RP): Final Report*, ASHRAE, Atlanta GA.

Contents

Documentation of the Analytical Verification Tests for Multi-zone Control Models in Whole Building Energy Simulation Programs 1

Test MSIdealCon: Master-slave zone control – Ideal control ... 2
Test MSVAVCon: Master-slave zone VAV control 7
Test MSOnOffCon: Master-slave zone on-off control 14

Analytical Testing Results of ESP-r and EnergyPlus 22

ESP-r Analytical Testing Results 23

EnergyPlus Analytical Testing Results 97

Documentation of the Analytical Verification Tests for Multi-zone Control Models in Whole Building Energy Simulation Programs

Test MSIdealCon: Master-slave zone control – Ideal control

Objective

The objective of this test is to find the response in the air temperature of one zone (the slave zone) when the air temperature in the other zone (the master zone) is maintained at a constant with an ideal system. This ideal system will supply the same amount of heat input as needed by the master zone to the slave zone. In another word, the dry bulb air temperature of the master zone will control the output of the ideal system. The slave zone, with zone load different from that of the master zone, will show different effects on the air temperature under this type of system control.

Analytical Model

The analytical solution is based on the steady state heat balance of the zone air and the steady state outside-inside convection through the exterior wall. It is assumed that the exterior wall has no thermal mass and its conductivity is very high so that it will have a uniform temperature. The exterior wall will have convective boundary conditions on either side. Convection is modeled as a fixed resistance between the surface and the adjacent air. The zone loads are made different by supplying different convective heat gain to the master and slave zone. The ideal system will supply whatever heat input the master zone needs to maintain a constant air temperature. The same amount of system heat input as to the master zone will be supplied to the slave zone simultaneously.

The difference in the zone loads should be reflected on the zone air temperatures. The master zone, with whatever heat input it needs to maintain a set point, will have a constant air temperature. The slave zone, under the ideal system controlled by the master zone air temperature, will show swings in the zone air temperature rather than maintain the set point.

Zone Description

The test zone geometry is two cubes with internal dimensions 3×3×3m. These two cubes have all mass-less adiabatic walls except that each has one exterior mass-less wall. The exterior surface may be selected to be any of the six surfaces of the zone, as any surface should have the same response. In other words, the user may wish to test the response of the ceiling or the floor in the same way as the walls. No windows are present in this test.

The effects of solar irradiation, long wave radiation, infiltration and radiative internal gains must be eliminated in this test. This can normally be achieved by setting suitable surface properties and by setting infiltration rate and radiative internal gains to zero. Zone orientation and other location parameters are also irrelevant in this test.

Different convective heat gains will be supplied to the two cubes. The zone air temperature in one of the cube (the master zone) will be maintained at a constant by an ideal system. The ideal system will also supply the same amount of heat input the master zone needs to the other cube (the slave zone).

Test Parameters

The user, when calculating the response, is able to set convection coefficients for both sides of the exterior wall. These coefficients have to be taken as constant coefficients. In addition, the intended inside air temperature of the master zone needs to be specified. The user is also able to schedule the outside air temperature and the convective heat gains for both zones for each hour of the simulation day. The scheduled hourly data will be put in an input file. To deal with sub-hourly short time step in the simulation, the user may need to set the time step too.

Test Output

The principle data of interest in this test are the predicted system heat output and the air temperatures of both zones. These data are listed in the analytical response data file along with the input data.

Test Results

The tabulated results included below have been produced with the following test parameters shown in Table MSIdealCon-A and Figure MSIdealCon-A. The analytical solution for these parameters is plotted in MSIdealCon-B. Tabulated results are presented in Table MSIdealCon-B.

Table MSIdealCon - A
Test parameters used in generating the tabulated results

Test Parameter	**Value**	**Units**
Master zone air set point	20.0	C
Exterior convection coefficient	12.5	$W/m^2.K$
Interior convection coefficient	3.1	$W/m^2.K$
Time step	60	Min/step
External air temperature	As shown in Figure MSIdealCon-B	C
Master zone convective heat gain	As shown in Figure MSIdealCon-A	W
Slave zone convective heat gain	As shown in Figure MSIdealCon-A	W

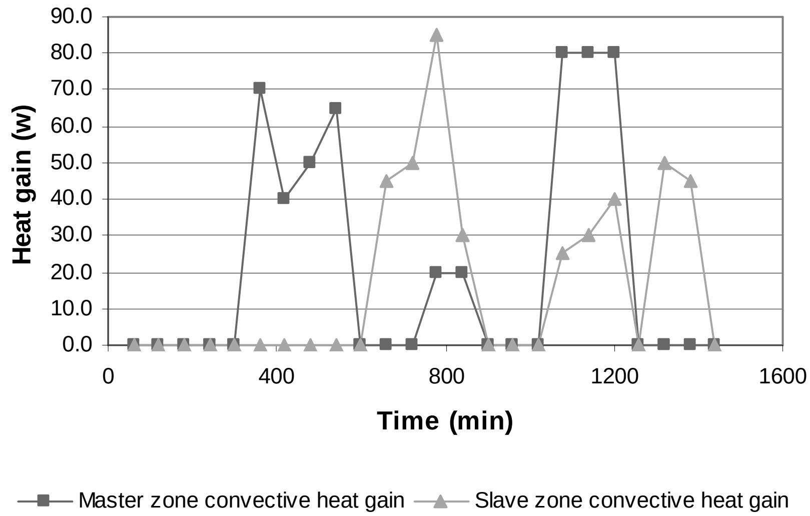


Figure MSIdealCon -A: Convective heat gain to the test zones

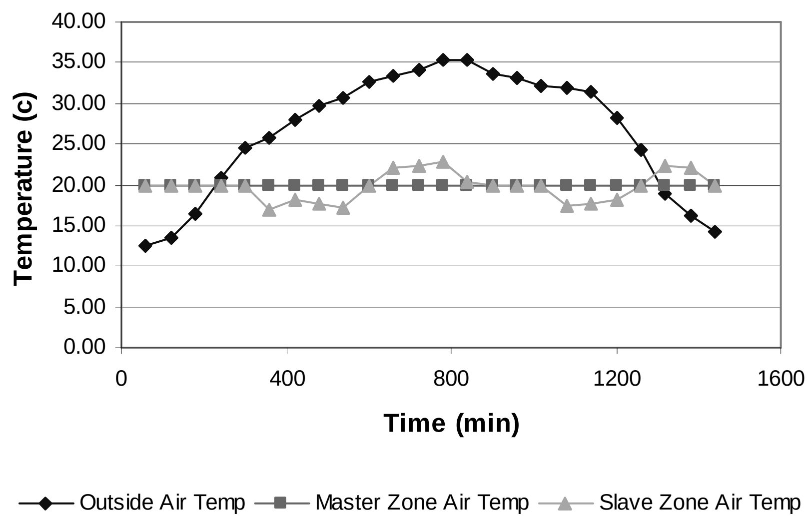


Figure MSIdealCon -B: The analytical solution for the parameters in Table MSIdealCon -A

Table MSIdealCon-B
Tabulated values of the analytical solution computed using the parameters in Table MSIdealCon -A

Time (min)	Outside Air Temp (c)	Master zone convective heat gain (w)	Slave zone convective heat gain (w)	Master Zone Air Temp (c)	Slave Zone Air Temp (c)	Ideal system heat input into each zone (w)
60	12.50	0.0	0.0	20.00	20.00	167.7
120	13.60	0.0	0.0	20.00	20.00	143.1

180	16.50	0.0	0.0	20.00	20.00	78.2
240	20.80	0.0	0.0	20.00	20.00	-17.9
300	24.60	0.0	0.0	20.00	20.00	-102.8
360	25.80	70.0	0.0	20.00	16.87	-199.7
420	27.90	40.0	0.0	20.00	18.21	-216.6
480	29.80	50.0	0.0	20.00	17.76	-269.1
540	30.60	65.0	0.0	20.00	17.09	-302.0
600	32.70	0.0	0.0	20.00	20.00	-283.9
660	33.40	0.0	45.0	20.00	22.01	-299.6
720	34.20	0.0	50.0	20.00	22.24	-317.5
780	35.40	20.0	85.0	20.00	22.91	-364.3
840	35.30	20.0	30.0	20.00	20.45	-362.0
900	33.50	0.0	0.0	20.00	20.00	-301.8
960	33.20	0.0	0.0	20.00	20.00	-295.1
1020	32.10	0.0	0.0	20.00	20.00	-270.5
1080	31.80	80.0	25.0	20.00	17.54	-343.8
1140	31.40	80.0	30.0	20.00	17.76	-334.9
1200	28.20	80.0	40.0	20.00	18.21	-263.3
1260	24.20	0.0	0.0	20.00	20.00	-93.9
1320	19.00	0.0	50.0	20.00	22.24	22.4
1380	16.30	0.0	45.0	20.00	22.01	82.7
1440	14.20	0.0	0.0	20.00	20.00	129.7

Analytical Solution

The analytical solution used in this test is based on the heat balance for the zone air and the convective heat transfer through the exterior wall for both the master and slave zones. For the master zone, the zone air heat balance equation is:

$$q''_{sys} + q''_{conv,im} + q''_{conv,em} = 0 \qquad \text{(MSIdealCon-1)}$$

where,

$q''_{sys} =$ the system heat input to maintain the master zone set point, W

$q''_{conv,im} =$ the convective internal heat gain to the master zone, W

$q''_{conv,em} =$ the master zone convective heat transfer through the exterior wall, W

Since the exterior wall is assumed to have no thermal mass and its conductivity is very high, its conduction thermal resistance can be ignored. The steady state inside-outside convective heat transfer in the master zone then is:

$$q''_{conv,em} = \frac{A\left(T_{ao} - T_{ai,m}\right)}{\frac{1}{h_o} + \frac{1}{h_i}} \qquad \text{(MSIdealCon-2)}$$

Where,

$T_{ao} =$ outside air temperature, C

$T_{ai,m} =$ master zone inside air temperature, C

$A =$ surface area of the exterior wall, m^2

$h_o =$ outside convection coefficient, W/m^{2}K

$h_i =$ inside convection coefficient, W/m^{2}K

Substitute Eq. (MSIdealCon-2) into (MSIdealCon-1) and solve for the system heat input to get:

$$q''_{sys} = -q''_{conv,im} - \frac{A\left(T_{ao} - T_{ai,m}\right)}{\frac{1}{h_o} + \frac{1}{h_i}} \quad \text{(MSIdealCon-3)}$$

Similarly for the slave zone, the zone air heat balance equation is:

$$q''_{sys} + q''_{conv,is} + q''_{conv,es} = 0 \quad \text{(MSIdealCon-4)}$$

where,

$q''_{conv,is} =$ the convective internal heat gain to the slave zone, W

$q''_{conv,es} =$ the slave zone convective heat transfer through the exterior wall, W

The steady state inside-outside convective heat transfer in the slave zone is:

$$q''_{conv,es} = \frac{A\left(T_{ao} - T_{ai,s}\right)}{\frac{1}{h_o} + \frac{1}{h_i}} \quad \text{(MSIdealCon-5)}$$

Where,

$T_{ai,s} =$ slave zone inside air temperature, C

Substitute Eq. (MSIdealCon-5) into (MSIdealCon-4) and solve for the slave zone air temperature to get:

$$T_{ai,s} = T_{ao} + \frac{\left(q''_{sys} + q''_{conv,is}\right)}{A}\left(\frac{1}{h_o} + \frac{1}{h_i}\right) \quad \text{(MSIdealCon-6)}$$

References

McQuiston, F.C., Parker, J.D., and Spitler, J.D. 2000. *Heating, Ventilating, and Air Conditioning Analysis and Design*, Fifth Edition. John Wiley and Sons, New York.

Spitler, J.D., S.J. Rees, D. Xiao. 2001. *Development of an analytical verification test suite for whole building energy simulation programs – building fabric (1052-RP): Final Report*, ASHRAE, Atlanta GA.

Test MSVAVCon: Master-slave zone VAV control

Objective

The objective of this test is to find the response in the air temperature of one zone (the slave zone) when the air temperature in the other zone (the master zone) is maintained at a constant with a variable air volume (VAV) system. The VAV system will adjust the air volume flow rate to the zone to satisfy different zone loads under a fixed system air temperature. The volume flow rate of the system air to the slave zone will equal to the volume flow rate to the master zone multiplied by a user specified constant. The dry bulb air temperature in the master zone will control the adjustment of the system air volume flow rate. The slave zone, with zone load different from that of the master zone, will show different effects on the air temperature under this type of system control.

Analytical Model

With a VAV system control, this test can be designed to use all adiabatic building envelopes. The zone loads are made different by supplying different convective heat gains to the master and slave zone. The analytical solution is then based on the heat balance of the zone air only. Rather than the direct system heat input in the ideal control test, the volume flow rate and temperature of the system air would affect the zone air heat balance this time. The VAV system will adjust the volume flow rate of the system air to maintain a constant air temperature in the master zone. The system air is assumed to be at the same humidity as that of the zone air so that only sensible heat gains from the system air will be considered.

The difference in the zone loads should be reflected on the zone air temperatures. The master zone will maintain its constant set point under the system adjustment. The slave zone, under the system controlled by the master zone air temperature, will show swings on the zone air temperature rather than maintain the set point.

Zone Description

The test zone geometry is two cubes with internal dimensions 3×3×3m. These two cubes have all mass-less adiabatic walls. No windows are present in this test.

The effects of solar irradiation, long wave radiation, infiltration and radiative internal gains must be eliminated in this test. This can normally be achieved by setting suitable surface properties and by setting infiltration rate and radiative internal gains to zero. Zone orientation and other location parameters are also irrelevant in this test.

Different convective heat gains will be supplied to the two cubes. The zone air temperature in one of the cube (the master zone) will be maintained at a constant by the system. The other cube (the slave zone) will accept a volume flow rate of system air under some user specified system air distribution and under the adjustment controlled by the master zone air temperature.

Test Parameters

The user, when calculating the response, will need to specify a fixed system air temperature. Also, a constant multiplier will be specified to multiply the master zone system air volume flow rate to get the slave zone system air volume flow rate.

In addition, the intended air temperature of the master zone and the initial air temperature in the slave zone need to be specified. The user is also able to schedule the convective heat gains for both zones for each hour of a simulation day. The convective heat gains should be properly scheduled so that the system air volume and system air temperature will be in a reasonable range. The scheduled hourly data will be put in an input file. To deal with sub-hourly short time step in the simulation, the user may need to set the time step too.

Test Output

The principle data of interest are the predicted system air volume flow rates sent to each zone and the air temperatures of both zones. These data are listed in the analytical response data file along with the input data.

Test Results

The tabulated results included below have been produced with the following test parameters shown in Table MSVAVCon-A and Figure MSVAVCon-A. The analytical solution for these parameters is plotted in Figure MSVAVCon-B~C for every time step. Tabulated results are presented in Table MSVAVCon-B for every ten time steps.

Table MSVAVCon - A
Test parameters used in generating the tabulated results

Test Parameter	**Value**	**Units**
Master zone air set point	22.0	C
The initial air temperature in the slave zone	17.0	C
The constant multiplier	2.0, 2.5	-
The fixed system air temperature	15	C
Time step	6	Min/step
Convective heat gains to the master and slave zone	As shown in Figure MSVAVCon-A	W

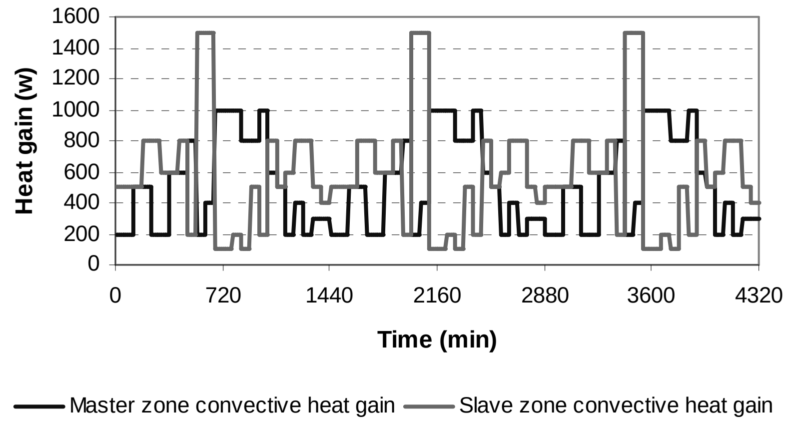


Figure MSVAVCon -A: Convective heat gains to the test zones

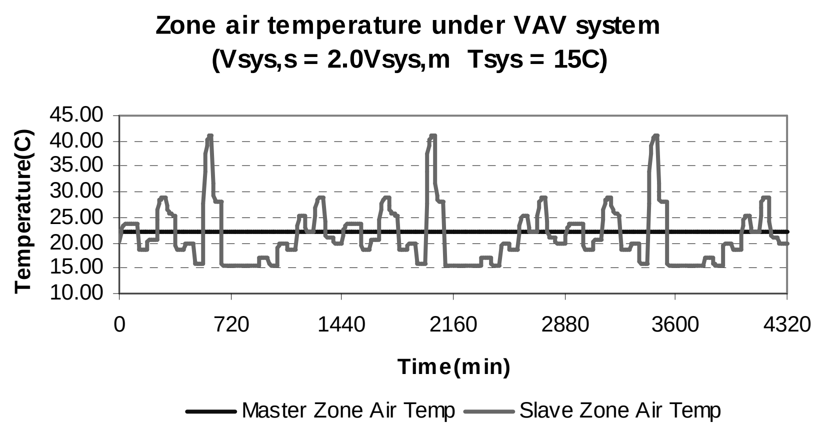


Figure MSVAVCon -B: The analytical solution for the parameters in Table MSVAVCon –A (plotted for every time step)

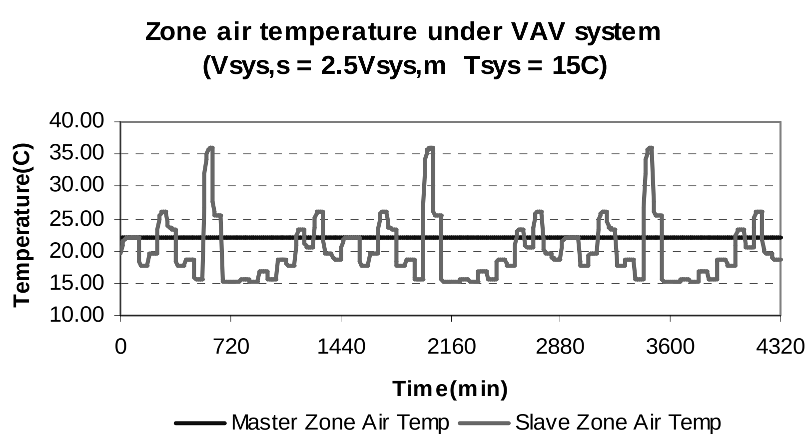


Figure MSVAVCon -C: The analytical solution for the parameters in Table MSVAVCon –A (plotted for every time step)

Table MSVAVCon-B
Tabulated values of the analytical solution computed using the parameters in Table MSVAVCon –A (tabulated every ten steps)

			Constant multiplier = 2.0				Constant multiplier = 2.5			
Time (min)	Master zone convective heat gain (w)	Slave zone convective heat gain (w)	Master Zone Air Temp (c)	Slave Zone Air Temp (c)	Master zone system air volume flow rate (m^3/s)	Slave zone system air volume flow rate (m^3/s)	Master Zone Air Temp (c)	Slave Zone Air Temp (c)	Master zone system air volume flow rate (m^3/s)	Slave zone system air volume flow rate (m^3/s)
60	200	500	22.00	23.74	0.0237	0.0474	22.00	22.00	0.0237	0.0592
120	200	500	22.00	23.75	0.0237	0.0474	22.00	22.00	0.0237	0.0592
180	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
240	500	800	22.00	20.60	0.0592	0.1185	22.00	19.48	0.0592	0.1481
300	200	800	22.00	28.98	0.0237	0.0474	22.00	26.20	0.0237	0.0592
360	200	600	22.00	25.51	0.0237	0.0474	22.00	23.40	0.0237	0.0592
420	600	600	22.00	18.50	0.0711	0.1421	22.00	17.80	0.0711	0.1777
480	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
540	800	200	22.00	15.88	0.0948	0.1895	22.00	15.70	0.0948	0.2369
600	200	1500	22.00	41.20	0.0237	0.0474	22.00	35.99	0.0237	0.0592
660	400	1500	22.00	28.13	0.0474	0.0948	22.00	25.50	0.0474	0.1185
720	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
780	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
840	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
900	800	100	22.00	15.44	0.0948	0.1895	22.00	15.35	0.0948	0.2369
960	800	500	22.00	17.19	0.0948	0.1895	22.00	16.75	0.0948	0.2369
1020	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
1080	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
1140	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
1200	200	600	22.00	25.49	0.0237	0.0474	22.00	23.40	0.0237	0.0592
1260	400	800	22.00	22.00	0.0474	0.0948	22.00	20.60	0.0474	0.1185
1320	200	800	22.00	28.99	0.0237	0.0474	22.00	26.20	0.0237	0.0592
1380	300	500	22.00	20.83	0.0355	0.0711	22.00	19.67	0.0355	0.0888
1440	300	400	22.00	19.67	0.0355	0.0711	22.00	18.73	0.0355	0.0888
1500	200	500	22.00	23.74	0.0237	0.0474	22.00	22.00	0.0237	0.0592
1560	200	500	22.00	23.75	0.0237	0.0474	22.00	22.00	0.0237	0.0592
1620	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
1680	500	800	22.00	20.60	0.0592	0.1185	22.00	19.48	0.0592	0.1481
1740	200	800	22.00	28.98	0.0237	0.0474	22.00	26.20	0.0237	0.0592
1800	200	600	22.00	25.51	0.0237	0.0474	22.00	23.40	0.0237	0.0592
1860	600	600	22.00	18.50	0.0711	0.1421	22.00	17.80	0.0711	0.1777
1920	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
1980	800	200	22.00	15.88	0.0948	0.1895	22.00	15.70	0.0948	0.2369
2040	200	1500	22.00	41.20	0.0237	0.0474	22.00	35.99	0.0237	0.0592
2100	400	1500	22.00	28.13	0.0474	0.0948	22.00	25.50	0.0474	0.1185
2160	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
2220	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
2280	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
2340	800	100	22.00	15.44	0.0948	0.1895	22.00	15.35	0.0948	0.2369
2400	800	500	22.00	17.19	0.0948	0.1895	22.00	16.75	0.0948	0.2369

2460	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
2520	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
2580	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
2640	200	600	22.00	25.49	0.0237	0.0474	22.00	23.40	0.0237	0.0592
2700	400	800	22.00	22.00	0.0474	0.0948	22.00	20.60	0.0474	0.1185
2760	200	800	22.00	28.99	0.0237	0.0474	22.00	26.20	0.0237	0.0592
2820	300	500	22.00	20.83	0.0355	0.0711	22.00	19.67	0.0355	0.0888
2880	300	400	22.00	19.67	0.0355	0.0711	22.00	18.73	0.0355	0.0888
2940	200	500	22.00	23.74	0.0237	0.0474	22.00	22.00	0.0237	0.0592
3000	200	500	22.00	23.75	0.0237	0.0474	22.00	22.00	0.0237	0.0592
3060	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
3120	500	800	22.00	20.60	0.0592	0.1185	22.00	19.48	0.0592	0.1481
3180	200	800	22.00	28.98	0.0237	0.0474	22.00	26.20	0.0237	0.0592
3240	200	600	22.00	25.51	0.0237	0.0474	22.00	23.40	0.0237	0.0592
3300	600	600	22.00	18.50	0.0711	0.1421	22.00	17.80	0.0711	0.1777
3360	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
3420	800	200	22.00	15.88	0.0948	0.1895	22.00	15.70	0.0948	0.2369
3480	200	1500	22.00	41.20	0.0237	0.0474	22.00	35.99	0.0237	0.0592
3540	400	1500	22.00	28.13	0.0474	0.0948	22.00	25.50	0.0474	0.1185
3600	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
3660	1000	100	22.00	15.35	0.1185	0.2369	22.00	15.28	0.1185	0.2961
3720	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
3780	800	100	22.00	15.44	0.0948	0.1895	22.00	15.35	0.0948	0.2369
3840	800	500	22.00	17.19	0.0948	0.1895	22.00	16.75	0.0948	0.2369
3900	1000	200	22.00	15.70	0.1185	0.2369	22.00	15.56	0.1185	0.2961
3960	600	800	22.00	19.67	0.0711	0.1421	22.00	18.73	0.0711	0.1777
4020	500	500	22.00	18.50	0.0592	0.1185	22.00	17.80	0.0592	0.1481
4080	200	600	22.00	25.49	0.0237	0.0474	22.00	23.40	0.0237	0.0592
4140	400	800	22.00	22.00	0.0474	0.0948	22.00	20.60	0.0474	0.1185
4200	200	800	22.00	28.99	0.0237	0.0474	22.00	26.20	0.0237	0.0592
4260	300	500	22.00	20.83	0.0355	0.0711	22.00	19.67	0.0355	0.0888
4320	300	400	22.00	19.67	0.0355	0.0711	22.00	18.73	0.0355	0.0888

Analytical Solution

The analytical solution used in this test is based on the heat balance for the zone air. Assume the system air flows into a zone is well mixed with the zone air before it flows out, the heat balance equation for the zone air is:

$$q''_{conv,i} + \dot{m}_{sys} C_{pa} T_{sys} = M_z C_{pa} \frac{dT_z}{dt} + \dot{m}_{sys} C_{pa} T_z \qquad \text{(MSVAVCon-1)}$$

where,

$q''_{conv,i} =$ the internal convective heat gain of the zone, W

$\dot{m}_{sys}$ = the mass flow rate of the system air, kg/s; $\dot{m}_{sys} = \rho_{air} v_{sys}$

$\rho_{air} =$ the density of the air, kg/m^3

$v_{sys} =$ the volume flow rate of the system air, m^3/s

M_z = the mass of the zone air, kg; $M_z = \rho_{air} V_z$
$V_z =$ the volume of the zone, 27.0 m^3
$C_{pa} =$ the specific heat capacity of the air, J/kg.K
$T_{sys} =$ the system air temperature, C
$T_z =$ the zone air temperature, C
$t =$ the time, s

Eq. (MSVAVCon-1) can be rewritten as:

$$\frac{dT_z}{dt} + \frac{\dot{m}_{sys}}{M_z} T_z = \frac{q^{"}_{conv,i} + \dot{m}_{sys} C_{pa} T_{sys}}{M_z C_{pa}} \quad \text{(MSVAVCon-2)}$$

In an appropriately short simulation time step, during which the system air temperature and flow rate can be considered as a constant, Eq. (MSVAVCon-2) is a first order ordinary differential equation with respect to the zone air temperature.

For the master zone, the zone air temperature will be maintained at a constant set point, therefore $\frac{dT_{zm}}{dt} = 0$ and its zone air heat balance equation can be simplified to:

$$\frac{\dot{m}_{sys,m}}{M_{zm}} T_{zm} = \frac{q^{"}_{conv,im} + \dot{m}_{sys,m} C_{pa} T_{sys}}{M_{zm} C_{pa}} \quad \text{(MSVAVCon-3)}$$

where,

$q^{"}_{conv,im} =$ the internal convective heat gain to the master zone, W
$\dot{m}_{sys,m}$ = the mass flow rate of the system air to the master zone, kg/s;
and $\dot{m}_{sys,m} = \rho_{air} v_{sys,m}$
$v_{sys,m} =$ the volume flow rate of the system air to the master zone, m^3/s
M_{zm} = the mass of the master zone air, kg; $M_{zm} = \rho_{air} V_{zm}$
$V_{zm} =$ the volume of the master zone, 27.0 m^3
$T_{zm} =$ the master zone air temperature, C

For the slave zone, the air temperature will float since the system is controlled by the thermostat in the master zone. Eq. (MSVAVCon-2) therefore cannot be simplified and have to be written for the slave zone as:

$$\frac{dT_{zs}}{dt} + \frac{\dot{m}_{sys,s}}{M_{zs}} T_{zs} = \frac{q^{"}_{conv,is} + \dot{m}_{sys,s} C_{pa} T_{sys}}{M_{zs} C_{pa}} \quad \text{(MSVAVCon-4)}$$

where,

$q^{"}_{conv,is} =$ the convective heat input to the slave zone, W
$\dot{m}_{sys,s}$ = the mass flow rate of the system air to the slave zone, kg/s;
and $\dot{m}_{sys,s} = \rho_{air} v_{sys,s}$
$v_{sys,s} =$ the volume flow rate of the system air to the slave zone, m^3/s;

and $v_{sys,s} = \alpha v_{sys,m}$

$\alpha =$ the constant multiplier to get $v_{sys,s}$ from $v_{sys,m}$

$M_{zs} =$ the mass of the slave zone air, kg; $M_{zs} = \rho_{air} V_{zs}$

$V_{zs} =$ the volume of the slave zone, 27.0 m^3

$T_{zs} =$ the slave zone air temperature, C

Multiply both sides of Eq. (MSVAVCon-4) by $e^{\frac{\dot{m}_{sys,s}}{M_{zs}}t}$ and integrate from *0* to *t* to get the slave zone air temperature as:

$$T_{zs}(t) = EXP\left(-\frac{\dot{m}_{sys,s}}{M_{zs}}t\right)\left\{\frac{q''_{conv,is} + \dot{m}_{sys,s}C_{pa}T_{sys}}{\dot{m}_{sys,s}C_{pa}}\left[EXP\left(\frac{\dot{m}_{sys,s}}{M_{zs}}t\right)-1\right] + T_{zs}(0)\right\}$$

(MSVAVCon-5)

where,

$T_{zs}(t) =$ the slave zone air temperature at time *t*, C

$T_{zs}(0) =$ the slave zone air temperature at time *0*, C

In the case of variable air volume system, Eq. (MSVAVCon-3) can be solved for the system air mass flow rate to the master zone as:

$$\dot{m}_{sys,m} = \frac{q''_{conv,im}}{c_{pa}\left(T_{zm} - T_{sys}\right)} \quad \text{(MSVAVCon-6)}$$

Eq. (MSVAVCon-6) can then be substituted into Eq. (MSVAVCon-5) to solve for the slave zone air temperature. Note that $\dot{m}_{sys,s} = \alpha \dot{m}_{sys,m}$ and T_{sys} will be a fixed known value specified by the user.

References

McQuiston, F.C., Parker, J.D., and Spitler, J.D. 2000. *Heating, Ventilating, and Air Conditioning Analysis and Design*, Fifth Edition. John Wiley and Sons, New York.

Spitler, J.D., S.J. Rees, D. Xiao. 2001. Development of an analytical verification test suite for whole building energy simulation programs – building fabric (1052-RP): Final Report, ASHRAE, Atlanta GA.

Test MSOnOffCon: Master-slave zone on-off control

Objective

The objective of this test is to find the response in the air temperature of one zone (the slave zone) when the air temperature in the other zone (the master zone) is maintained at a constant with an on-off controlled constant air volume system. The volume flow rate of the system air to the slave zone will equal to the volume flow rate to the master zone multiplied by a user specified constant. The system will turn on and turn off based on the dry bulb temperature in the master zone. The slave zone, with zone load different from that of the master zone, will show different effects on the air temperature under this type of system control.

Analytical Model

The test is designed to use all adiabatic building envelopes. The zone loads are made different by supplying different convective heat gains to the master and slave zone. The analytical solution is then based on the heat balance of the zone air only. Rather than the direct system heat input in the ideal control test, the volume flow rate and temperature of the system air would affect the zone air heat balance this time. With a dead band range, the system will turn on and turn off to maintain a constant air temperature in the master zone. The system air is assumed to be at the same humidity as that of the zone air so that only sensible heat gains from the system air will be considered.

The difference in the zone loads should be reflected on the zone air temperatures. The master zone will maintain its constant set point under the system adjustment. The slave zone, under the system controlled by the master zone air temperature, will show swings on the zone air temperature rather than maintain the set point.

Zone Description

The test zone geometry is two cubes with internal dimensions 3×3×3m. These two cubes have all mass-less adiabatic walls. No windows are present in this test.

The effects of solar irradiation, long wave radiation, infiltration and radiative internal gains must be eliminated in this test. This can normally be achieved by setting suitable surface properties and by setting infiltration rate and radiative internal gains to zero. Zone orientation and other location parameters are also irrelevant in this test.

Different convective heat gains will be supplied to the two cubes. The zone air temperature in one of the cube (the master zone) will be maintained at a constant by the system. The other cube (the slave zone) will accept a volume flow rate of system air under some user specified system air distribution and under the adjustment controlled by the master zone air temperature.

Test Parameters

The user, when calculating the response, will need to specify a fixed system air temperature and a fixed system air volume flow rate to the master zone. Also, a constant multiplier will be specified to multiply the master zone system air volume flow rate to get the slave zone system air volume flow rate.

In addition, the master zone set point, dead band range, and the initial air temperature of both zones need to be specified. The user is also able to schedule the convective heat gains for both zones for each hour of a simulation day. The convective heat gains should be properly scheduled so that the system air volume and system air temperature will be in a reasonable range. The scheduled hourly data will be put in an input file. To deal with sub-hourly short time step in the simulation, the user may need to set the time step too.

Test Output

The principle data of interest are the predicted system air volume flow rates sent to each zone and the air temperatures of both zones. These data are listed in the analytical response data file along with the input data.

Test Results

The tabulated results included below have been produced with the following test parameters shown in Table MSOnOffCon-A and Figure MSOnOffCon-A. The analytical solution for these parameters is plotted in Figure MSOnOffCon-B every ten time steps and tabulated in Table MSOnOffCon-B for every hundred time steps.

Table MSOnOffCon - A
Test parameters used in generating the tabulated results

Test Parameter	Value	Units
Master zone air set point	22.0	C
Dead band range	±0.1	C
The initial air temperature of both zones	17.0	C
The fixed system air temperature	15	C
The fixed system air volume flow rate to the master zone	0.1184	M^3/s
The constant multiplier	1.2	-
Time step	6	Second/step
Convective heat gains to the master and slave zone	As shown in Figure MSOnOffCon-A	W

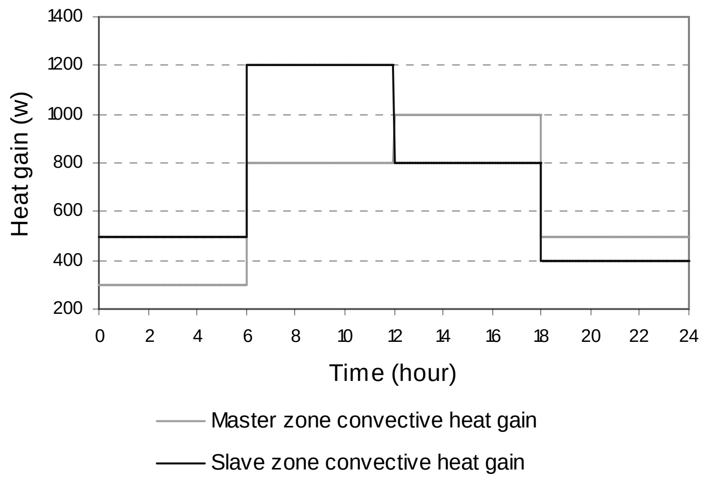


Figure MSOnOffCon -A: Convective heat gains to the test zones

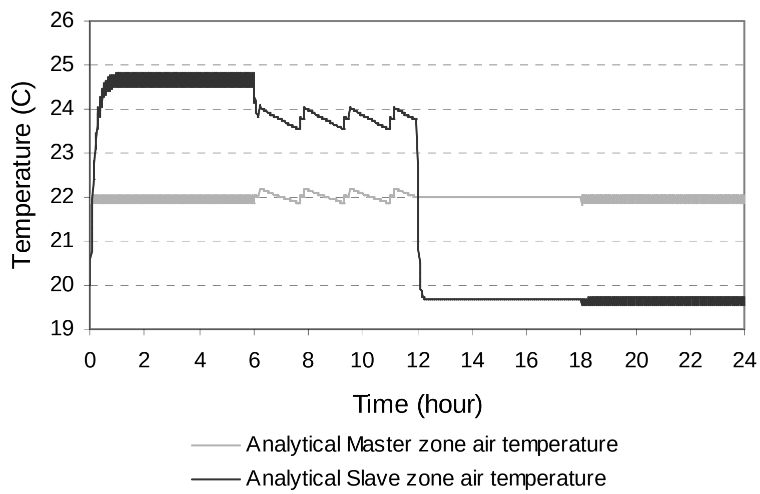


Figure MSOnOffCon -B: The analytical solution for the parameters in Table MSOnOffCon – A (plotted for every ten time step)

Table MSOnOffCon-B

Tabulated values of the analytical solution computed using the parameters in Table MSOnOffCon –A (tabulated every hundred steps)

Time (Seconds)	Master zone convective heat gain (W)	Slave zone convective heat gain (W)	Master Zone Air Temp (C)	Slave Zone Air Temp (C)	Master zone system air volume flow rate (m^3/s)	Slave zone system air volume flow rate (m^3/s)
600	300	500	22.0557	22.8386	0	0
1200	300	500	22.0575	24.0515	0	0
1800	300	500	22.0584	24.5219	0	0
2400	300	500	22.0587	24.7043	0	0

3000	300	500	22.0589	24.7750	0	0
3600	300	500	22.0590	24.8025	0	0
4200	300	500	22.0590	24.8131	0	0
4800	300	500	22.0590	24.8173	0	0
5400	300	500	22.0590	24.8189	0	0
6000	300	500	22.0590	24.8195	0	0
6600	300	500	22.0590	24.8197	0	0
7200	300	500	22.0590	24.8198	0	0
7800	300	500	22.0590	24.8198	0	0
8400	300	500	22.0590	24.8199	0	0
9000	300	500	22.0590	24.8199	0	0
9600	300	500	22.0590	24.8199	0	0
10200	300	500	22.0590	24.8199	0	0
10800	300	500	22.0590	24.8199	0	0
11400	300	500	22.0590	24.8199	0	0
12000	300	500	22.0590	24.8199	0	0
12600	300	500	22.0590	24.8199	0	0
13200	300	500	22.0590	24.8199	0	0
13800	300	500	22.0590	24.8199	0	0
14400	300	500	22.0590	24.8199	0	0
15000	300	500	22.0590	24.8199	0	0
15600	300	500	22.0590	24.8199	0	0
16200	300	500	22.0590	24.8199	0	0
16800	300	500	22.0590	24.8199	0	0
17400	300	500	22.0590	24.8199	0	0
18000	300	500	22.0590	24.8199	0	0
18600	300	500	22.0590	24.8199	0	0
19200	300	500	22.0590	24.8199	0	0
19800	300	500	22.0590	24.8199	0	0
20400	300	500	22.0590	24.8199	0	0
21000	300	500	22.0590	24.8199	0	0
21600	300	500	22.0590	24.8199	0	0
22200	800	1200	22.0172	23.8512	0	0
22800	800	1200	22.1646	24.0002	0	0
23400	800	1200	22.1241	23.9323	0.1184	0.14208
24000	800	1200	22.0846	23.8719	0.1184	0.14208
24600	800	1200	22.0461	23.8138	0.1184	0.14208
25200	800	1200	22.0086	23.7575	0.1184	0.14208
25800	800	1200	21.9721	23.7030	0.1184	0.14208
26400	800	1200	21.9365	23.6502	0.1184	0.14208
27000	800	1200	21.9019	23.5990	0.1184	0.14208
27600	800	1200	21.8681	23.5494	0.1184	0.14208
28200	800	1200	22.0156	23.7705	0	0
28800	800	1200	22.1630	23.9916	0	0
29400	800	1200	22.1225	23.9298	0.1184	0.14208
30000	800	1200	22.0830	23.8700	0.1184	0.14208

30600	800	1200	22.0445	23.8119	0.1184	0.14208
31200	800	1200	22.0071	23.7557	0.1184	0.14208
31800	800	1200	21.9706	23.7013	0.1184	0.14208
32400	800	1200	21.9351	23.6485	0.1184	0.14208
33000	800	1200	21.9005	23.5974	0.1184	0.14208
33600	800	1200	21.8668	23.5478	0.1184	0.14208
34200	800	1200	22.0142	23.7689	0	0
34800	800	1200	22.1616	23.9900	0	0
35400	800	1200	22.1211	23.9283	0.1184	0.14208
36000	800	1200	22.0817	23.8685	0.1184	0.14208
36600	800	1200	22.0433	23.8105	0.1184	0.14208
37200	800	1200	22.0059	23.7543	0.1184	0.14208
37800	800	1200	21.9694	23.6999	0.1184	0.14208
38400	800	1200	21.9339	23.6472	0.1184	0.14208
39000	800	1200	21.8994	23.5961	0.1184	0.14208
39600	800	1200	22.0468	23.8172	0	0
40200	800	1200	22.1942	24.0383	0	0
40800	800	1200	22.1529	23.9751	0.1184	0.14208
41400	800	1200	22.1126	23.9138	0.1184	0.14208
42000	800	1200	22.0734	23.8544	0.1184	0.14208
42600	800	1200	22.0352	23.7969	0.1184	0.14208
43200	800	1200	21.9980	23.7411	0.1184	0.14208
43800	1000	800	22.0029	19.8421	0.1184	0.14208
44400	1000	800	22.0032	19.6762	0.1184	0.14208
45000	1000	800	22.0033	19.6692	0.1184	0.14208
45600	1000	800	22.0033	19.6689	0.1184	0.14208
46200	1000	800	22.0033	19.6688	0.1184	0.14208
46800	1000	800	22.0033	19.6688	0.1184	0.14208
47400	1000	800	22.0033	19.6688	0.1184	0.14208
48000	1000	800	22.0033	19.6688	0.1184	0.14208
48600	1000	800	22.0033	19.6688	0.1184	0.14208
49200	1000	800	22.0033	19.6688	0.1184	0.14208
49800	1000	800	22.0033	19.6688	0.1184	0.14208
50400	1000	800	22.0033	19.6688	0.1184	0.14208
51000	1000	800	22.0033	19.6688	0.1184	0.14208
51600	1000	800	22.0033	19.6688	0.1184	0.14208
52200	1000	800	22.0033	19.6688	0.1184	0.14208
52800	1000	800	22.0033	19.6688	0.1184	0.14208
53400	1000	800	22.0033	19.6688	0.1184	0.14208
54000	1000	800	22.0033	19.6688	0.1184	0.14208
54600	1000	800	22.0033	19.6688	0.1184	0.14208
55200	1000	800	22.0033	19.6688	0.1184	0.14208
55800	1000	800	22.0033	19.6688	0.1184	0.14208
56400	1000	800	22.0033	19.6688	0.1184	0.14208
57000	1000	800	22.0033	19.6688	0.1184	0.14208
57600	1000	800	22.0033	19.6688	0.1184	0.14208

58200	1000	800	22.0033	19.6688	0.1184	0.14208
58800	1000	800	22.0033	19.6688	0.1184	0.14208
59400	1000	800	22.0033	19.6688	0.1184	0.14208
60000	1000	800	22.0033	19.6688	0.1184	0.14208
60600	1000	800	22.0033	19.6688	0.1184	0.14208
61200	1000	800	22.0033	19.6688	0.1184	0.14208
61800	1000	800	22.0033	19.6688	0.1184	0.14208
62400	1000	800	22.0033	19.6688	0.1184	0.14208
63000	1000	800	22.0033	19.6688	0.1184	0.14208
63600	1000	800	22.0033	19.6688	0.1184	0.14208
64200	1000	800	22.0033	19.6688	0.1184	0.14208
64800	1000	800	22.0033	19.6688	0.1184	0.14208
65400	500	400	22.0390	19.7000	0	0
66000	500	400	21.8637	19.5585	0.1184	0.14208
66600	500	400	22.0478	19.7048	0.1184	0.14208
67200	500	400	22.0509	19.7074	0	0
67800	500	400	21.8668	19.5600	0.1184	0.14208
68400	500	400	22.0487	19.7051	0.1184	0.14208
69000	500	400	22.0512	19.7074	0	0
69600	500	400	21.8669	19.5600	0.1184	0.14208
70200	500	400	22.0487	19.7051	0.1184	0.14208
70800	500	400	22.0512	19.7074	0	0
71400	500	400	21.8669	19.5600	0.1184	0.14208
72000	500	400	22.0487	19.7051	0.1184	0.14208
72600	500	400	22.0512	19.7074	0	0
73200	500	400	21.8669	19.5600	0.1184	0.14208
73800	500	400	22.0487	19.7051	0.1184	0.14208
74400	500	400	22.0512	19.7074	0	0
75000	500	400	21.8669	19.5600	0.1184	0.14208
75600	500	400	22.0487	19.7051	0.1184	0.14208
76200	500	400	22.0512	19.7074	0	0
76800	500	400	21.8669	19.5600	0.1184	0.14208
77400	500	400	22.0487	19.7051	0.1184	0.14208
78000	500	400	22.0512	19.7074	0	0
78600	500	400	21.8669	19.5600	0.1184	0.14208
79200	500	400	22.0487	19.7051	0.1184	0.14208
79800	500	400	22.0512	19.7074	0	0
80400	500	400	21.8669	19.5600	0.1184	0.14208
81000	500	400	22.0487	19.7051	0.1184	0.14208
81600	500	400	22.0512	19.7074	0	0
82200	500	400	21.8669	19.5600	0.1184	0.14208
82800	500	400	22.0487	19.7051	0.1184	0.14208
83400	500	400	22.0512	19.7074	0	0
84000	500	400	21.8669	19.5600	0.1184	0.14208
84600	500	400	22.0487	19.7051	0.1184	0.14208
85200	500	400	22.0512	19.7074	0	0

85800	500	400	21.8669	19.5600	0.1184	0.14208
86400	500	400	22.0487	19.7051	0.1184	0.14208

Analytical Solution

The analytical solution used in this test is based on the heat balance for the zone air. Assume the system air flows into a zone is well mixed with the zone air before it flows out, the heat balance equation for the zone air is:

$$q^{''}_{conv,i} + \dot{m}_{sys} C_{pa} T_{sys} = M_z C_{pa} \frac{dT_z}{dt} + \dot{m}_{sys} C_{pa} T_z \quad \text{(MSOnOffCon-1)}$$

where,

$q^{''}_{conv,i} =$ the internal convective heat gain of the zone, W

$\dot{m}_{sys}$ = the mass flow rate of the system air, kg/s; $\dot{m}_{sys} = \rho_{air} v_{sys}$

$\rho_{air} =$ the density of the air, kg/m^3

$v_{sys} =$ the volume flow rate of the system air, m^3/s

M_z = the mass of the zone air, kg; $M_z = \rho_{air} V_z$

$V_z =$ the volume of the zone, 27.0 m^3

$C_{pa} =$ the specific heat capacity of the air, J/kg.K

$T_{sys} =$ the system air temperature, C

$T_z =$ the zone air temperature, C

$t =$ the time, s

Eq. (MSOnOffCon-1) can be rewritten as:

$$\frac{dT_z}{dt} + \frac{\dot{m}_{sys}}{M_z} T_z = \frac{q^{''}_{conv,i} + \dot{m}_{sys} C_{pa} T_{sys}}{M_z C_{pa}} \quad \text{(MSOnOffCon-2)}$$

In an appropriately short simulation time step, during which the system air temperature and flow rate can be considered as a constant, Eq. (MSOnOffCon-2) is a first order ordinary differential equation with respect to the zone air temperature.

When the system is on, Eq. (MSOnOffCon-2) can be solved to get the zone air temperature by multiplying both sides of Eq. (MSOnOffCon-2) by $e^{\frac{\dot{m}_{sys}}{M_z} t}$ and integrate from *0* to *t* as:

$$T_z(t) = EXP\left(-\frac{\dot{m}_{sys}}{M_z} t\right)\left\{\frac{q^{''}_{conv,i} + \dot{m}_{sys} C_{pa} T_{sys}}{\dot{m}_{sys} C_{pa}}\left[EXP\left(\frac{\dot{m}_{sys}}{M_z} t\right) - 1\right] + T_z(0)\right\}$$

(MSOnOffCon-3)

where,

$T_z(t) =$ the zone air temperature at time *t*, C

$T_z(0) =$ the zone air temperature at time *0*, C

When the system is off, Eq. (MSOnOffCon-2) can be rewritten as:

$$\frac{dT_z}{dt} = \frac{q''_{conv,i}}{M_z C_{pa}} \qquad \text{(MSOnOffCon-4)}$$

Eq. (MSOnOffCon-4) can be solved to get the zone air temperature by directly integrating from *0* to *t* as:

$$T_z(t) = \frac{q''_{conv,i}}{M_z C_{pa}} t + T_z(0) \qquad \text{(MSOnOffCon-5)}$$

where,

$T_z(t) =$ the zone air temperature at time *t*, C

$T_z(0) =$ the zone air temperature at time *0*, C

References

McQuiston, F.C., Parker, J.D., and Spitler, J.D. 2000. *Heating, Ventilating, and Air Conditioning Analysis and Design*, Fifth Edition. John Wiley and Sons, New York.

Spitler, J.D., S.J. Rees, D. Xiao. 2001. *Development of an analytical verification test suite for whole building energy simulation programs – building fabric (1052-RP): Final Report*, ASHRAE, Atlanta GA.

Analytical Testing Results of ESP-r and EnergyPlus

ESP-r Analytical Testing Results

ESP-r single-zone comparison results: Test SSCond

Test parameters

Test Parameter	Value	Units
Number of fabric layers	3	-
Thermal conductivity: Layer 1	0.1	W/m.K
Thickness: Layer 1	0.1	m
Thermal conductivity: Layer 2	0.05	W/m.K
Thickness: Layer 2	0.05	m
Thermal conductivity: Layer 3	0.25	W/m.K
Thickness: Layer 3	0.01	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	12.5	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.8	-
Inside correlation coefficient ‘A’	3.1	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.8	-

Tabulated results

ESP-r result load in one hour	**Analytical solution load in one hour**
wh	**wh**
110.54	110.54

Comment: The ESP-r resultant zone is exactly the same as analytical zone load for the Steady State Conduction case.

ESP-r single-zone comparison results: Test SSConv

Test parameters

Test Parameter	Value	Units
Thermal conductivity	1.0	W/m.K
Thickness	0.1	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	12.5	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.8	-
Inside correlation coefficient ‘A’	3.1	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.8	-

Tabulated results

ESP-r result load in one hour (wh)	Analytical solution load in one hour (wh)
537.17	537.23

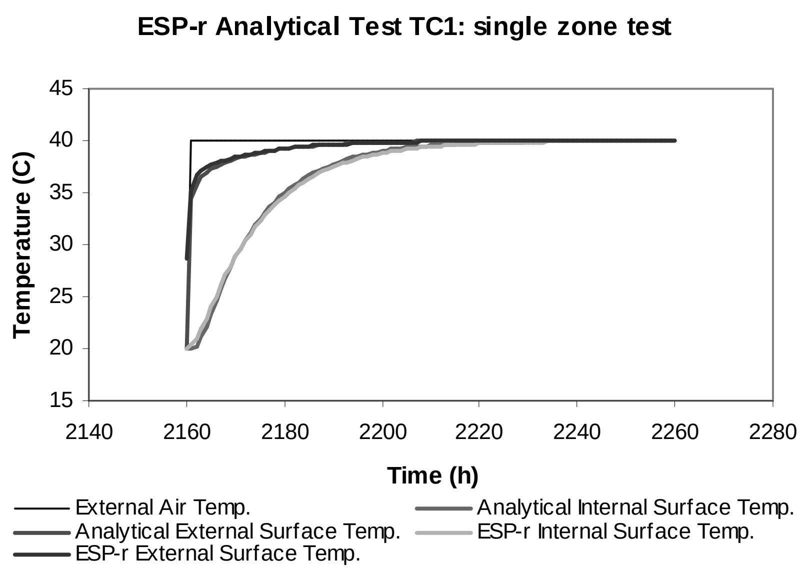
Comment: The ESP-r result matches well with the analytical solution for the Steady State Convection case with the maximum difference of 0.011% for zone load in one hour.

ESP-r single zone comparison results: Test Tc1

Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	20.0	^oC
Temperature step (ΔT)	20.0	^oC
External convection coefficient	12.5	$W/m^2.K$

Plotted result



Tabulated results

Time	External Air Temp. ©	Analytical Internal Surface Temp. ©	Analytical External Surface Temp. ©	ESP-r Internal Surface Temp. ©	ESP-r External Surface Temp. ©
2160	20.00	20.00	20.00	20.03	28.58
2161	40.00	20.01	34.41	20.36	35.24
2162	40.00	20.28	35.84	21.04	36.65
2163	40.00	21.07	36.53	21.96	37.13
2164	40.00	22.16	36.97	22.98	37.41

2165	40.00	23.36	37.28	24.03	37.63
2166	40.00	24.56	37.53	25.08	37.82
2167	40.00	25.71	37.74	26.09	37.99
2168	40.00	26.80	37.92	27.05	38.14
2169	40.00	27.81	38.09	27.96	38.28
2170	40.00	28.75	38.24	28.81	38.40
2171	40.00	29.62	38.38	29.61	38.52
2172	40.00	30.42	38.50	30.35	38.63
2173	40.00	31.16	38.62	31.04	38.73
2174	40.00	31.85	38.72	31.68	38.82
2175	40.00	32.48	38.82	32.28	38.90
2176	40.00	33.06	38.91	32.83	38.98
2177	40.00	33.60	39.00	33.34	39.06
2178	40.00	34.09	39.08	33.82	39.12
2179	40.00	34.55	39.15	34.26	39.19
2180	40.00	34.97	39.21	34.68	39.24
2181	40.00	35.36	39.27	35.06	39.30
2182	40.00	35.72	39.33	35.41	39.35
2183	40.00	36.05	39.38	35.74	39.40
2184	40.00	36.36	39.43	36.05	39.44
2185	40.00	36.64	39.47	36.33	39.48
2186	40.00	36.90	39.52	36.59	39.52
2187	40.00	37.14	39.55	36.84	39.55
2188	40.00	37.36	39.59	37.07	39.58
2189	40.00	37.57	39.62	37.28	39.61
2190	40.00	37.75	39.65	37.47	39.64
2191	40.00	37.93	39.68	37.65	39.67
2192	40.00	38.09	39.70	37.82	39.69
2193	40.00	38.24	39.72	37.98	39.71
2194	40.00	38.37	39.75	38.12	39.73
2195	40.00	38.50	39.77	38.26	39.75
2196	40.00	38.62	39.78	38.38	39.77
2197	40.00	38.72	39.80	38.50	39.79
2198	40.00	38.82	39.82	38.60	39.80
2199	40.00	38.91	39.83	38.70	39.82
2200	40.00	39.00	39.84	38.80	39.83
2201	40.00	39.07	39.86	38.88	39.84
2202	40.00	39.15	39.87	38.96	39.85
2203	40.00	39.21	39.88	39.04	39.86
2204	40.00	39.27	39.89	39.11	39.87
2205	40.00	39.33	39.90	39.17	39.88
2206	40.00	39.38	39.90	39.23	39.89
2207	40.00	39.43	39.91	39.29	39.90
2208	40.00	39.47	39.92	39.34	39.91
2209	40.00	39.51	39.92	39.39	39.91
2210	40.00	39.55	39.93	39.43	39.92
2211	40.00	39.59	39.94	39.47	39.92

2212	40.00	39.62	39.94	39.51	39.93
2213	40.00	39.65	39.94	39.54	39.94
2214	40.00	39.68	39.95	39.58	39.94
2215	40.00	39.70	39.95	39.61	39.94
2216	40.00	39.72	39.96	39.64	39.95
2217	40.00	39.75	39.96	39.66	39.95
2218	40.00	39.76	39.96	39.69	39.96
2219	40.00	39.78	39.97	39.71	39.96
2220	40.00	39.80	39.97	39.73	39.96
2221	40.00	39.82	39.97	39.75	39.96
2222	40.00	39.83	39.97	39.77	39.97
2223	40.00	39.84	39.98	39.79	39.97
2224	40.00	39.86	39.98	39.80	39.97
2225	40.00	39.87	39.98	39.82	39.97
2226	40.00	39.88	39.98	39.83	39.98
2227	40.00	39.89	39.98	39.84	39.98
2228	40.00	39.89	39.98	39.85	39.98
2229	40.00	39.90	39.98	39.86	39.98
2230	40.00	39.91	39.99	39.87	39.98
2231	40.00	39.92	39.99	39.88	39.98
2232	40.00	39.92	39.99	39.89	39.98
2233	40.00	39.93	39.99	39.90	39.99
2234	40.00	39.94	39.99	39.91	39.99
2235	40.00	39.94	39.99	39.91	39.99
2236	40.00	39.94	39.99	39.92	39.99
2237	40.00	39.95	39.99	39.93	39.99
2238	40.00	39.95	39.99	39.93	39.99
2239	40.00	39.96	39.99	39.94	39.99
2240	40.00	39.96	39.99	39.94	39.99
2241	40.00	39.96	39.99	39.95	39.99
2242	40.00	39.97	39.99	39.95	39.99
2243	40.00	39.97	40.00	39.95	39.99
2244	40.00	39.97	40.00	39.96	39.99
2245	40.00	39.97	40.00	39.96	39.99
2246	40.00	39.98	40.00	39.96	39.99
2247	40.00	39.98	40.00	39.97	40.00
2248	40.00	39.98	40.00	39.97	40.00
2249	40.00	39.98	40.00	39.97	40.00
2250	40.00	39.98	40.00	39.97	40.00
2251	40.00	39.98	40.00	39.97	40.00
2252	40.00	39.98	40.00	39.98	40.00
2253	40.00	39.99	40.00	39.98	40.00
2254	40.00	39.99	40.00	39.98	40.00
2255	40.00	39.99	40.00	39.98	40.00
2256	40.00	39.99	40.00	39.98	40.00
2257	40.00	39.99	40.00	39.98	40.00
2258	40.00	39.99	40.00	39.99	40.00

2259	40.00	39.99	40.00	39.99	40.00
2260	40.00	39.99	40.00	39.99	40.00

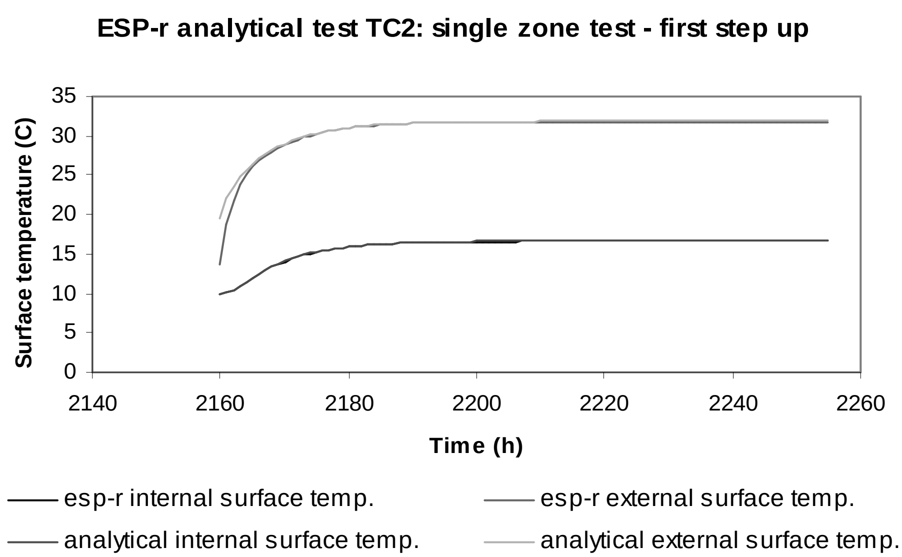
Comment: ESP-r responds to step changes in external dry bulb temperature in approximately the same way as the analytical solution. Except the first hour of the step change occurs, the maximum difference in external surface temperature was 0.83 ^{o}C, with 85 hours out of 100 hours having a difference within 0.1 ^{o}C. The maximum difference in internal surface temperature was 0.89 ^{o}C, with 75 hours out of 100 hours having a difference within 0.25 ^{o}C. It was suspected the maximum difference occurs because ESP-r takes the average of the step change within the hour the step change happens.

ESP-r single zone comparison results: Test Tc2

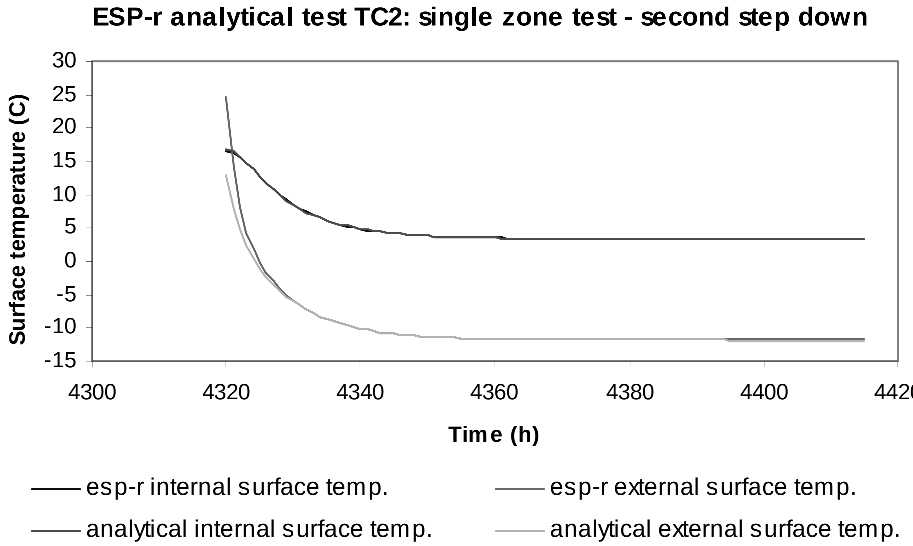
Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	10.0	^{o}C
Temperature step (ΔT)	30.0	^{o}C
External convection coefficient	2.6	W/m^2.K
Internal convection coefficient	3.2	W/m^2.K

Plotted results: First step change



Plotted results: Second step change



Tabulated results: First step

Time (hour)	ESP-r Internal surface temp. ©	ESP-r External surface temp. ©	Analytical Internal surface temp. ©	Analytical External surface temp. ©
2160	10.01	13.65	10.00	19.40
2161	10.15	18.80	10.12	21.96
2162	10.48	21.82	10.47	23.59
2163	10.93	23.75	10.96	24.77
2164	11.44	25.07	11.50	25.70
2165	11.96	26.06	12.04	26.47
2166	12.46	26.83	12.54	27.12
2167	12.93	27.47	13.00	27.67
2168	13.35	28.01	13.41	28.16
2169	13.73	28.48	13.78	28.59
2170	14.07	28.88	14.11	28.97
2171	14.37	29.23	14.41	29.30
2172	14.64	29.54	14.67	29.59
2173	14.87	29.81	14.90	29.85
2174	15.08	30.05	15.10	30.08
2175	15.27	30.26	15.28	30.28
2176	15.43	30.44	15.44	30.46
2177	15.57	30.61	15.58	30.62
2178	15.70	30.75	15.71	30.76
2179	15.81	30.88	15.82	30.89
2180	15.91	30.99	15.92	31.00
2181	15.99	31.09	16.01	31.10

2182	16.07	31.17	16.08	31.18
2183	16.14	31.25	16.15	31.26
2184	16.20	31.32	16.21	31.33
2185	16.25	31.38	16.27	31.39
2186	16.30	31.43	16.31	31.44
2187	16.34	31.48	16.36	31.49
2188	16.37	31.52	16.39	31.53
2189	16.40	31.55	16.43	31.57
2190	16.43	31.59	16.45	31.60
2191	16.46	31.61	16.48	31.63
2192	16.48	31.64	16.50	31.65
2193	16.50	31.66	16.52	31.68
2194	16.51	31.68	16.54	31.70
2195	16.53	31.70	16.56	31.71
2196	16.54	31.71	16.57	31.73
2197	16.55	31.73	16.58	31.74
2198	16.56	31.74	16.59	31.76
2199	16.57	31.75	16.60	31.77
2200	16.58	31.76	16.61	31.78
2201	16.59	31.76	16.62	31.79
2202	16.59	31.77	16.63	31.79
2203	16.60	31.78	16.63	31.80
2204	16.60	31.78	16.64	31.81
2205	16.61	31.79	16.64	31.81
2206	16.61	31.79	16.65	31.82
2207	16.62	31.80	16.65	31.82
2208	16.62	31.80	16.65	31.82
2209	16.62	31.80	16.66	31.83
2210	16.62	31.80	16.66	31.83
2211	16.63	31.81	16.66	31.83
2212	16.63	31.81	16.66	31.83
2213	16.63	31.81	16.67	31.84
2214	16.63	31.81	16.67	31.84
2215	16.63	31.81	16.67	31.84
2216	16.63	31.81	16.67	31.84
2217	16.63	31.82	16.67	31.84
2218	16.63	31.82	16.67	31.84
2219	16.63	31.82	16.67	31.84
2220	16.64	31.82	16.67	31.85
2221	16.64	31.82	16.67	31.85
2222	16.64	31.82	16.68	31.85
2223	16.64	31.82	16.68	31.85
2224	16.64	31.82	16.68	31.85
2225	16.64	31.82	16.68	31.85
2226	16.64	31.82	16.68	31.85
2227	16.64	31.82	16.68	31.85
2228	16.64	31.82	16.68	31.85
2229	16.64	31.82	16.68	31.85

2230	16.64	31.82	16.68	31.85
2231	16.64	31.82	16.68	31.85
2232	16.64	31.82	16.68	31.85
2233	16.64	31.82	16.68	31.85
2234	16.64	31.82	16.68	31.85
2235	16.64	31.82	16.68	31.85
2236	16.64	31.82	16.68	31.85
2237	16.64	31.82	16.68	31.85
2238	16.64	31.82	16.68	31.85
2239	16.64	31.82	16.68	31.85
2240	16.64	31.82	16.68	31.85
2241	16.64	31.82	16.68	31.85
2242	16.64	31.82	16.68	31.85
2243	16.64	31.82	16.68	31.85
2244	16.64	31.82	16.68	31.85
2245	16.64	31.82	16.68	31.85
2246	16.64	31.82	16.68	31.85
2247	16.64	31.82	16.68	31.85
2248	16.64	31.82	16.68	31.85
2249	16.64	31.82	16.68	31.85
2250	16.64	31.82	16.68	31.85
2251	16.64	31.82	16.68	31.85
2252	16.64	31.82	16.68	31.85
2253	16.64	31.82	16.68	31.85
2254	16.64	31.82	16.68	31.85
2255	16.64	31.82	16.68	31.85

Tabulated results: Second step

Time (hour)	ESP-r		Analytical	
	Internal surface temp. ©	External surface temp. ©	Internal surface temp. ©	External surface temp. ©
4320	16.61	24.53	16.67	13.04
4321	16.33	14.23	16.44	7.93
4322	15.69	8.18	15.75	4.68
4323	14.79	4.33	14.76	2.31
4324	13.76	1.68	13.67	0.45
4325	12.72	-0.29	12.60	-1.08
4326	11.72	-1.85	11.60	-2.38
4327	10.79	-3.12	10.68	-3.50
4328	9.94	-4.20	9.85	-4.47
4329	9.18	-5.13	9.11	-5.33
4330	8.50	-5.93	8.45	-6.08
4331	7.90	-6.63	7.87	-6.74
4332	7.36	-7.25	7.35	-7.33
4333	6.89	-7.79	6.88	-7.85
4334	6.48	-8.27	6.48	-8.31
4335	6.11	-8.69	6.11	-8.71

4336	5.78	-9.06	5.79	-9.07
4337	5.50	-9.39	5.51	-9.39
4338	5.24	-9.68	5.26	-9.67
4339	5.02	-9.93	5.04	-9.92
4340	4.83	-10.15	4.84	-10.14
4341	4.65	-10.35	4.67	-10.34
4342	4.50	-10.52	4.51	-10.51
4343	4.36	-10.68	4.38	-10.67
4344	4.25	-10.81	4.25	-10.80
4345	4.14	-10.93	4.15	-10.92
4346	4.05	-11.04	4.05	-11.03
4347	3.97	-11.13	3.97	-11.12
4348	3.90	-11.21	3.89	-11.21
4349	3.83	-11.29	3.83	-11.28
4350	3.78	-11.35	3.77	-11.35
4351	3.73	-11.41	3.72	-11.40
4352	3.68	-11.45	3.67	-11.46
4353	3.65	-11.50	3.63	-11.50
4354	3.61	-11.54	3.60	-11.54
4355	3.58	-11.57	3.57	-11.58
4356	3.56	-11.60	3.54	-11.61
4357	3.53	-11.63	3.51	-11.64
4358	3.51	-11.65	3.49	-11.66
4359	3.49	-11.67	3.47	-11.68
4360	3.48	-11.69	3.45	-11.70
4361	3.46	-11.70	3.44	-11.72
4362	3.45	-11.72	3.42	-11.73
4363	3.44	-11.73	3.41	-11.75
4364	3.43	-11.74	3.40	-11.76
4365	3.42	-11.75	3.39	-11.77
4366	3.42	-11.76	3.38	-11.78
4367	3.41	-11.77	3.38	-11.79
4368	3.40	-11.77	3.37	-11.80
4369	3.40	-11.78	3.36	-11.80
4370	3.39	-11.79	3.36	-11.81
4371	3.39	-11.79	3.36	-11.81
4372	3.39	-11.79	3.35	-11.82
4373	3.38	-11.80	3.35	-11.82
4374	3.38	-11.80	3.34	-11.82
4375	3.38	-11.80	3.34	-11.83
4376	3.38	-11.81	3.34	-11.83
4377	3.37	-11.81	3.34	-11.83
4378	3.37	-11.81	3.34	-11.84
4379	3.37	-11.81	3.33	-11.84
4380	3.37	-11.81	3.33	-11.84
4381	3.37	-11.81	3.33	-11.84
4382	3.37	-11.81	3.33	-11.84
4383	3.37	-11.82	3.33	-11.84

4384	3.37	-11.82	3.33	-11.84
4385	3.36	-11.82	3.33	-11.85
4386	3.36	-11.82	3.33	-11.85
4387	3.36	-11.82	3.33	-11.85
4388	3.36	-11.82	3.32	-11.85
4389	3.36	-11.82	3.32	-11.85
4390	3.36	-11.82	3.32	-11.85
4391	3.36	-11.82	3.32	-11.85
4392	3.36	-11.82	3.32	-11.85
4393	3.36	-11.82	3.32	-11.85
4394	3.36	-11.82	3.32	-11.85
4395	3.36	-11.82	3.32	-11.85
4396	3.36	-11.82	3.32	-11.85
4397	3.36	-11.82	3.32	-11.85
4398	3.36	-11.82	3.32	-11.85
4399	3.36	-11.82	3.32	-11.85
4400	3.36	-11.82	3.32	-11.85
4401	3.36	-11.82	3.32	-11.85
4402	3.36	-11.82	3.32	-11.85
4403	3.36	-11.82	3.32	-11.85
4404	3.36	-11.82	3.32	-11.85
4405	3.36	-11.82	3.32	-11.85
4406	3.36	-11.82	3.32	-11.85
4407	3.36	-11.82	3.32	-11.85
4408	3.36	-11.82	3.32	-11.85
4409	3.36	-11.82	3.32	-11.85
4410	3.36	-11.82	3.32	-11.85
4411	3.36	-11.82	3.32	-11.85
4412	3.36	-11.82	3.32	-11.85
4413	3.36	-11.82	3.32	-11.85
4414	3.36	-11.82	3.32	-11.85
4415	3.36	-11.82	3.32	-11.85

Comment: The ESP-r result shows response to step changes in master zone dry bulb temperature in approximately the same way as the analytical solution. In the first step, the maximum difference in internal surface temperature is –0.08 ^{o}C, with 90 hours out of 95 hours have an difference within ±0.05 ^{o}C. In the second step, the maximum difference in internal surface temperature is 0.12 ^{o}C, with 87 hours out of 95 hours have an difference within ±0.05 ^{o}C. In both steps, there are 5-6 hours when the differences in external surface temperature are relatively large, but the temperature difference quickly reduces to within ±0.2 ^{o}C after that. Again it was suspected the maximum difference occurs because ESP-r takes the average of the step change within the hour the step change happens.

ESP-r single zone comparison results: Test ExtSolRad

Test parameters (Layer 1 is outside, layer 3 is inside)

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Solar absorption of the surface 'α'	0.9	-
Number of layers: 'N'	3	-
Thermal conductivity: layer 1 'K_1'	0.15	W/mK
Thickness: layer 1 'L_1'	0.1	m
Thermal conductivity: layer 2 'K_2'	0.05	W/mK
Thickness: layer 2 'L_2'	0.1	m
Thermal conductivity: layer 3 'K_3'	0.15	W/mK
Thickness: layer 3 'L_3'	0.1	m
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	12.5	W/m^{2}K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.333	-
Inside correlation coefficient 'A'	3.1	W/m^{2}K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.345	-

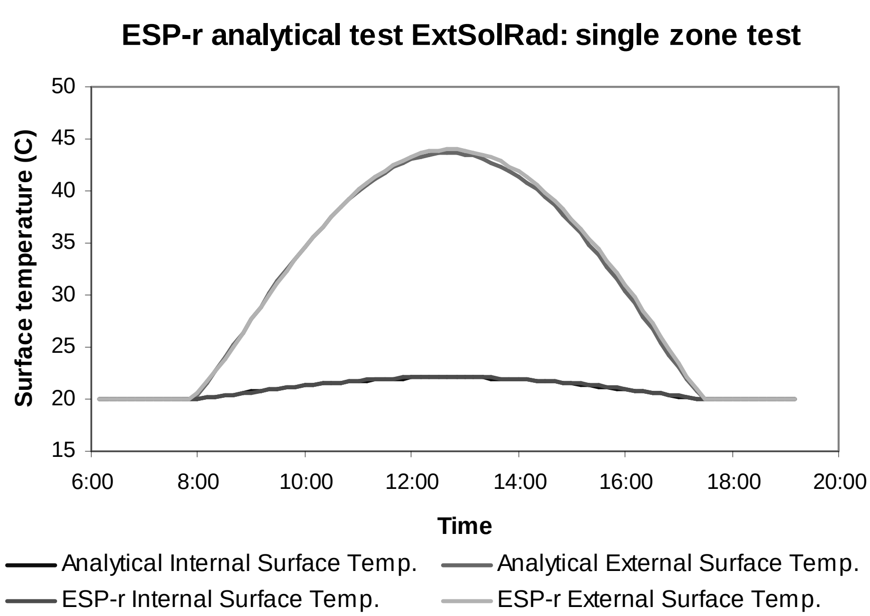
Tabulated results

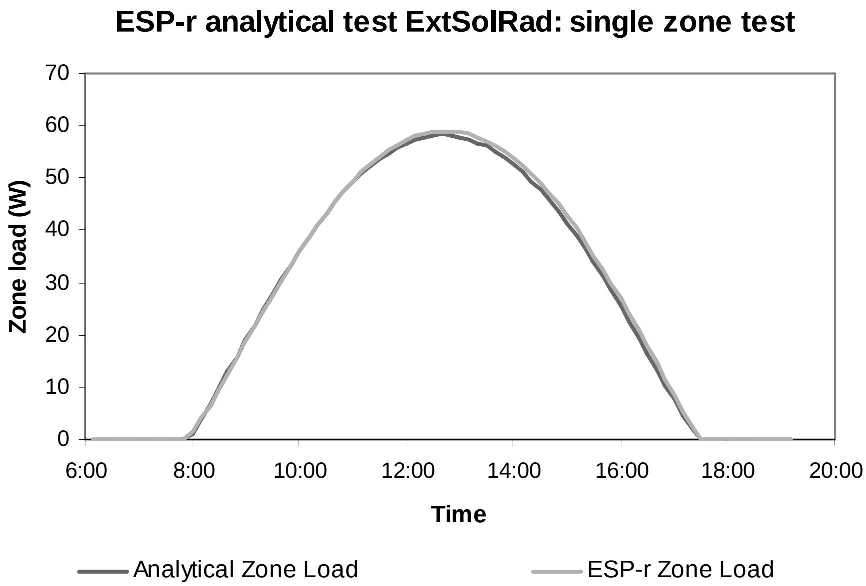
	Analytical			ESP-r		
Time	Internal Surface Temp. ©	External Surface Temp. ©	Zone Load (W)	Internal Surface Temp. ©	External Surface Temp. ©	Zone Load (W)
6:10	20.00	20.00	0.00	20.00	20.00	0.00
6:20	20.00	20.00	0.00	20.00	20.00	0.00
6:30	20.00	20.00	0.00	20.00	20.00	0.00
6:40	20.00	20.00	0.00	20.00	20.00	0.00
6:50	20.00	20.00	0.00	20.00	20.00	0.00
7:00	20.00	20.00	0.00	20.00	20.00	0.00
7:10	20.00	20.00	0.00	20.00	20.00	0.00
7:20	20.00	20.00	0.00	20.00	20.00	0.00
7:30	20.00	20.00	0.00	20.00	20.00	0.00

7:40	20.00	20.00	0.00	20.00	20.00	0.00
7:50	20.00	20.00	0.00	20.00	20.00	0.00
8:00	20.04	20.47	1.16	20.06	20.67	1.64
8:10	20.14	21.61	3.95	20.14	21.64	4.03
8:20	20.24	22.76	6.80	20.24	22.69	6.62
8:30	20.35	24.00	9.86	20.34	23.82	9.41
8:40	20.46	25.23	12.88	20.44	25.03	12.37
8:50	20.57	26.43	15.82	20.56	26.30	15.51
9:00	20.68	27.74	19.05	20.67	27.63	18.78
9:10	20.79	28.90	21.92	20.78	28.80	21.67
9:20	20.90	30.16	25.00	20.88	29.98	24.56
9:30	21.00	31.32	27.87	20.98	31.16	27.46
9:40	21.10	32.46	30.68	21.09	32.33	30.34
9:50	21.20	33.56	33.37	21.19	33.49	33.21
10:00	21.29	34.61	35.97	21.29	34.64	36.03
10:10	21.38	35.64	38.49	21.38	35.65	38.50
10:20	21.47	36.62	40.92	21.47	36.62	40.90
10:30	21.55	37.53	43.14	21.55	37.55	43.19
10:40	21.63	38.44	45.40	21.63	38.45	45.40
10:50	21.69	39.21	47.28	21.70	39.30	47.49
11:00	21.76	39.99	49.22	21.77	40.10	49.47
11:10	21.82	40.63	50.78	21.83	40.78	51.13
11:20	21.87	41.25	52.30	21.89	41.40	52.66
11:30	21.92	41.81	53.69	21.94	41.96	54.05
11:40	21.97	42.29	54.88	21.98	42.47	55.30
11:50	22.01	42.75	56.00	22.02	42.92	56.40
12:00	22.03	43.06	56.77	22.06	43.30	57.34
12:10	22.06	43.33	57.44	22.08	43.56	57.99
12:20	22.08	43.52	57.91	22.10	43.76	58.48
12:30	22.08	43.62	58.14	22.11	43.90	58.81
12:40	22.09	43.70	58.34	22.11	43.96	58.97
12:50	22.09	43.66	58.26	22.11	43.96	58.97
13:00	22.08	43.52	57.90	22.11	43.90	58.81
13:10	22.06	43.38	57.56	22.09	43.72	58.38
13:20	22.04	43.07	56.79	22.07	43.48	57.79
13:30	22.01	42.77	56.06	22.04	43.18	57.04
13:40	21.97	42.36	55.05	22.01	42.81	56.13
13:50	21.93	41.93	53.98	21.97	42.37	55.06
14:00	21.89	41.37	52.62	21.93	41.88	53.84
14:10	21.84	40.80	51.20	21.88	41.27	52.34
14:20	21.77	40.11	49.50	21.82	40.60	50.70
14:30	21.71	39.41	47.78	21.75	39.88	48.93
14:40	21.64	38.59	45.75	21.69	39.11	47.02
14:50	21.57	37.76	43.72	21.61	38.28	44.98
15:00	21.49	36.83	41.43	21.53	37.40	42.81
15:10	21.40	35.90	39.15	21.45	36.42	40.42
15:20	21.31	34.88	36.63	21.36	35.41	37.92

15:30	21.22	33.80	33.97	21.27	34.36	35.33
15:40	21.12	32.71	31.28	21.17	33.27	32.65
15:50	21.02	31.59	28.52	21.07	32.14	29.89
16:00	20.92	30.44	25.69	20.97	30.99	27.05
16:10	20.81	29.20	22.66	20.86	29.75	24.00
16:20	20.70	27.96	19.61	20.75	28.51	20.93
16:30	20.60	26.74	16.60	20.64	27.25	17.84
16:40	20.48	25.47	13.47	20.53	25.99	14.75
16:50	20.38	24.25	10.46	20.42	24.73	11.64
17:00	20.27	23.09	7.61	20.31	23.47	8.54
17:10	20.16	21.85	4.56	20.19	22.18	5.36
17:20	20.06	20.71	1.75	20.08	20.92	2.27
17:30	20.00	20.00	0.00	20.00	20.03	0.08
17:40	20.00	20.00	0.00	20.00	20.02	0.05
17:50	20.00	20.00	0.00	20.00	20.01	0.03
18:00	20.00	20.00	0.00	20.00	20.00	0.00
18:10	20.00	20.00	0.00	20.00	20.00	0.00
18:20	20.00	20.00	0.00	20.00	20.00	0.00
18:30	20.00	20.00	0.00	20.00	20.00	0.00
18:40	20.00	20.00	0.00	20.00	20.00	0.00
18:50	20.00	20.00	0.00	20.00	20.00	0.00
19:00	20.00	20.00	0.00	20.00	20.00	0.00
19:10	20.00	20.00	0.00	20.00	20.00	0.00

Plotted results





Comment: ESP-r result shows it responds to exterior solar beam radiation in approximately the same way as analytical solution does in the condition of ExtSolRad case. The maximum difference between the loads calculated by ESP-r and the analytical solution is 1.38 W, which is about 2.37% of the peak analytical load. The maximum difference between the external surface temperatures is 0.57 ^{o}C. The maximum difference between the internal surface temperatures is only 0.05 ^{o}C.

Note that diffuse irradiation is set to zero in the test weather files so that loads are only induced by direct irradiation. It was found that setting the emissivity of the external surface to a very small value (0.01) is not enough to avoid external long wave radiation in this test. Both the view factors between the external surface and the sky and that between external surface and the ground were tentatively set to zero to obtain zero external long wave radiation. Internal long wave radiation was avoided by setting the emissivity of the internal surface to a very small value (0.01). In addition, the default reflectance of the ground needs to be reset to zero so that no radiation will be reflected from the ground to the external surface.

ESP-r single zone comparison results: Test SolRadGlazing

Test parameters

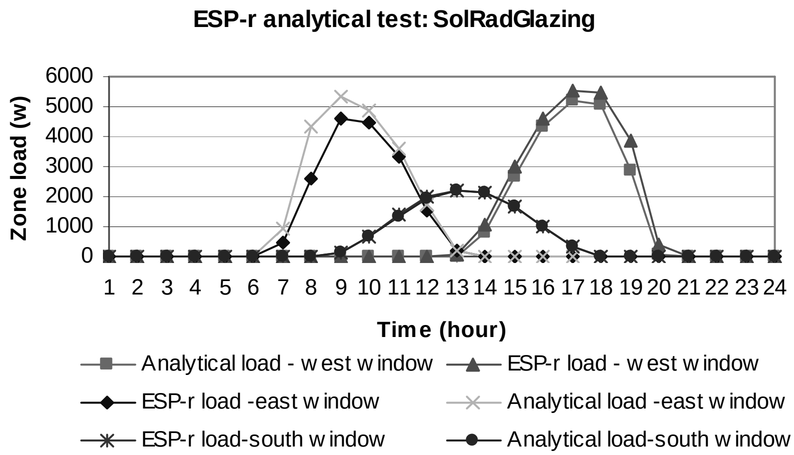
Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	90, 180, 270	Degree
Thickness of the surface 'L'	0.0023	m
Extinction coefficient of the surface 'K'	10.0	m^{-1}
Refractive index of the surface 'n_g'	1.526	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.2	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.333	-
Inside correlation coefficient 'A'	3.1	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.345	-

Tabulated results

	East window load (w)		South window load (w)		West window load (w)	
Hour	ESP-r	Analytical	ESP-r	Analytical	ESP-r	Analytical
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	450	935	0	0	0	0
8	2610	4305	0	0	0	0
9	4590	5307	130	100	0	0
10	4500	4898	700	641	10	0
11	3330	3626	1400	1360	10	0
12	1530	1756	1980	1932	0	0
13	180	205	2210	2201	40	6
14	0	0	2120	2115	1070	777
15	0	0	1680	1699	3000	2686
16	0	0	990	1033	4630	4321
17	0	0	320	342	5540	5219
18	0	0	10	15	5500	5070

19	0	0	0	0	3900	2871
20	0	0	0	0	420	45
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0

Plotted results



Comment: ESP-r result shows response to exterior solar beam radiation in approximately the same way as the analytical solution. ESP-r under-predicts zone loads from the east-facing window and over-predicts zone loads from the west-facing window due to the weather data interpolation. But the total loads in the day are approximately conservative, with a 1.15% difference from the analytical total load. The maximum differences between ESP-r predicted and analytical loads reaches 10.34% and 7.44% of the analytical peak load for the east and west facing window, and is only 1.27% of the analytical peak load for the south facing window.

When a simulation time step shorter than one hour is used, the weather data interpolation in ESP-r makes the solar irradiation reaches the value given in the weather data at the end of an hour, for which an average value is given. This weather data interpolation causes under-predicting in the morning hours when the solar radiation is increasing, and over-predicting in the afternoon hours when the solar radiation is decreasing. This problem may be fixed by using a better interpolation method or by creating appropriate weather data input that fits the ESP-r interpolation method.

In addition to the points mentioned in the ExtSolRad test (as needed to avoid long wave radiation and ground reflection), the ESP-r default insolation (or could we say internal solar distribution) has to be modified. Since the ESP-r default insolation treats the transmitted solar radiation diffusively, all internal surfaces including the window surface from which the solar radiation comes in will receive diffuse radiation. This will leads part of the incoming solar radiation to be transmitted back out from the window, which is not conformed to the analytical assumption. The internal insolation can be specified to either one or two surfaces different from the window surface to avoid this problem.

ESP-r single zone comparison results: Test SolRadShade(1)

(This is the result before the claimed bug was fixed)

Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Thickness of the surface 'L'	0.0023	m
Extinction coefficient of the surface 'K'	10.0	m^{-1}
Refractive index of the surface 'n_g'	1.526	-
Depth of the horizontal fin 'P_h'*	0.6	m
Depth of the vertical fin 'P_v'*	0.6	m
Vertical fin is on which side of the window*	Right/Left	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.2	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.333	-
Inside correlation coefficient 'A'	3.1	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.345	-

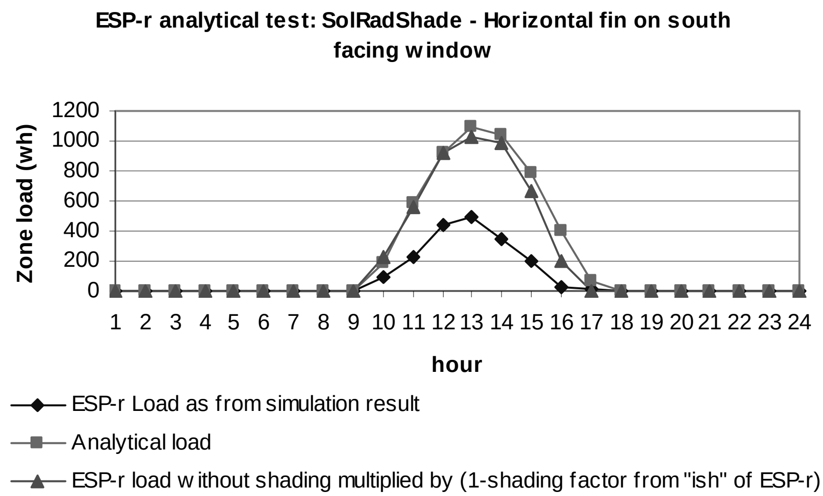
* Combinations of these parameter values are used as noted in the results

Tabulated and plotted results

1. South facing window with horizontal shade

Hour	ESP-r Load as from simulation result (w)	Analytical load (w)	ESP-r load without shading multiplied by (1-shading factor from "ish" of ESP-r) (w)	ESP-r load without shading (w)	Shading factor from "ish" of ESP-r
1	0	0	0	0	1.0000
2	0	0	0	0	1.0000
3	0	0	0	0	1.0000
4	0	0	0	0	1.0000
5	0	0	0	0	1.0000
6	0	0	0	0	1.0000
7	0	0	0	0	1.0000
8	0	0	0	0	1.0000
9	0	2	0	130	1.0000
10	90	188	233	700	0.6667

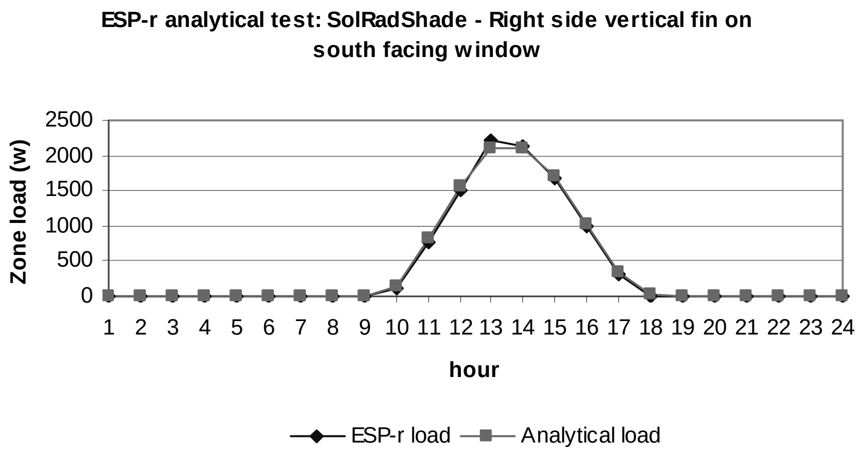
11	230	581	560	1400	0.6000
12	440	923	924	1980	0.5333
13	490	1090	1031	2210	0.5333
14	350	1036	989	2120	0.5333
15	200	783	672	1680	0.6000
16	30	397	198	990	0.8000
17	10	60	0	320	1.0000
18	0	0	0	10	1.0000
19	0	0	0	0	1.0000
20	0	0	0	0	1.0000
21	0	0	0	0	1.0000
22	0	0	0	0	1.0000
23	0	0	0	0	1.0000
24	0	0	0	0	1.0000



2. Vertical fin on right side of south facing window

Hour	ESP-r load (w)	Analytical load (w)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	120	151
11	760	827
12	1500	1572

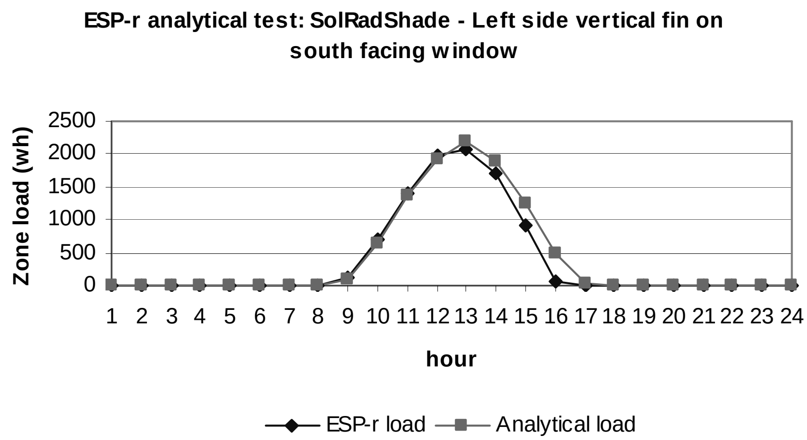
13	2210	2113
14	2120	2115
15	1680	1699
16	990	1033
17	320	342
18	0	15
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0



3. Vertical fin on left side of south facing window

Hour	ESP-r load (w)	Analytical load (w)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	130	100
10	700	641
11	1400	1360
12	1980	1932
13	2060	2193
14	1700	1895
15	900	1238

16	70	480
17	10	18
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0



Comment:
In the test case of south facing window with vertical fin on right side, the ESP-r result matches well with analytical result. The maximum zone load difference (97.38 W) is 4.60% of the analytical peak load. The average zone load difference is about 1.95% of the analytical peak load.

In the test case of south facing window with vertical fin on left side, the ESP-r zone load follows similar trend as that of analytical zone load. But ESP-r shows more shading effects under same conditions. The maximum zone load difference (410.35 W) reaches 19.40% of the analytical peak load. The average zone load difference rises to 6.47% of the analytical peak load.

In the test case of south facing window with horizontal shade, the original ESP-r simulation result of zone load is much lower than analytical zone load. The maximum zone load difference (686.35 W) is 62.94% of the analytical peak load. The average zone load difference is about 32.80% of the analytical peak load. In searching the reason for the difference, it was found that the zone load is much different if we multiply the zone load without shading by the difference between 1.0 and the shading factor output from the "ish" of ESP-r. ("ish" is the solar shading and isolation module of ESP-r) The zone load treated in this way matches the analytical zone load better than the original ESP-r simulation result. In addition, the difference between the zone load treated in this way and analytical zone load shows similar trend as in the left side vertical fin test case. Both of them show lower zone load then analytical result in the afternoon. In other words, ESP-r shows more shading effect in the afternoon.

The reason that ESP-r shows more shading effect in the afternoon may come from the ESP-r “ish” treatment that only the hourly shading data for one day in a month is retained. In that day, the solar declination is judged to be closest to the average value for that month.

There is also a bug claimed, but has not been verified, about calculating the solar transmission through windows in ESP-r when detailed internal solar distribution model is used. The detailed internal solar distribution model does need to be enabled in doing the solar shading test with ESP-r.

ESP-r single zone comparison results: Test SolRadShade(2)

(This is the result after the claimed bug was fixed)

Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle ‘ε’	90	Degree
Surface azimuth ‘ψ’	180	Degree
Thickness of the surface ‘L’	0.0023	m
Extinction coefficient of the surface ‘K’	10.0	m^{-1}
Refractive index of the surface ‘n_g’	1.526	-
Depth of the horizontal fin ‘P_h’*	0.6	m
Depth of the vertical fin‘ P_v’*	0.6	m
Vertical fin is on which side of the window*	Right/Left	-
External air temperature ‘$T_{a,o}$’	20	C
Internal air temperature ‘$T_{a,i}$’	20	C
Outside correlation coefficient ‘A’	8.2	W/m^2K
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.333	-
Inside correlation coefficient ‘A’	3.1	W/m^2K
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.345	-

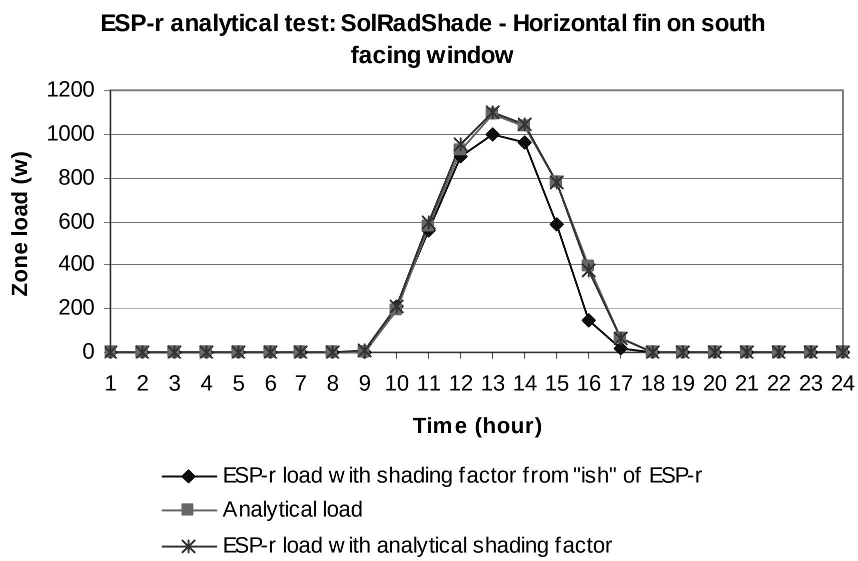
* Combinations of these parameter values are used as noted in the results

Tabulated and plotted results

1. South facing window with horizontal shade

Hour	ESP-r load with shading factor from "ish" of ESP-r (w)	ESP-r load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	10	2
10	210	210	188
11	560	600	581

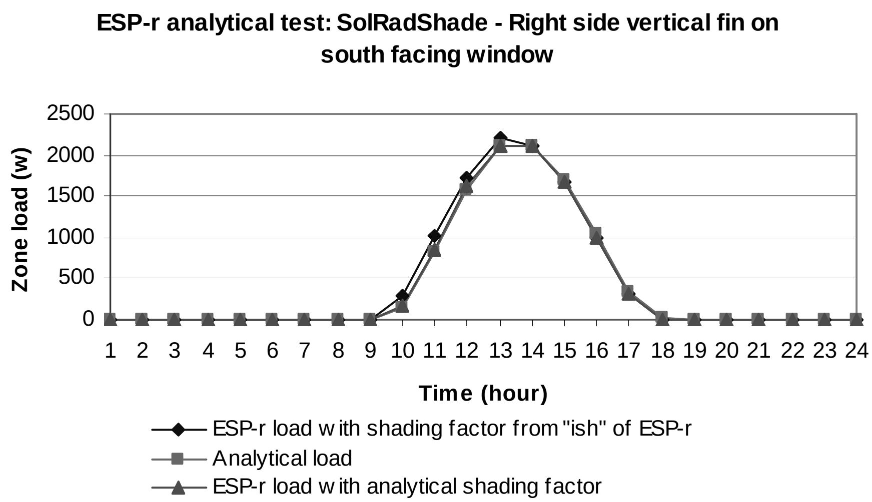
12	900	950	923
13	1000	1100	1090
14	960	1040	1036
15	590	780	783
16	150	380	397
17	20	60	60
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



2. Vertical fin on right side of south facing window

Hour	ESP-r load with shading factor from "ish" of ESP-r (w)	ESP-r load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	280	170	151
11	1030	850	827

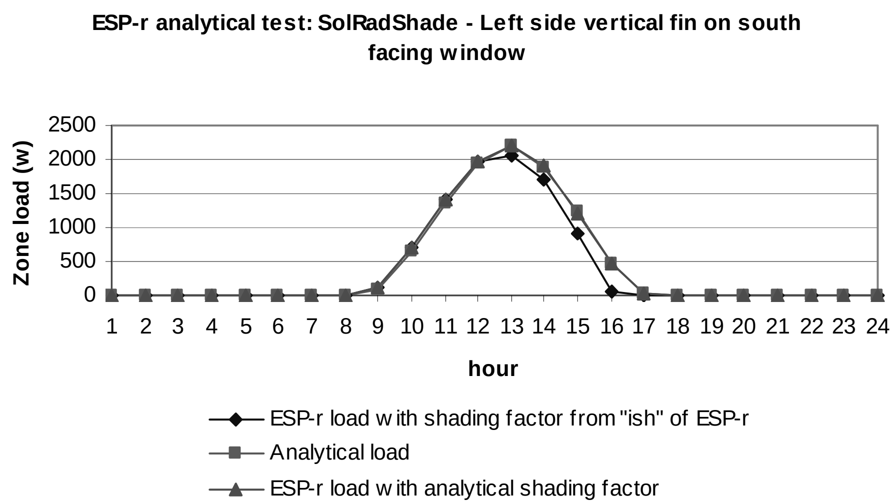
12	1720	1620	1572
13	2210	2120	2113
14	2120	2120	2115
15	1680	1680	1699
16	990	990	1033
17	320	320	342
18	0	0	15
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



3. Vertical fin on left side of south facing window

Hour	ESP-r load with shading factor from "ish" of ESP-r (w)	ESP-r load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	130	130	100
10	700	700	641

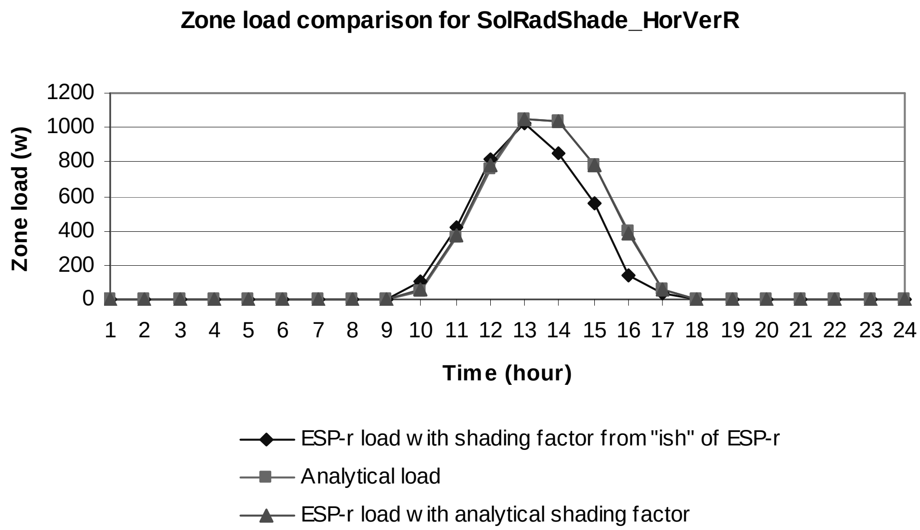
11	1400	1400	1360
12	1980	1980	1932
13	2060	2200	2193
14	1700	1900	1895
15	900	1220	1238
16	70	460	480
17	10	30	18
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



4. South facing window with horizontal shade and right side vertical fin

Hour	ESP-r load with shading factor from "ish" of ESP-r (w)	ESP-r load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	100	60	51
11	420	370	355

12	810	780	752
13	1030	1050	1047
14	850	1040	1036
15	560	780	783
16	140	380	397
17	30	60	60
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



Comment:
In the test case of south facing window with horizontal shade, the maximum zone load difference (246.89 W) is 22.64% of the analytical peak load. The average zone load difference is about 7.23% of the analytical peak load.

In the test case of south facing window with vertical fin on right side, the maximum zone load difference (202.56 W) is 9.58% of the analytical peak load. The average zone load difference is about 3.57% of the analytical peak load.

In the test case of south facing window with vertical fin on left side, the maximum zone load difference (410.35 W) reaches 18.71% of the analytical peak load. The average zone load difference is about 6.24% of the analytical peak load.

In the test case of south facing window with horizontal shade and right side vertical fin, the maximum zone load difference (256.89 W) is 24.54% of the analytical peak load. The average zone load difference is about 10.56% of the analytical peak load.

The claimed bug, about calculating the solar transmission through window when detailed solar insolation is specified, has been verified and fixed after reported to the ESP-r support. The differences remained can all be explained now by the shading factor difference between the analytical and "ish" calculated values. In all test cases, the ESP-r loads with analytical shading factors match analytical loads.

The reason for the shading factor difference may come from the ESP-r "ish" treatment that only the hourly shading data for one day in a month is retained. In that day, the solar declination is judged to be closest to the average value for that month.

ESP-r single zone comparison results: Test WinReveal

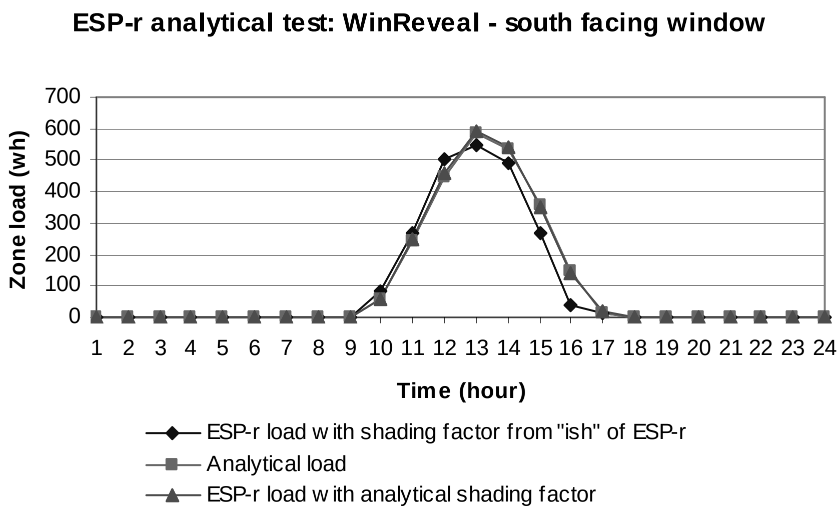
Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Thickness of the window surface	0.0023	m
Depth of the window reveal 'R'	0.3	m
Length of the window 'B'	2.0	m
Height of the window 'H'	2.0	m
Extinction coefficient of the window surface 'K'	10.0	m^{-1}
Refractive index of the window surface 'n_g'	1.526	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.2	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.333	-
Inside correlation coefficient 'A'	3.1	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.345	-

Tabulated and plotted results

Hour	ESP-r load with shading factor from "ish" of ESP-r (w)	ESP-r load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	80	60	57
11	270	250	243
12	500	460	448
13	550	590	587
14	490	540	534
15	270	350	357

16	40	140	148
17	10	20	13
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



Comment: ESP-r result shows similar shading effects for exterior solar beam irradiation as that of the analytical solution under the condition of WinReveal case. The maximum zone load difference (108.11 W) reaches 18.43% of the analytical peak load, with an average difference of 8.12% of the analytical peak load.

Again ESP-r shows more shading effect than analytical solution in the afternoon. The reason may be the same as that described in the SolRadShade test since window reveal test is a special case of external shading.

ESP-r single zone comparison results: Test IntSolarDist

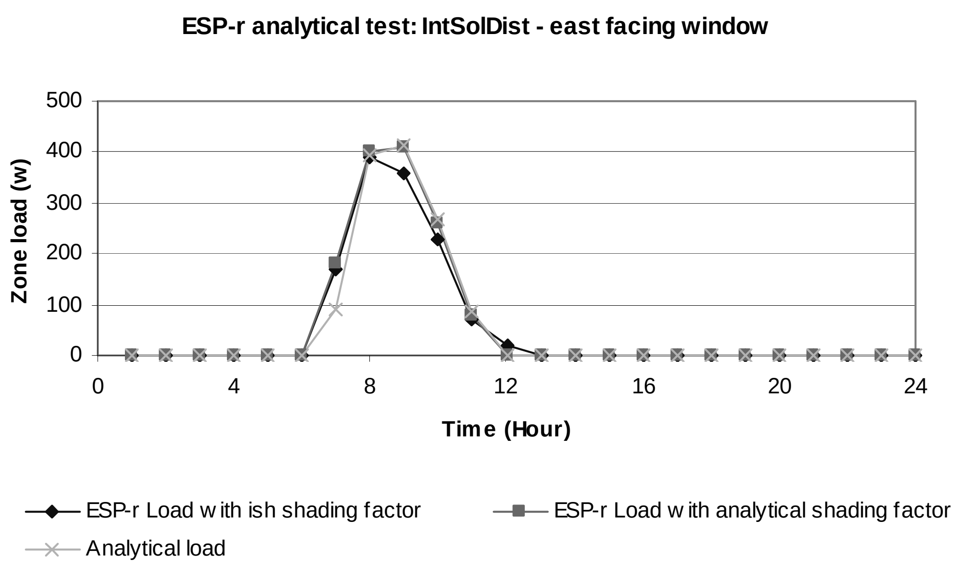
Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	90	Degree
Thickness of the window surface	.0023	m
Depth of the horizontal fin 'P_h'	0.5	m
Depth of the vertical fin'P_v'	0.5	m
Extinction coefficient of the window surface 'K'	10.0	m^{-1}
Refractive index of the window surface 'n_g'	1.526	-
Solar absorption of the internal surfaces	1.0	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.23	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.333	-
Inside correlation coefficient 'A'	3.076	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.345	-

Tabulated and plotted results

Hour	ESP-r Load with ish shading factor (w)	ESP-r Load with analytical shading factor (w)	Analytical load (w)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	170	180	89
8	390	400	393
9	360	410	414
10	230	260	267
11	70	80	86
12	20	0	0
13	0	0	0

14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0



Comment: The maximum difference between the ESP-r and analytical load (81.30 W) is about 19.65% of the peak analytical load, with an average difference of 9.22%. Again the difference can be explained mostly by the shading factor difference of the analytical and ESP-r calculated values.

Note that ESP-r will under-predict zone load from an east-facing window because of the weather data interpolation it used (as indicated in the SolRadGlazing test), the above plotted results are obtained with weather data that doesn't make average for each hour. Instead, the solar data at the end of each hour (as can be obtained from the analytical solution) was directly written in the weather file for each hour. This fits the weather data interpolation of ESP-r more properly. However, the solar radiation used in the simulation after the weather data interpolation still has some deviation from the weather data after this adjustment. This explains that at hour seven, the ESP-r load with analytical shading factor remains a relatively big difference from the analytical load.

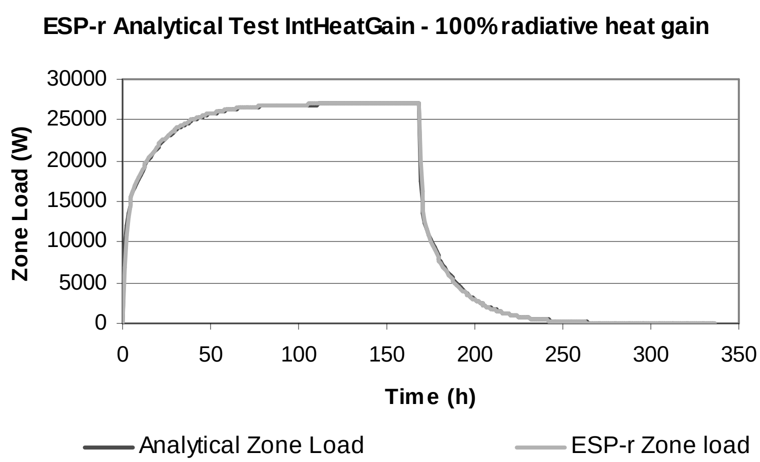
As already mentioned in the glazing surface test, ESP-r permits the choice of different solar insolation patterns and it's necessary to evoke the detailed insolation model while doing all the solar tests involving glazing surfaces. In this solar distribution test, the solar insolation is specified to be the same as that required by the analytical test, i.e., the transmitted solar radiation is insolated to the internal surface opposite to the external surface.

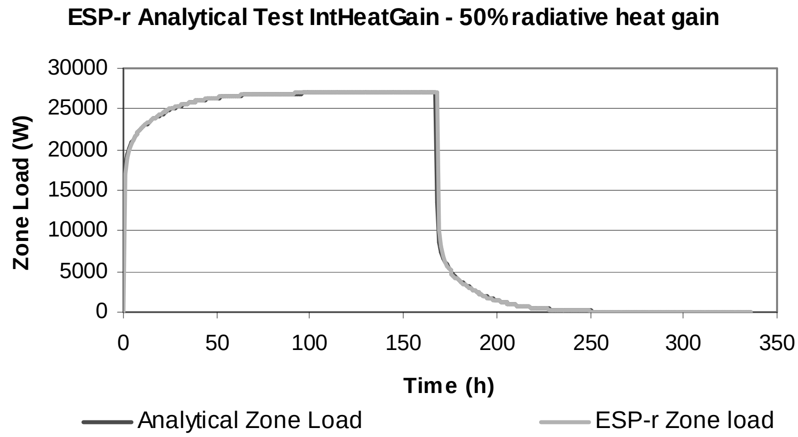
ESP-r single zone comparison results: Test IntHeatGain

Test parameters

Test parameters	Value	Units
Thermal conductivity	0.14	W/mK
Thickness	0.1	m
Density	500	Kg/m^3
Specific heat capacity	2500	J/kgK
Internal air temperature	20.0	C
Internal convection coefficient	3.1	W/m^2K
Step size of the internal heat gain	27000	W
Radiative fraction of the internal heat gain	0.5 and 1.0	-

Plotted results: 100% & 50% radiative heat gain





Note: Before hour zero, there is no internal heat gain

Tabulated results: 100% & 50% radiative heat gain

Time	100% RADIATIVE		50% RADIATIVE	
	Analytical load (W)	ESP-r load (W)	Analytical Load (W)	ESP-r Load (W)
0	0	0	13500	40
1	9565	6930	18279	16950
2	11996	10770	19495	18870
3	13496	13000	20245	19980
4	14574	14430	20784	20700
5	15416	15450	21205	21210
6	16114	16230	21554	21600
7	16720	16880	21857	21930
8	17262	17440	22128	22210
9	17758	17950	22376	22460
10	18218	18410	22606	22690
11	18650	18840	22822	22910
12	19058	19250	23026	23110
13	19443	19630	23219	23300
14	19808	19990	23401	23480
15	20156	20330	23575	23660
16	20485	20650	23740	23820
17	20799	20960	23897	23970
18	21098	21250	24046	24120
19	21382	21530	24188	24260
20	21652	21790	24323	24390
21	21909	22050	24452	24520
22	22154	22290	24574	24640
23	22387	22510	24691	24750
24	22609	22730	24802	24860
25	22820	22940	24907	24960

26	23021	23130	25008	25060
27	23212	23320	25103	25150
28	23394	23500	25194	25240
29	23567	23670	25281	25330
30	23732	23830	25363	25410
31	23889	23980	25442	25490
32	24038	24130	25516	25560
33	24180	24260	25587	25630
34	24316	24400	25655	25690
35	24445	24520	25719	25760
36	24567	24640	25781	25820
37	24684	24760	25839	25870
38	24795	24860	25894	25930
39	24900	24970	25947	25980
40	25001	25070	25998	26030
41	25097	25160	26045	26080
42	25188	25250	26091	26120
43	25274	25330	26134	26160
44	25357	25410	26176	26200
45	25435	25490	26215	26240
46	25510	25560	26252	26280
47	25581	25630	26288	26310
48	25649	25700	26322	26350
49	25714	25760	26354	26380
50	25775	25820	26385	26410
51	25833	25880	26414	26440
52	25889	25930	26442	26460
53	25942	25980	26468	26490
54	25992	26030	26493	26510
55	26040	26080	26517	26540
56	26086	26120	26540	26560
57	26129	26170	26562	26580
58	26170	26210	26582	26600
59	26210	26240	26602	26620
60	26247	26280	26621	26640
61	26283	26320	26638	26660
62	26317	26350	26655	26670
63	26349	26380	26672	26690
64	26380	26410	26687	26700
65	26409	26440	26701	26720
66	26437	26470	26715	26730
67	26463	26490	26729	26740
68	26488	26520	26741	26760
69	26512	26540	26753	26770
70	26535	26560	26765	26780
71	26557	26580	26776	26790
72	26578	26600	26786	26800
73	26597	26620	26796	26810

74	26616	26640	26805	26820
75	26634	26660	26814	26830
76	26651	26670	26822	26840
77	26667	26690	26831	26840
78	26682	26700	26838	26850
79	26697	26720	26846	26860
80	26711	26730	26853	26870
81	26724	26740	26859	26870
82	26737	26760	26865	26880
83	26749	26770	26871	26880
84	26760	26780	26877	26890
85	26771	26790	26883	26890
86	26781	26800	26888	26900
87	26791	26810	26893	26900
88	26801	26820	26897	26910
89	26810	26830	26902	26910
90	26818	26840	26906	26920
91	26826	26840	26910	26920
92	26834	26850	26914	26930
93	26841	26860	26918	26930
94	26848	26870	26921	26930
95	26855	26870	26924	26940
96	26861	26880	26928	26940
97	26867	26880	26931	26940
98	26873	26890	26933	26940
99	26878	26890	26936	26950
100	26883	26900	26939	26950
101	26888	26900	26941	26950
102	26893	26910	26944	26950
103	26898	26910	26946	26960
104	26902	26920	26948	26960
105	26906	26920	26950	26960
106	26910	26930	26952	26960
107	26913	26930	26954	26960
108	26917	26930	26956	26970
109	26920	26940	26957	26970
110	26923	26940	26959	26970
111	26926	26940	26960	26970
112	26929	26940	26962	26970
113	26932	26950	26963	26970
114	26935	26950	26964	26970
115	26937	26950	26966	26980
116	26939	26950	26967	26980
117	26942	26960	26968	26980
118	26944	26960	26969	26980
119	26946	26960	26970	26980
120	26948	26960	26971	26980
121	26950	26960	26972	26980

122	26951	26970	26973	26980
123	26953	26970	26974	26980
124	26955	26970	26974	26980
125	26956	26970	26975	26980
126	26957	26970	26976	26990
127	26959	26970	26976	26990
128	26960	26970	26977	26990
129	26961	26980	26978	26990
130	26963	26980	26978	26990
131	26964	26980	26979	26990
132	26965	26980	26979	26990
133	26966	26980	26980	26990
134	26967	26980	26980	26990
135	26968	26980	26981	26990
136	26969	26980	26981	26990
137	26969	26980	26982	26990
138	26970	26980	26982	26990
139	26971	26980	26983	26990
140	26972	26990	26983	26990
141	26972	26990	26983	26990
142	26973	26990	26984	26990
143	26974	26990	26984	26990
144	26974	26990	26984	26990
145	26975	26990	26984	26990
146	26975	26990	26985	26990
147	26976	26990	26985	26990
148	26976	26990	26985	26990
149	26977	26990	26985	26990
150	26977	26990	26986	27000
151	26978	26990	26986	27000
152	26978	26990	26986	27000
153	26978	26990	26986	27000
154	26979	26990	26986	27000
155	26979	26990	26987	27000
156	26979	26990	26987	27000
157	26980	26990	26987	27000
158	26980	26990	26987	27000
159	26980	26990	26987	27000
160	26980	26990	26987	27000
161	26981	26990	26987	27000
162	26981	26990	26988	27000
163	26981	26990	26988	27000
164	26981	26990	26988	27000
165	26982	26990	26988	27000
166	26982	27000	26988	27000
167	26982	27000	26988	27000
168	26982	27000	13488	27000
169	17418	20030	8709	10010

170	14987	16200	7493	8100
171	13487	13960	6743	6980
172	12409	12530	6204	6270
173	11567	11520	5783	5760
174	10869	10740	5434	5370
175	10263	10090	5132	5050
176	9722	9530	4861	4760
177	9226	9020	4613	4510
178	8765	8560	4383	4280
179	8333	8130	4167	4070
180	7926	7730	3963	3860
181	7541	7350	3770	3670
182	7176	6990	3588	3490
183	6829	6650	3414	3320
184	6499	6330	3249	3160
185	6185	6020	3092	3010
186	5887	5730	2943	2860
187	5603	5450	2801	2730
188	5332	5190	2666	2590
189	5075	4940	2538	2470
190	4830	4700	2415	2350
191	4597	4470	2299	2240
192	4376	4260	2188	2130
193	4165	4050	2082	2030
194	3964	3850	1982	1930
195	3773	3670	1886	1830
196	3591	3490	1795	1750
197	3418	3320	1709	1660
198	3253	3160	1626	1580
199	3096	3010	1548	1500
200	2947	2860	1473	1430
201	2805	2730	1402	1360
202	2669	2590	1335	1300
203	2541	2470	1270	1230
204	2418	2350	1209	1170
205	2302	2240	1151	1120
206	2191	2130	1095	1060
207	2085	2030	1042	1010
208	1984	1930	992	960
209	1889	1830	944	920
210	1798	1750	899	870
211	1711	1660	855	830
212	1628	1580	814	790
213	1550	1510	775	750
214	1475	1430	738	720
215	1404	1360	702	680
216	1336	1300	668	650
217	1272	1230	636	620

218	1211	1180	605	590
219	1152	1120	576	560
220	1097	1060	548	530
221	1044	1010	522	510
222	993	960	497	480
223	945	920	473	460
224	900	870	450	440
225	857	830	428	420
226	815	790	408	400
227	776	750	388	380
228	738	720	369	360
229	703	680	351	340
230	669	650	334	320
231	637	620	318	310
232	606	590	303	290
233	577	560	288	280
234	549	530	274	270
235	523	510	261	250
236	497	480	249	240
237	473	460	237	230
238	450	440	225	220
239	429	420	214	210
240	408	400	204	200
241	388	380	194	190
242	370	360	185	180
243	352	340	176	170
244	335	320	167	160
245	319	310	159	150
246	303	290	152	150
247	289	280	144	140
248	275	270	137	130
249	262	250	131	130
250	249	240	124	120
251	237	230	118	110
252	226	220	113	110
253	215	210	107	100
254	204	200	102	100
255	194	190	97	90
256	185	180	93	90
257	176	170	88	90
258	168	160	84	80
259	160	150	80	80
260	152	150	76	70
261	145	140	72	70
262	138	130	69	70
263	131	130	65	60
264	125	120	62	60
265	119	110	59	60

266	113	110	56	50
267	107	100	54	50
268	102	100	51	50
269	97	90	49	50
270	93	90	46	40
271	88	90	44	40
272	84	80	42	40
273	80	80	40	40
274	76	70	38	40
275	72	70	36	30
276	69	70	34	30
277	66	60	33	30
278	62	60	31	30
279	59	60	30	30
280	57	50	28	30
281	54	50	27	30
282	51	50	26	20
283	49	50	24	20
284	46	40	23	20
285	44	40	22	20
286	42	40	21	20
287	40	40	20	20
288	38	40	19	20
289	36	30	18	20
290	34	30	17	20
291	33	30	16	20
292	31	30	16	10
293	30	30	15	10
294	28	30	14	10
295	27	30	13	10
296	26	20	13	10
297	24	20	12	10
298	23	20	12	10
299	22	20	11	10
300	21	20	11	10
301	20	20	10	10
302	19	20	10	10
303	18	20	9	10
304	17	20	9	10
305	16	20	8	10
306	16	10	8	10
307	15	10	7	10
308	14	10	7	10
309	13	10	7	10
310	13	10	6	10
311	12	10	6	10
312	12	10	6	10
313	11	10	6	10

314	11	10	5	0
315	10	10	5	0
316	10	10	5	0
317	9	10	5	0
318	9	10	4	0
319	8	10	4	0
320	8	10	4	0
321	7	10	4	0
322	7	10	4	0
323	7	10	3	0
324	6	10	3	0
325	6	10	3	0
326	6	10	3	0
327	6	10	3	0
328	5	0	3	0
329	5	0	3	0
330	5	0	2	0
331	5	0	2	0
332	4	0	2	0
333	4	0	2	0
334	4	0	2	0
335	4	0	2	0
336	4	0	2	0

Comment: The ESP-r results and analytical results match well in response to a step change in internal convective and/or radiative heat gain in the Internal Heat Gain case. Almost all differences in the zone load are within ±1%. As the situation in many step change cases, large difference occurs at the beginning of the step changes. This is suspected due to ESP-r takes the average change within the period the step change happens.

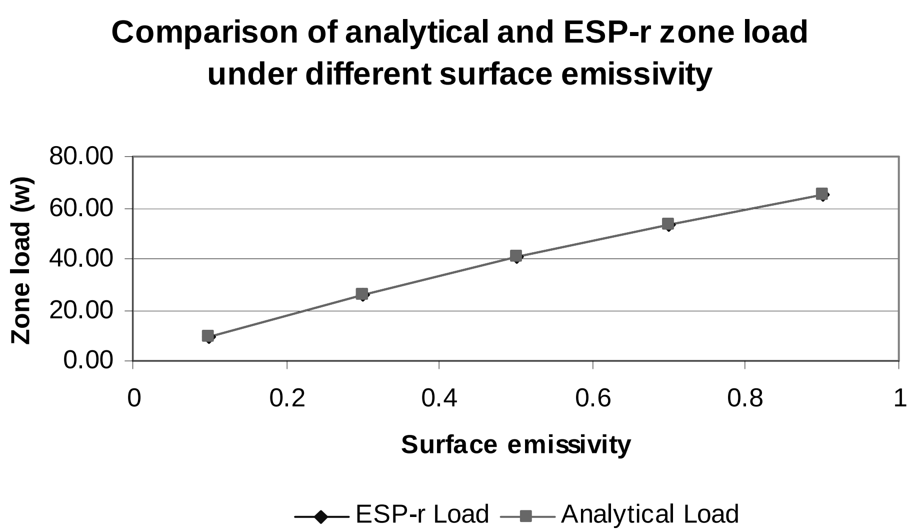
ESP-r single zone comparison results: Test ExtLWRad

Test parameters

Test parameters	Value	Units
Emissivity of the external surface	0.1 - 0.9	-
Thermal conductivity of the external surface	1.0	W/mK
Thickness of the external surface	0.1	m
Sky temperature	7.36	C
External air temperature	20	C
Internal air temperature	20	C
Outside correlation coefficient 'A'	12.5	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.33	-
Inside correlation coefficient 'A'	3.1	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.33	-

Tabulated and plotted results:

Emissivity of the external surface	ESP-r Load (w)	Analytical Load (w)
0.1	9.37	9.34
0.3	26.25	26.10
0.5	40.88	40.73
0.7	53.72	53.63
0.9	65.09	65.10



Comment: The ESP-r results are approximately the same as analytical solution in the external long wave radiation case, with a maximum difference of 0.57% for the emissivities tested. The sky temperature used in ESP-r needs to be obtained by using the trace facility in ESP-r. Selecting the view factors and long wave option in the trace facility will lead ESP-r dump the long wave radiation related information during the simulation process, which including the sky temperatures.

ESP-r single zone comparison results: Test IntRad

Test parameters

Test parameters	Value	Units
Width of the cuboid	3.0	m
Outside air temperature	40	C
Inside air temperature	20	C
External convection coefficient	12.5	W/m^2K
Internal convection coefficient	3.1	W/m^2K

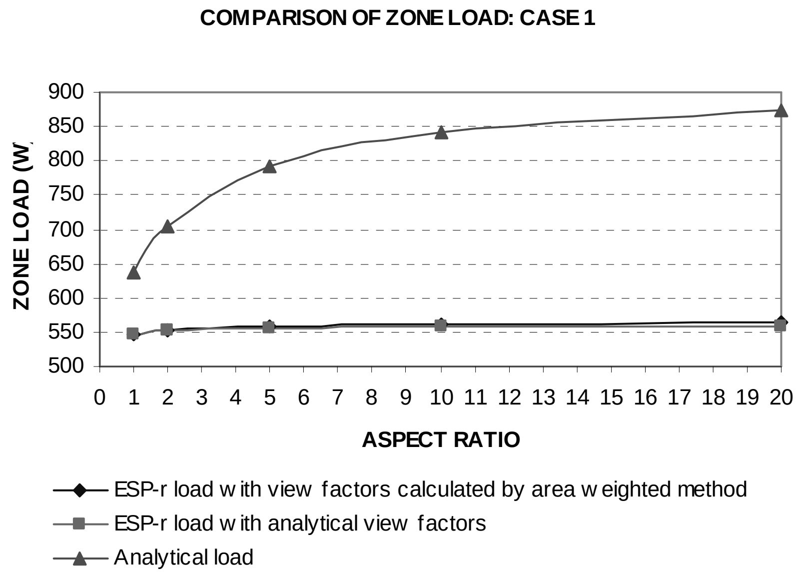
(Note: Emissivities of the surfaces as listed in different cases.)

Tabulated and plotted results:

Note: With the new released ESP-r as of June 2002, the view factor calculation module ("mrt") of ESP-r has been found to work correctly. The view factors calculated by "mrt" now agree with the analytical view factors. Therefore, in the results shown below, the "*ESP-r load with analytical view factors*" should be equal to the "*ESP-r load with view factors calculated by the mrt module*". In another word, the "mrt" problem mentioned in the following comments has already been fixed.

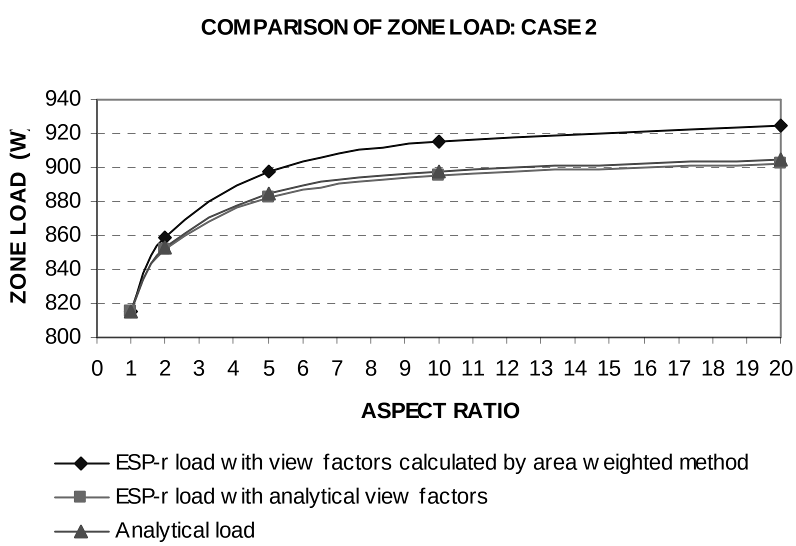
Case 1: *EMISSIVITY of the EXTERIOR SURFACE =0.9*
EMISSIVITY of OTHER SURFACES =0.1

Aspect ratio	ESP-r load with view factors calculated by area weighted method (w)	ESP-r load with analytical view factors (w)	Analytical load (w)
1	545.34	545.34	636.89
2	552.70	551.76	705.07
5	559.25	556.71	793.39
10	561.99	558.56	842.82
20	563.49	559.61	874.43



Case 2: *EMISSIVITY of ALL THE SURFACES =0.9*

Aspect ratio	ESP-r load with view factors calculated by area weighted method (w)	ESP-r load with analytical view factors (w)	Analytical load (w)
1	814.86	814.86	814.71
2	858.24	851.70	852.59
5	897.88	882.87	884.78
10	914.78	895.44	897.87
20	924.17	902.37	904.92

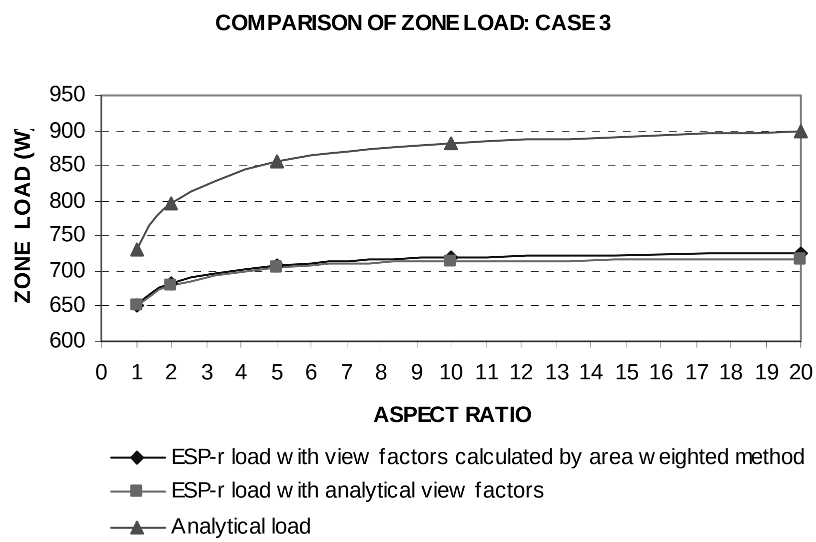


Case 3:

EMISSIVITY of the EXTERIOR SURFACE =0.9

EMISSIVITY of the SURFACE OPPOSITE to the EXTERIOR SURFACE =0.1
EMISSIVITY of OTHER SURFACES =0.3

Aspect ratio	ESP-r load with view factors calculated by area weighted method (w)	ESP-r load with analytical view factors (w)	Analytical load (w)
1	650.84	650.84	730.55
2	681.90	681.04	796.90
5	708.75	705.09	857.15
10	719.69	712.48	883.01
20	725.81	716.87	897.39



Comment:

1. The “default” view factor calculation in ESP-r is done by simple area-weighted method, which can create exact view factors only for a perfect cubic. The area-weighted method is clearly shown to be incorrect in all three cases tested. The view factor calculation module “mrt” of ESP-r is currently not working. “mrt” is claimed to be used for more accurate view factor calculation.
2. It was found that in case 2, where the surface emissivities are all same high value (0.9), the ESP-r results match with analytical solution well (with maximum error percentage of 0.28%), using analytical view factors manually edited into the view factor file.
3. When various relatively low surface emissivities were set, significant deviation was found between the ESP-r results and the analytical results (with maximum error percentage of 36.00% for case 1 and 20.12% for case 3 under analytical view factors). This is because ESP-r considers the ray paths of diffuse reflections involving only three surfaces at a time (means direct reflections between surfaces i and j, with reflections to and from a third surface k; reflections from all k-th surfaces are then summed to account for all surfaces in the enclosure). This simplification becomes inaccurate in the case of low emmisivity surfaces (Clark 1985).

ESP-r comparison results: Test Infiltration-1
(Single zone & inter-zone)

Test parameters

Test parameters	Value	Units
Outside air temperature	10	C
Inside air temperature	20	C
Outside humidity ratio	0.0046	-
Infiltration rate	0.5	m^3/s

Tabulated results:

ESP-r Infiltration Load (W)	Analytical Infiltration Load (W)
5940.15	6304.72

Note: Atmospheric pressure = 101325 pa

Comment:

1. A difference of 5.78% in the test zone infiltration loads was found between ESP-r result and the analytical result in the Infiltration-1 case.
2. By looking through the source code of ESP-r, it appears this deviation comes from the different method used by ESP-r to calculate the infiltration load. ESP-r supplies a simple way to schedule the infiltration flow rate of the test zone in addition to the network airflow calculation and the CFD (Computational Fluid Dynamics) airflow calculations. In this simple schedule, the infiltration flow rate is specified by the user in Air Changes per Hour (ACH). An infiltration conductance is then calculated as the infiltration flow rate (ACH) multiplied by the zone volume and a coefficient of 0.33. The infiltration load is the product of the resulted infiltration conductance and the inside-outside air temperature difference.

   Check the result manually for this test case, the infiltration flow rate is about 66.667 (ACH), multiplied by the test zone volume (27 m^3) and the coefficient 0.33, the infiltration conductance is 594.0. The inside-outside air temperature difference is 10 (C), the product of the infiltration conductance and the inside-outside air temperature difference is 5940.0. Both the infiltration conductance and the infiltration load is approximately the same as the trace output of the ESP-r simulation.

   No reference has been identified regarding this method of infiltration load calculation either in the ESP-r source code or in the ESP-r user's guide up to this time. The coefficient of 0.33 is treated like a hard code in the source code, without any comment about its source. It seems like 0.33 is a constant value representing the product of the density and the specific heat of the air (ρc_p) divided by a unit conversion factor of 3600. The specific heat of air used in ESP-r is 1006 J/kgk (got by looking through the source code). It then appears that ESP-r is using a constant density for the air under all conditions, regardless what the air temperature is. Applying a constant air density for all conditions in infiltration load calculation is obviously not as accurate as the way in the analytical solution.

3. Applying the test in an inter-zone case created same result. This was done by setting up a zone in the condition of outside and specifying the original infiltration rate for the inside zone as a ventilation rate from this zone.

ESP-r comparison results: Test Infiltration-2
(Single zone & inter-zone)

Test parameters

Test parameters	Value	Units
Outside air temperature	10	C
Inside air temperature	20	C
Outside humidity ratio	0.0046	-
Discharge coefficient "C_D"	0.6	-
Flow exponent "x"	0.65	-

Tabulated results:

Single zone case:

ESP-r Infiltration Load (W)	Analytical Infiltration Load (W)
1493.27	1510.30

Note: Atmospheric pressure = 101325 pa

Inter-zone case:

ESP-r Zone Load (W)		Analytical Zone Load (W)	
Cooling zone	Heating zone	Cooling zone	Heating zone
-1468.57	1493.27	-1510.30	1510.30

Comment:

1. Rather than scheduling the test zone infiltration rate as in the Infiltration-1 case, this test is done by defining an airflow network in ESP-r. The network is defined as two nodes (the test zone internal node and the outside boundary node) connected by an opening component (one for opening 1, another for opening 2 as in the analytical test). The opening component is chosen to be the same type as used by the analytical solution (Power law flow component, type17 in ESP-r). The flow coefficient and flow exponent of the opening component is specified to be the same as that in the analytical solution.
2. The mass flow solver (mfs) of ESP-r supplies three definable iteration stop criteria. One is the largest percentage residual flow error allowed in any node (ERRMAX, default is 0.01); the second is the largest absolute residual flow error allowed in any node (FLOMAX, default is 0.0005); the third is the maximum number of iterations allowed during one time step. Iteration stops whenever a stop criterion is reached. There is also a "flag" indicating whether the iteration process was successful (if yes OK=1 else OK=0) (Hensen 1991; ESRU 1996).

It was found that the "OK" flag was always 0.00 in the airflow result file for this test, indicating the network airflow solution was unsuccessful. However the number of iterations was much less than the maximum number of iterations allowed. Debugging the source code execution for this test clearly showed that the iteration was stopped because the largest percentage residual flow error criterion was reached (ERRMAX=0.00834, less than 0.01). The value of the "OK" flag (IOK in the source code) was clearly 1 not 0, indicating the iteration process was successful not failed. The "OK" flag only became 0 when it appeared in the output file.

Carefully checking the source code, it was found the problem is caused by the output format for the "OK" flag. The following lines appear in the MFOUTP subroutine (mfmach.F) of ESP-r:

```
C Date, time, climate data, # of iterations  and solution success flag
      if(irdact.eq.0) then
      WRITE(IFRES,1000)
IRD,IRM,IRY,FLWTIM,DRYB,WDIR,WSPD,ITER,IOK
^
^
^
1000 FORMAT(' Date: ',I2,'/',I2,'/',I4,1X,F6.3,2X,
     &       'Dryb=',F5.1,'  Wdir=',F5.0,'  Wvel=',F5.1,3X,'It=',I5,
     &       ' OK=',F4.2)
```

But IOK is of integer type in the source code (in Fortran 77 language). Revising the output format for the "OK" flag as " 'OK=',I2" instead of " ' OK=',F4.2" and re-run the test, the "OK" flag became 1 in the output file.

This is probably only a little bug in the source code, but it did cause confusion whenever doing an airflow network simulation with mfs.

3. For the single zone case, the difference in the test zone infiltration loads between ESP-r result and the analytical result is about 1.13%.
4. The ESP-r calculated result is approximately the same as the analytical solution because the default stack effect calculation in ESP-r is similar to the approach by Walton (Hensen 1991), which is also the source of the analytical solution.
5. Like in the Infiltration-1 test, this test was also applied to an inter-zone case. The resulted "heating" zone load of the inter-zone case was exactly the same as that in a single zone case. The difference in the "cooling" zone load between the ESP-r result and the analytical result is about 2.76%.
6. It should be noted that for the inter-zone case, the absolute zone loads for both zones are equal in the analytical solution, while it's different in the ESP-r result. It is believed this be due to the mass flow residual caused by the iteration process. The resulted mass flow rates from ESP-r are: 0.14844 kg/s from the "cooling" zone to the "heating" zone; 0.14598 kg/s from the "heating" zone to the "cooling"

zone. The specific heat of air used in ESP-r is 1006 J/kgk (got through the source code). Multiply the mass flow rate to each zone by the specific heat of air and the temperature difference between the two zones respectively, the resulted zone loads (heating & cooling) are very close to the zones loads at the ESP-r output file.

ESP-r inter-zone comparison results: Test SSCond

Test parameters

Test Parameter	Value	Units
Number of fabric layers	3	-
Thermal conductivity: Layer 1	0.1	W/m.K
Thickness: Layer 1	0.1	m
Thermal conductivity: Layer 2	0.05	W/m.K
Thickness: Layer 2	0.05	m
Thermal conductivity: Layer 3	0.25	W/m.K
Thickness: Layer 3	0.01	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient 'A'	3.1	$W/m^2.K$
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.0	-
Inside correlation coefficient 'A'	3.1	$W/m^2.K$
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.0	-

Tabulated results

ESP-r result load in one hour	**Analytical solution load in one hour**
wh	**wh**
100.53	100.36

Comment: The ESP-r result matches well with the analytical solution for the Steady State Conduction case with the maximum difference of 0.17% for zone load in one hour.

ESP-r inter-zone comparison results: Test SSConv

Test parameters

Test Parameter	Value	Units
Thermal conductivity	1.0	W/m.K
Thickness	0.1	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	3.076	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated results

ESP-r result load in one hour (wh)	Analytical solution load in one hour (wh)
362.31	359.91

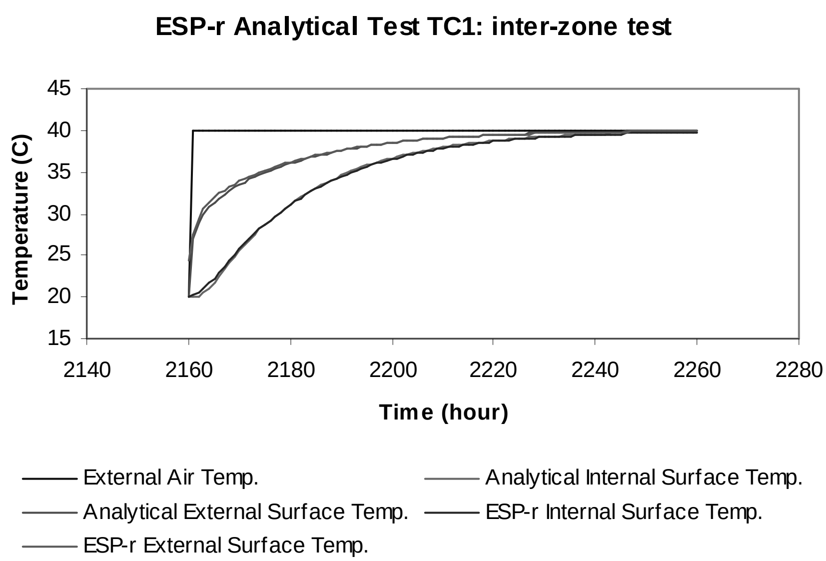
Comment: The ESP-r result matches well with the analytical solution for the Steady State Convection case with the maximum difference of 0.67% for zone load in one hour.

ESP-r inter-zone comparison results: Test Tc1

Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	20.0	^oC
Temperature step (ΔT)	20.0	^oC
External convection coefficient	3.1	$W/m^2.K$

Plotted result



Tabulated results

Note: the internal surface temperature in the ESP-r test corresponds to the surface of the inter-zone structure facing to the salve zone, and the external surface temperature corresponds to the surface facing to the master zone.

Time (hour)	External Air Temp. (C)	Analytical		ESP-r	
		Internal Surface Temp. (C)	External Surface Temp. (C)	Internal Surface Temp. (C)	External Surface Temp. (C)
2160	20.00	20.00	20.00	20.02	24.43
2161	40.00	20.00	27.06	20.19	27.59
2162	40.00	20.12	28.85	20.54	29.41

2163	40.00	20.49	29.96	21.04	30.55
2164	40.00	21.07	30.76	21.65	31.34
2165	40.00	21.77	31.39	22.31	31.94
2166	40.00	22.53	31.91	23.01	32.43
2167	40.00	23.30	32.35	23.71	32.85
2168	40.00	24.06	32.76	24.41	33.22
2169	40.00	24.80	33.12	25.10	33.56
2170	40.00	25.52	33.47	25.76	33.87
2171	40.00	26.21	33.79	26.41	34.17
2172	40.00	26.86	34.09	27.03	34.45
2173	40.00	27.49	34.38	27.62	34.71
2174	40.00	28.09	34.65	28.19	34.95
2175	40.00	28.66	34.90	28.73	35.19
2176	40.00	29.21	35.15	29.25	35.41
2177	40.00	29.72	35.38	29.75	35.63
2178	40.00	30.22	35.60	30.22	35.83
2179	40.00	30.69	35.82	30.68	36.02
2180	40.00	31.13	36.02	31.11	36.21
2181	40.00	31.56	36.21	31.52	36.38
2182	40.00	31.97	36.39	31.91	36.55
2183	40.00	32.35	36.56	32.29	36.71
2184	40.00	32.72	36.73	32.64	36.86
2185	40.00	33.07	36.89	32.98	37.01
2186	40.00	33.40	37.04	33.31	37.15
2187	40.00	33.72	37.18	33.62	37.28
2188	40.00	34.02	37.31	33.91	37.40
2189	40.00	34.31	37.44	34.19	37.52
2190	40.00	34.58	37.57	34.46	37.64
2191	40.00	34.84	37.68	34.72	37.75
2192	40.00	35.09	37.79	34.96	37.85
2193	40.00	35.32	37.90	35.20	37.95
2194	40.00	35.55	38.00	35.42	38.05
2195	40.00	35.76	38.10	35.63	38.14
2196	40.00	35.97	38.19	35.83	38.22
2197	40.00	36.16	38.27	36.03	38.31
2198	40.00	36.34	38.36	36.21	38.38
2199	40.00	36.52	38.44	36.39	38.46
2200	40.00	36.69	38.51	36.55	38.53
2201	40.00	36.85	38.58	36.71	38.60
2202	40.00	37.00	38.65	36.86	38.66
2203	40.00	37.14	38.72	37.01	38.73
2204	40.00	37.28	38.78	37.15	38.78
2205	40.00	37.41	38.84	37.28	38.84
2206	40.00	37.53	38.89	37.41	38.89
2207	40.00	37.65	38.95	37.53	38.95
2208	40.00	37.77	39.00	37.64	38.99
2209	40.00	37.87	39.04	37.75	39.04
2210	40.00	37.97	39.09	37.85	39.09

2211	40.00	38.07	39.13	37.95	39.13
2212	40.00	38.16	39.18	38.05	39.17
2213	40.00	38.25	39.22	38.14	39.21
2214	40.00	38.34	39.25	38.22	39.24
2215	40.00	38.42	39.29	38.31	39.28
2216	40.00	38.49	39.32	38.39	39.31
2217	40.00	38.57	39.36	38.46	39.34
2218	40.00	38.63	39.39	38.53	39.37
2219	40.00	38.70	39.42	38.60	39.40
2220	40.00	38.76	39.44	38.66	39.43
2221	40.00	38.82	39.47	38.73	39.46
2222	40.00	38.88	39.50	38.79	39.48
2223	40.00	38.93	39.52	38.84	39.51
2224	40.00	38.98	39.54	38.90	39.53
2225	40.00	39.03	39.57	38.95	39.55
2226	40.00	39.08	39.59	38.99	39.57
2227	40.00	39.12	39.61	39.04	39.59
2228	40.00	39.17	39.62	39.09	39.61
2229	40.00	39.21	39.64	39.13	39.63
2230	40.00	39.24	39.66	39.17	39.65
2231	40.00	39.28	39.68	39.21	39.66
2232	40.00	39.31	39.69	39.24	39.68
2233	40.00	39.35	39.71	39.28	39.69
2234	40.00	39.38	39.72	39.31	39.71
2235	40.00	39.41	39.73	39.34	39.72
2236	40.00	39.44	39.75	39.37	39.73
2237	40.00	39.46	39.76	39.40	39.75
2238	40.00	39.49	39.77	39.43	39.76
2239	40.00	39.51	39.78	39.46	39.77
2240	40.00	39.54	39.79	39.48	39.78
2241	40.00	39.56	39.80	39.51	39.79
2242	40.00	39.58	39.81	39.53	39.80
2243	40.00	39.60	39.82	39.55	39.81
2244	40.00	39.62	39.83	39.57	39.82
2245	40.00	39.64	39.84	39.59	39.83
2246	40.00	39.66	39.85	39.61	39.83
2247	40.00	39.67	39.85	39.63	39.84
2248	40.00	39.69	39.86	39.65	39.85
2249	40.00	39.70	39.87	39.66	39.86
2250	40.00	39.72	39.87	39.68	39.86
2251	40.00	39.73	39.88	39.69	39.87
2252	40.00	39.74	39.88	39.71	39.88
2253	40.00	39.76	39.89	39.72	39.88
2254	40.00	39.77	39.90	39.73	39.89
2255	40.00	39.78	39.90	39.75	39.89
2256	40.00	39.79	39.91	39.76	39.90
2257	40.00	39.80	39.91	39.77	39.90
2258	40.00	39.81	39.91	39.78	39.91

2259	40.00	39.82	39.92	39.79	39.91
2260	40.00	39.83	39.92	39.80	39.91

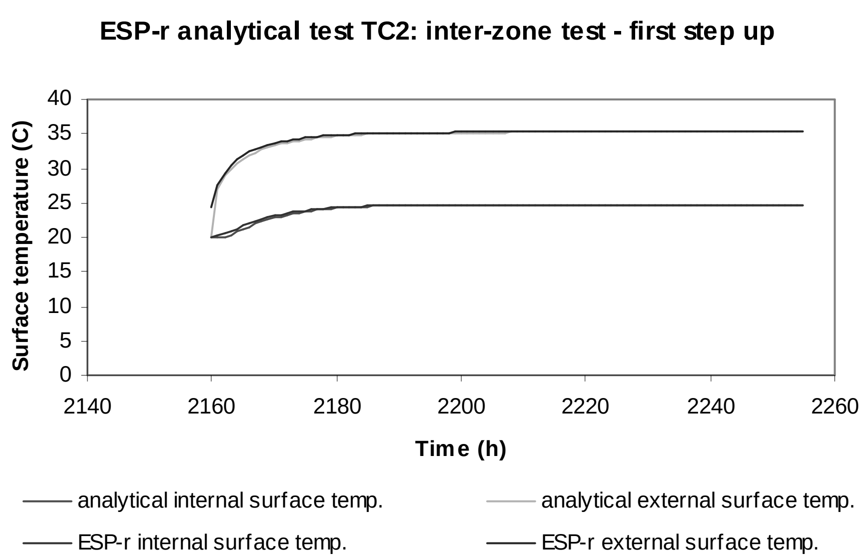
Comment: ESP-r responds to step changes in external dry bulb temperature in approximately the same way as the analytical solution. Except the first hour of the step change occurs, the maximum difference in external surface temperature was 4.43 ^{o}C, with 84 hours out of 100 hours having a difference within 0.25 ^{o}C. The maximum difference in internal surface temperature was 0.58 ^{o}C, with 87 hours out of 100 hours having a difference within 0.10 ^{o}C. It was suspected the maximum difference occurs because ESP-r takes the average of the step change within the hour the step change happens.

ESP-r inter-zone comparison results: Test Tc2

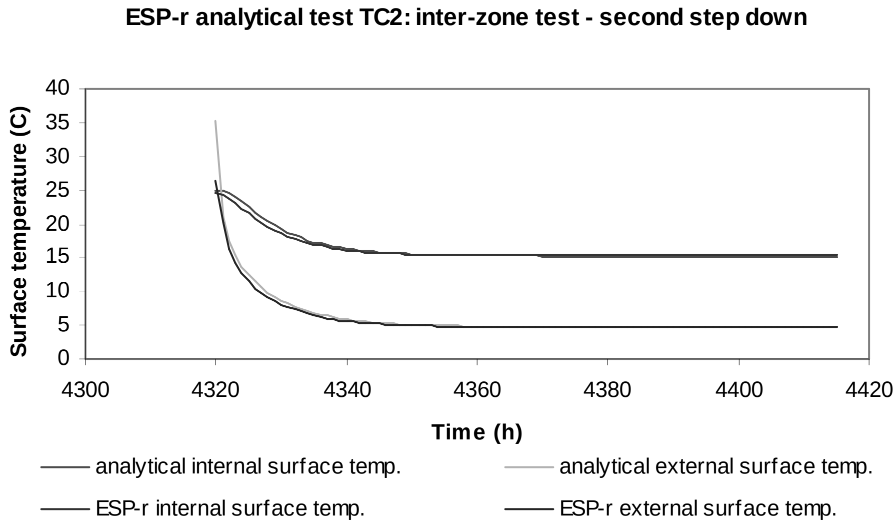
Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	20.0	^oC
Temperature step (ΔT)	20.0	^oC
External convection coefficient	3.1	$W/m^2.K$
Internal convection coefficient	3.1	$W/m^2.K$

Plotted results: First step change



Plotted results: Second step change



Tabulated results: First step

Note: the internal surface temperature in the ESP-r test corresponds to the surface of the inter-zone structure facing to the salve zone, and the external surface temperature corresponds to the surface facing to the master zone.

Time (hour)	ESP-r		Analytical	
	Internal surface temp. (C)	External surface temp. (C)	Internal surface temp. (C)	External surface temp. (C)
2160	20.02	24.43	20.00	20.00
2161	20.18	27.59	20.00	27.06
2162	20.46	29.41	20.09	28.85
2163	20.83	30.54	20.35	29.96
2164	21.22	31.33	20.73	30.76
2165	21.60	31.91	21.13	31.38
2166	21.96	32.37	21.52	31.88
2167	22.29	32.75	21.89	32.31
2168	22.59	33.07	22.23	32.67
2169	22.85	33.35	22.53	32.98
2170	23.09	33.59	22.79	33.25
2171	23.29	33.80	23.03	33.49
2172	23.47	33.98	23.23	33.70
2173	23.63	34.14	23.42	33.89
2174	23.77	34.28	23.58	34.05
2175	23.89	34.40	23.72	34.19
2176	23.99	34.50	23.85	34.32

2177	24.09	34.60	23.96	34.43
2178	24.17	34.68	24.05	34.52
2179	24.24	34.75	24.14	34.61
2180	24.30	34.81	24.21	34.68
2181	24.36	34.87	24.28	34.75
2182	24.41	34.92	24.34	34.81
2183	24.45	34.96	24.39	34.86
2184	24.48	35.00	24.43	34.90
2185	24.52	35.03	24.47	34.94
2186	24.55	35.06	24.51	34.98
2187	24.57	35.08	24.54	35.01
2188	24.59	35.10	24.57	35.04
2189	24.61	35.12	24.59	35.06
2190	24.63	35.14	24.61	35.08
2191	24.64	35.15	24.63	35.10
2192	24.65	35.17	24.65	35.12
2193	24.67	35.18	24.66	35.13
2194	24.68	35.19	24.67	35.14
2195	24.68	35.19	24.68	35.15
2196	24.69	35.20	24.69	35.16
2197	24.70	35.21	24.70	35.17
2198	24.70	35.21	24.71	35.18
2199	24.71	35.22	24.72	35.19
2200	24.71	35.22	24.72	35.19
2201	24.72	35.23	24.73	35.20
2202	24.72	35.23	24.73	35.20
2203	24.72	35.23	24.74	35.21
2204	24.73	35.24	24.74	35.21
2205	24.73	35.24	24.74	35.21
2206	24.73	35.24	24.75	35.21
2207	24.73	35.24	24.75	35.22
2208	24.73	35.24	24.75	35.22
2209	24.74	35.25	24.75	35.22
2210	24.74	35.25	24.75	35.22
2211	24.74	35.25	24.75	35.22
2212	24.74	35.25	24.76	35.23
2213	24.74	35.25	24.76	35.23
2214	24.74	35.25	24.76	35.23
2215	24.74	35.25	24.76	35.23
2216	24.74	35.25	24.76	35.23
2217	24.74	35.25	24.76	35.23
2218	24.74	35.25	24.76	35.23
2219	24.74	35.25	24.76	35.23
2220	24.74	35.25	24.76	35.23
2221	24.74	35.25	24.76	35.23
2222	24.74	35.25	24.76	35.23
2223	24.74	35.25	24.76	35.23
2224	24.74	35.25	24.76	35.23

2225	24.74	35.25	24.76	35.23
2226	24.74	35.25	24.76	35.23
2227	24.74	35.25	24.76	35.23
2228	24.74	35.25	24.76	35.23
2229	24.74	35.25	24.76	35.23
2230	24.74	35.25	24.76	35.23
2231	24.74	35.25	24.76	35.23
2232	24.74	35.25	24.76	35.23
2233	24.74	35.25	24.76	35.23
2234	24.74	35.26	24.76	35.23
2235	24.74	35.26	24.76	35.23
2236	24.74	35.26	24.76	35.23
2237	24.74	35.26	24.76	35.23
2238	24.74	35.26	24.76	35.23
2239	24.74	35.26	24.76	35.23
2240	24.74	35.26	24.76	35.23
2241	24.74	35.26	24.76	35.23
2242	24.74	35.26	24.76	35.23
2243	24.74	35.26	24.76	35.23
2244	24.74	35.26	24.76	35.23
2245	24.74	35.26	24.77	35.23
2246	24.74	35.26	24.77	35.23
2247	24.74	35.26	24.77	35.23
2248	24.75	35.26	24.77	35.23
2249	24.75	35.26	24.77	35.23
2250	24.75	35.26	24.77	35.23
2251	24.75	35.26	24.77	35.23
2252	24.75	35.26	24.77	35.23
2253	24.75	35.26	24.77	35.23
2254	24.75	35.26	24.77	35.23
2255	24.75	35.26	24.77	35.23

Tabulated results: Second step

Time (hour)	ESP-r		Analytical	
	Internal surface temp. (C)	External surface temp. (C)	Internal surface temp. (C)	External surface temp. (C)
4320	24.70	26.40	24.77	35.23
4321	24.39	20.07	24.76	21.12
4322	23.82	16.44	24.58	17.53
4323	23.09	14.17	24.06	15.31
4324	22.31	12.60	23.31	13.71
4325	21.54	11.44	22.51	12.47
4326	20.82	10.51	21.72	11.47
4327	20.16	9.75	20.98	10.62
4328	19.57	9.11	20.31	9.90
4329	19.04	8.56	19.71	9.27

4330	18.57	8.08	19.18	8.73
4331	18.16	7.66	18.71	8.25
4332	17.80	7.30	18.30	7.83
4333	17.49	6.98	17.93	7.46
4334	17.21	6.70	17.61	7.14
4335	16.97	6.46	17.32	6.85
4336	16.76	6.25	17.07	6.60
4337	16.57	6.06	16.85	6.38
4338	16.41	5.90	16.66	6.19
4339	16.26	5.75	16.49	6.02
4340	16.14	5.63	16.34	5.87
4341	16.03	5.52	16.21	5.74
4342	15.93	5.42	16.09	5.62
4343	15.85	5.34	15.99	5.52
4344	15.78	5.27	15.90	5.43
4345	15.71	5.20	15.82	5.35
4346	15.65	5.14	15.75	5.28
4347	15.60	5.09	15.69	5.22
4348	15.56	5.05	15.63	5.16
4349	15.52	5.01	15.58	5.11
4350	15.49	4.98	15.54	5.07
4351	15.46	4.95	15.51	5.04
4352	15.44	4.93	15.47	5.00
4353	15.41	4.90	15.44	4.97
4354	15.39	4.88	15.42	4.95
4355	15.38	4.87	15.40	4.93
4356	15.36	4.85	15.38	4.91
4357	15.35	4.84	15.36	4.89
4358	15.34	4.83	15.35	4.88
4359	15.33	4.82	15.33	4.86
4360	15.32	4.81	15.32	4.85
4361	15.31	4.80	15.31	4.84
4362	15.30	4.79	15.30	4.83
4363	15.30	4.79	15.29	4.82
4364	15.29	4.78	15.29	4.82
4365	15.29	4.78	15.28	4.81
4366	15.28	4.77	15.27	4.80
4367	15.28	4.77	15.27	4.80
4368	15.28	4.77	15.27	4.80
4369	15.27	4.76	15.26	4.79
4370	15.27	4.76	15.26	4.79
4371	15.27	4.76	15.26	4.79
4372	15.27	4.76	15.25	4.78
4373	15.27	4.76	15.25	4.78
4374	15.26	4.75	15.25	4.78
4375	15.26	4.75	15.25	4.78
4376	15.26	4.75	15.25	4.78
4377	15.26	4.75	15.24	4.77

4378	15.26	4.75	15.24	4.77
4379	15.26	4.75	15.24	4.77
4380	15.26	4.75	15.24	4.77
4381	15.26	4.75	15.24	4.77
4382	15.26	4.75	15.24	4.77
4383	15.26	4.75	15.24	4.77
4384	15.26	4.75	15.24	4.77
4385	15.26	4.75	15.24	4.77
4386	15.26	4.75	15.24	4.77
4387	15.26	4.75	15.24	4.77
4388	15.26	4.75	15.24	4.77
4389	15.26	4.75	15.24	4.77
4390	15.26	4.75	15.24	4.77
4391	15.26	4.75	15.24	4.77
4392	15.26	4.75	15.24	4.77
4393	15.26	4.75	15.24	4.77
4394	15.26	4.75	15.24	4.77
4395	15.26	4.75	15.24	4.77
4396	15.26	4.75	15.24	4.77
4397	15.26	4.75	15.24	4.77
4398	15.26	4.75	15.24	4.77
4399	15.26	4.75	15.24	4.77
4400	15.26	4.75	15.24	4.77
4401	15.26	4.75	15.24	4.77
4402	15.26	4.75	15.24	4.77
4403	15.26	4.75	15.24	4.77
4404	15.26	4.75	15.24	4.77
4405	15.26	4.75	15.24	4.77
4406	15.26	4.75	15.24	4.77
4407	15.26	4.75	15.24	4.77
4408	15.26	4.75	15.24	4.77
4409	15.26	4.75	15.24	4.77
4410	15.26	4.75	15.23	4.77
4411	15.26	4.75	15.23	4.77
4412	15.26	4.75	15.23	4.77
4413	15.26	4.75	15.23	4.77
4414	15.26	4.75	15.23	4.77
4415	15.26	4.75	15.23	4.77

Comment: The ESP-r result shows response to step changes in master zone dry bulb temperature in approximately the same way as the analytical solution. In the first step, the maximum difference in internal surface temperature is 0.49 ^oC, with 82 hours out of 95 hours have an difference within ±0.2 ^oC. In the second step, the maximum difference in internal surface temperature is -1.00 ^oC, with 76 hours out of 95 hours have an difference within ±0.2 ^oC. In both steps, there are 3-4 hours when the differences in external surface temperature are relatively large, but the temperature difference quickly reduces to within

±0.1 ^{o}C (or ±0.2 ^{o}C for the second step) after that. Again it was suspected the maximum difference occurs because ESP-r takes the average of the step change within the hour the step change happens.

ESP-r inter-zone comparison results: Test MSIdealCon

Test parameters

Test Parameter	Value	Units
Master zone air set point	20.0	C
Exterior convection coefficient	12.5	$W/m^2.K$
Interior convection coefficient	3.1	$W/m^2.K$
Time step	60	Min/step
External air temperature	35.3	C
Master zone convective heat input	20	W
Slave zone convective heat input	85	W

Tabulated results

Ideal system heat input into each zone (w)	Analytical result		ESP-r result	
	Master Zone Air Temp (c)	Slave Zone Air Temp (c)	Master Zone Air Temp (c)	Slave Zone Air Temp (c)
362.0	20	22.91	20	22.91

Comment: To do this test in ESP-r, two ideal basic heating/cooling control functions were first defined. The sensors of both functions measure the air temperature in the master zone. The actuator of one function actuates the air temperature in the master zone, the other actuate the air temperature in the slave zone. Both control functions have the same set point. The result of this way showed the master zone is controlled as expected, but the zone air temperature in the slave zone reacts in a free-floating way. By changing the set point of the slave zone to a different value than the master zone set point, the slave zone air temperature will be perfectly maintained at this set point.

Tracing the zone air energy balance in the simulation found that the sensor of the slave zone control function always measures the perfectly controlled master zone air temperature. When the set point of the two control functions are the same, the slave zone will not receive any system heat input and thus lead to a free floating slave zone air temperature. When the set point of the control functions are different, the slave zone control function will supply whatever the slave zone needs to maintain its set point, rather than the master zone system heat input. Therefore the slave zone air temperature is perfectly controlled at its own set point.

In order to supply the system heat input in the way as designed in the analytical test, it was then decided to do this test in another way. For the master zone, an ideal control loop using basic heating/cooling control law is defined. The maximum heating/cooling capacity is set to be very large to supply whatever the master needs to maintain the set point. For the slave zone, an ideal fixed heat injection/extraction control loop is defined. The heat injection/extraction flux is set to be the ideal system heat input that obtained from the analytical solution (result showed that ESP-r supplied the same amount of system heat input to the master zone, as expected). ESP-r results under this way matched well with analytical results.

ESP-r inter-zone comparison results: Test MSVAVCon

Test parameters

Test Parameter	Value	Units
Master zone air set point	22.0	C
The initial air temperature in the slave zone	17.0	C
The constant multiplier	1.2	-
The fixed system air temperature	15	C
Time step	6	Second/step
Convective heat gains to the master and slave zone	As shown in Figure MSVAVCon-A	W

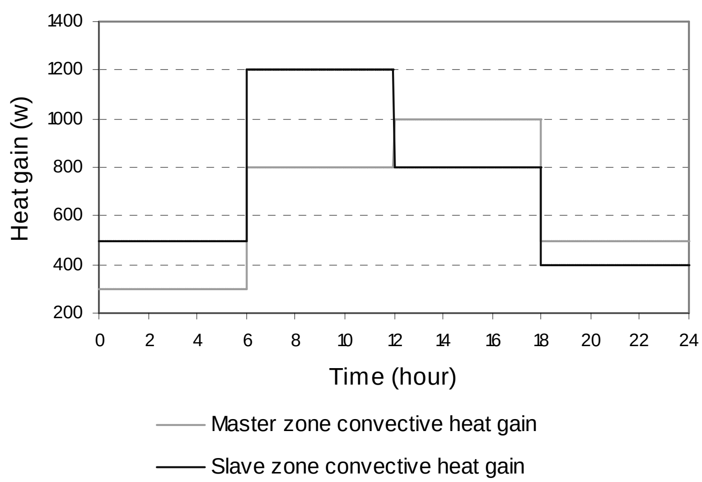


Figure MSVAVCon -A: Convective heat gains to the test zones

Plotted results

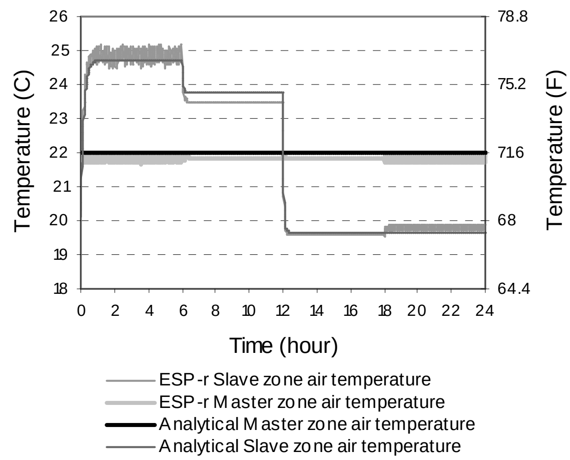


Figure MSVAVCon -B: Zone air temperatures predicted by ESP-r program and analytical solution

Comment: The results were obtained using a simulation time step of six seconds. The maximum differences between ESP-r and the analytical solution in the master and slave zone temperatures are 0.34 ^oC and 0.48 ^oC respectively. It might also be noted that some offset occurs in the master zone—this is caused by the proportional control of the airflow rate. Also, some system cycling is observable in the ESP-r solution for the first and fourth period of the day. During these times, the master zone is operating with a relatively low cooling load, and the damper controller appears to have too much gain. However, given the fact that the test zones have no thermal mass, except for the zone air, it is probably unrealistic to expect that perfect control be achieved.

In doing the test, an additional zone (the "mixing" zone) was defined to serve as a surrogate for a cold deck. A schematic representation of the airflow network is shown in Figure MSVAVCon-C. Standard ESP-r flow components were used to create the network. The four Type 15 power law flow components are specified with:

$$\dot{m} = a\Delta P^b \quad (1)$$

The flow exponent, *b*, is set to 1, and the values of *a* are set to cause the flow in the slave zone to be (nearly) exactly proportional to the flow to the master zone. The constant airflow rate fan, Type 35, is combined with a bypass loop (containing a Type 40 common orifice flow element) and a Type 410 damper.

A thermostat in the master zone controls the damper, and the specified airflow network is able to maintain the ratio between the airflow to the two zones within 2% of the desired ratio. This results in a close approximation to the test case.

In this control test, some transient inter-zone airflow re-circulation occurs. The hourly-average error in the zone loads is on the order of 6-8%. It is possible that this error could be reduced by a different choice of airflow network and/or components.

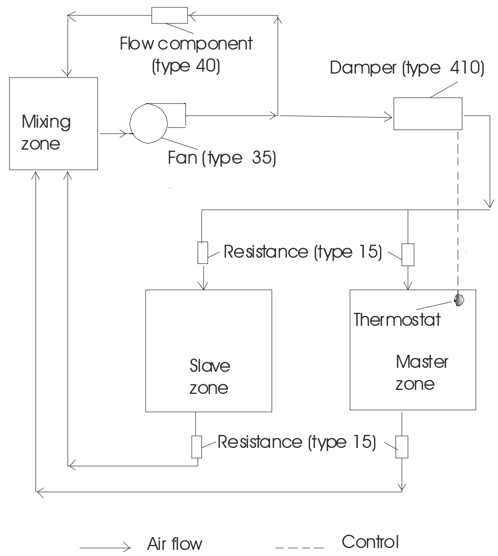


Figure MSVAVCon -C: Airflow Network Used in ESP-r for VAV control test with ESP-r program

ESP-r inter-zone comparison results: Test MSOnOffCon

Test parameters

Test Parameter	Value	Units
Master zone air set point	22.0	C
Dead band range	±0.1	C
The initial air temperature of both zones	17.0	C
The fixed system air temperature	15	C
The fixed system air volume flow rate to the master zone	0.1184	M^3/s
The constant multiplier	1.2	-
Time step	6	Second/step
Convective heat gains to the master and slave zone	As shown in Figure MSOnOffCon-A	W

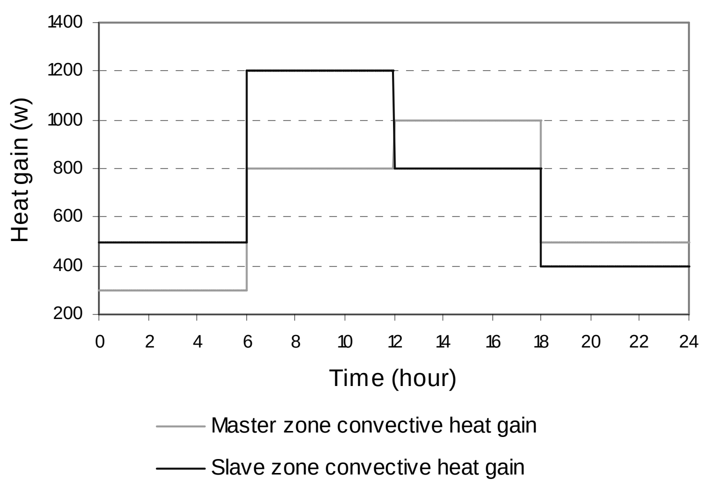


Figure MSOnOffCon -A: Convective heat gains to the test zones

Plotted results

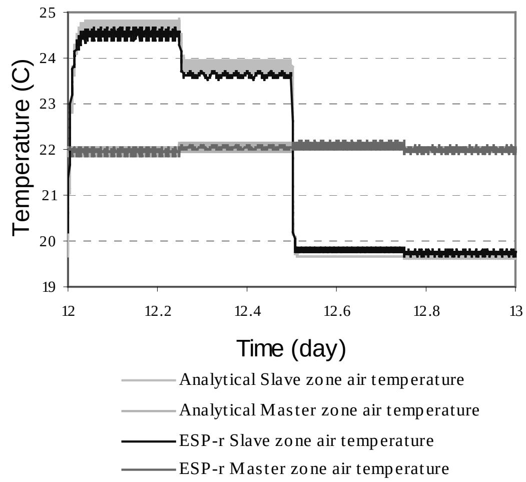


Figure MSOnOffCon - B: Zone air temperatures predicted by ESP-r program and analytical solution

Comment: The results were obtained using a simulation time step of six seconds. For this test, both the analytical solution and the ESP-r show the cycling behaviour expected for an on-off control. In the third period, the master zone is at its design capacity, and therefore, the system stays on all the time. ESP-r continues to cycle the system on and off. This may be due to the different value of c_p used by ESP-r. It might also be noted that ESP-r and the analytical solution appear to cycle at different frequencies. Although the ESP-r simulation is performed with six second time steps, results are only output every minute. This may mask some of the cycling behaviour. Again, given the atypically low thermal mass in the zone, it is probably unrealistic to expect a perfect match of the cycling frequency.

The On-Off control test uses an airflow network that is similar, but simpler, than the VAV network. The bypass loop and damper are eliminated, and the constant airflow rate fan is merely switched on and off. The configuration may experience some flow between the master zone and slave zone. This is eliminated by applying on-off control to some of the flow junctions.

EnergyPlus Analytical Testing Results

EnergyPlus single-zone comparison results: Test SSCond

Test parameters

Test Parameter	Value	Units
Number of fabric layers	3	-
Thermal conductivity: Layer 1	0.1	W/m.K
Thickness: Layer 1	0.1	m
Thermal conductivity: Layer 2	0.05	W/m.K
Thickness: Layer 2	0.05	m
Thermal conductivity: Layer 3	0.25	W/m.K
Thickness: Layer 3	0.05	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	10.22	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated results

EnergyPlus result load in one hour	Analytical solution load in one hour
wh	**wh**
102.94	102.94

Comment: The EnergyPlus resultant zone load is approximately the same as analytical zone load for the Steady State Conduction case.

EnergyPlus single-zone comparison results: Test SSConv

Test parameters

Test Parameter	Value	Units
Thermal conductivity	1.0	W/m.K
Thickness	0.1	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	10.22	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated results

EnergyPlus result load in one hour (wh)	Analytical solution load in one hour (wh)
516.31	516.31

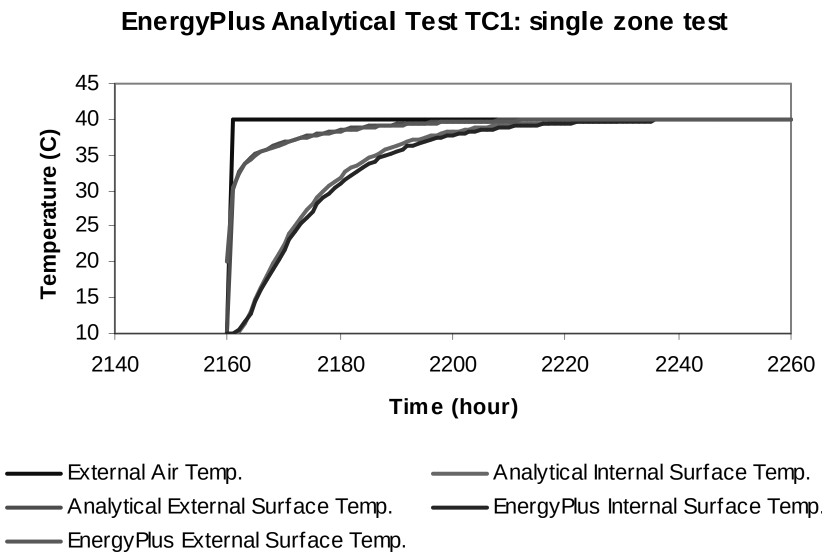
Comment: The EnergyPlus resultant zone load is approximately the same as analytical zone load for the Steady State Conduction case.

EnergyPlus single zone comparison results: Test Tc1

Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	10.0	^oC
Temperature step (ΔT)	30.0	^oC
External convection coefficient	10.22	$W/m^2.K$

Plotted result



Tabulated results

	External Air Temp.	Analytical		EnergyPlus	
		Internal Surface Temp.	External Surface Temp.	Internal Surface Temp.	External Surface Temp.
Time	(C)	(C)	(C)	(C)	(C)
2160	10.00	10.00	10.00	10.00	20.07
2161	40.00	10.01	30.18	10.08	30.37
2162	40.00	10.38	32.57	10.56	32.53
2163	40.00	11.48	33.76	11.56	33.70
2164	40.00	13.02	34.52	12.93	34.46
2165	40.00	14.74	35.07	14.46	35.01

2166	40.00	16.48	35.51	16.03	35.44
2167	40.00	18.15	35.88	17.58	35.80
2168	40.00	19.74	36.20	19.06	36.12
2169	40.00	21.23	36.49	20.47	36.40
2170	40.00	22.62	36.76	21.79	36.65
2171	40.00	23.90	37.00	23.03	36.89
2172	40.00	25.10	37.22	24.19	37.10
2173	40.00	26.20	37.43	25.27	37.30
2174	40.00	27.23	37.62	26.28	37.49
2175	40.00	28.17	37.80	27.22	37.66
2176	40.00	29.05	37.96	28.10	37.82
2177	40.00	29.87	38.11	28.91	37.97
2178	40.00	30.62	38.25	29.67	38.11
2179	40.00	31.32	38.38	30.38	38.24
2180	40.00	31.96	38.50	31.04	38.36
2181	40.00	32.56	38.61	31.65	38.47
2182	40.00	33.11	38.72	32.23	38.58
2183	40.00	33.62	38.81	32.76	38.67
2184	40.00	34.10	38.90	33.26	38.76
2185	40.00	34.53	38.98	33.72	38.85
2186	40.00	34.94	39.06	34.15	38.93
2187	40.00	35.32	39.13	34.55	39.00
2188	40.00	35.66	39.19	34.92	39.07
2189	40.00	35.99	39.25	35.27	39.13
2190	40.00	36.28	39.31	35.60	39.19
2191	40.00	36.56	39.36	35.90	39.25
2192	40.00	36.82	39.41	36.18	39.30
2193	40.00	37.05	39.45	36.44	39.35
2194	40.00	37.27	39.49	36.69	39.39
2195	40.00	37.47	39.53	36.91	39.43
2196	40.00	37.66	39.56	37.13	39.47
2197	40.00	37.84	39.60	37.32	39.51
2198	40.00	38.00	39.63	37.51	39.54
2199	40.00	38.14	39.65	37.68	39.57
2200	40.00	38.28	39.68	37.84	39.60
2201	40.00	38.41	39.70	37.98	39.63
2202	40.00	38.53	39.73	38.12	39.66
2203	40.00	38.64	39.75	38.25	39.68
2204	40.00	38.74	39.77	38.37	39.70
2205	40.00	38.83	39.78	38.48	39.72
2206	40.00	38.92	39.80	38.59	39.74
2207	40.00	39.00	39.81	38.68	39.76
2208	40.00	39.07	39.83	38.77	39.78
2209	40.00	39.14	39.84	38.86	39.79
2210	40.00	39.21	39.85	38.94	39.81
2211	40.00	39.27	39.86	39.01	39.82
2212	40.00	39.32	39.87	39.08	39.83
2213	40.00	39.37	39.88	39.14	39.84

2214	40.00	39.42	39.89	39.20	39.85
2215	40.00	39.46	39.90	39.25	39.86
2216	40.00	39.50	39.91	39.30	39.87
2217	40.00	39.54	39.91	39.35	39.88
2218	40.00	39.57	39.92	39.40	39.89
2219	40.00	39.60	39.93	39.44	39.90
2220	40.00	39.63	39.93	39.47	39.90
2221	40.00	39.66	39.94	39.51	39.91
2222	40.00	39.69	39.94	39.54	39.92
2223	40.00	39.71	39.95	39.57	39.92
2224	40.00	39.73	39.95	39.60	39.93
2225	40.00	39.75	39.95	39.63	39.93
2226	40.00	39.77	39.96	39.66	39.94
2227	40.00	39.79	39.96	39.68	39.94
2228	40.00	39.80	39.96	39.70	39.95
2229	40.00	39.82	39.97	39.72	39.95
2230	40.00	39.83	39.97	39.74	39.95
2231	40.00	39.84	39.97	39.76	39.96
2232	40.00	39.85	39.97	39.77	39.96
2233	40.00	39.87	39.97	39.79	39.96
2234	40.00	39.88	39.98	39.80	39.96
2235	40.00	39.88	39.98	39.82	39.97
2236	40.00	39.89	39.98	39.83	39.97
2237	40.00	39.90	39.98	39.84	39.97
2238	40.00	39.91	39.98	39.85	39.97
2239	40.00	39.92	39.98	39.86	39.97
2240	40.00	39.92	39.99	39.87	39.98
2241	40.00	39.93	39.99	39.88	39.98
2242	40.00	39.93	39.99	39.89	39.98
2243	40.00	39.94	39.99	39.89	39.98
2244	40.00	39.94	39.99	39.90	39.98
2245	40.00	39.95	39.99	39.91	39.98
2246	40.00	39.95	39.99	39.91	39.98
2247	40.00	39.95	39.99	39.92	39.99
2248	40.00	39.96	39.99	39.92	39.99
2249	40.00	39.96	39.99	39.93	39.99
2250	40.00	39.96	39.99	39.93	39.99
2251	40.00	39.97	39.99	39.94	39.99
2252	40.00	39.97	39.99	39.94	39.99
2253	40.00	39.97	39.99	39.95	39.99
2254	40.00	39.97	40.00	39.95	39.99
2255	40.00	39.98	40.00	39.95	39.99
2256	40.00	39.98	40.00	39.96	39.99
2257	40.00	39.98	40.00	39.96	39.99
2258	40.00	39.98	40.00	39.96	39.99
2259	40.00	39.98	40.00	39.96	39.99
2260	40.00	39.98	40.00	39.97	39.99

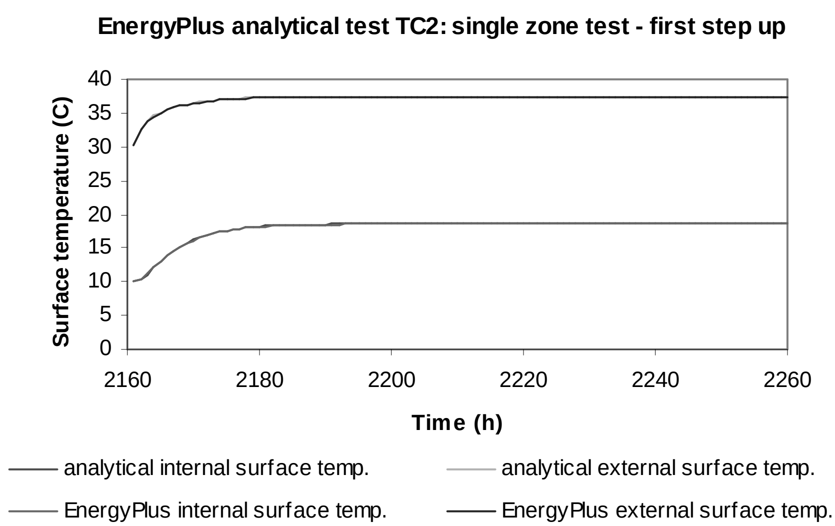
Comment: EnergyPlus responds to step changes in external dry bulb temperature in approximately the same way as the analytical solution. Except the first hour of the step change occurs, the maximum difference in external surface temperature was 0.19 ^oC, with 78 hours out of 100 hours having a difference within 0.1 ^oC. The maximum difference in internal surface temperature was 0.96 ^oC, with 59 hours out of 100 hours having a difference within 0.3 ^oC.

EnergyPlus single zone comparison results: Test Tc2

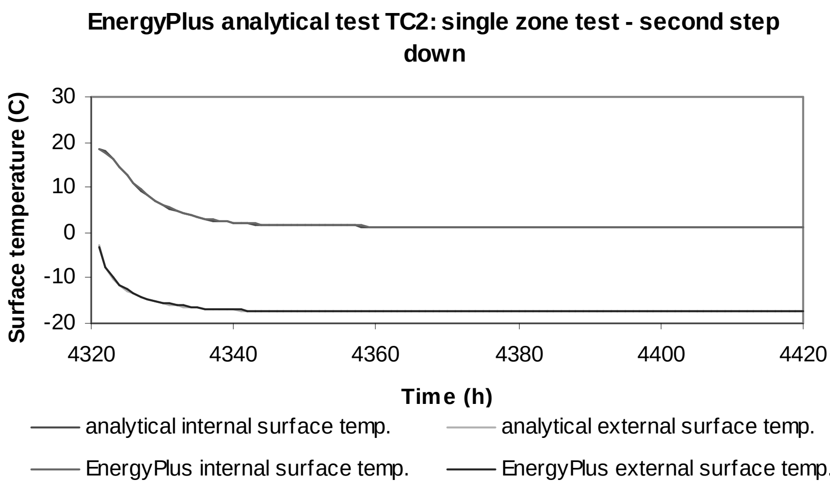
Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	10.0	^oC
Temperature step (ΔT)	30.0	^oC
External convection coefficient	10.22	$W/m^2.K$
Internal convection coefficient	3.076	$W/m^2.K$

Plotted results: First step change



Plotted results: Second step change



Tabulated results: First step

	EnergyPlus		Analytical	
Time	Internal surface temp.	External surface temp.	Internal surface temp.	External surface temp.
(hour)	(C)	(C)	(C)	(C)
2161	10.08	30.37	10.01	30.18
2162	10.47	32.53	10.30	32.57
2163	11.22	33.70	11.06	33.76
2164	12.12	34.45	12.02	34.52
2165	13.01	35.00	12.97	35.06
2166	13.82	35.41	13.84	35.47
2167	14.54	35.74	14.59	35.80
2168	15.16	36.01	15.23	36.07
2169	15.69	36.24	15.77	36.29
2170	16.14	36.42	16.22	36.48
2171	16.52	36.58	16.61	36.63
2172	16.84	36.71	16.93	36.76
2173	17.11	36.82	17.19	36.87
2174	17.34	36.92	17.42	36.96
2175	17.53	37.00	17.61	37.03
2176	17.70	37.06	17.77	37.09
2177	17.83	37.12	17.90	37.15
2178	17.95	37.16	18.01	37.19
2179	18.05	37.20	18.10	37.23
2180	18.13	37.24	18.18	37.26
2181	18.20	37.27	18.24	37.29
2182	18.26	37.29	18.30	37.31

2183	18.31	37.31	18.34	37.33
2184	18.35	37.33	18.38	37.34
2185	18.39	37.34	18.41	37.35
2186	18.42	37.35	18.44	37.36
2187	18.44	37.36	18.46	37.37
2188	18.46	37.37	18.48	37.38
2189	18.48	37.38	18.50	37.39
2190	18.49	37.39	18.51	37.39
2191	18.51	37.39	18.52	37.40
2192	18.52	37.40	18.53	37.40
2193	18.53	37.40	18.54	37.40
2194	18.53	37.40	18.54	37.41
2195	18.54	37.40	18.55	37.41
2196	18.55	37.41	18.55	37.41
2197	18.55	37.41	18.56	37.41
2198	18.55	37.41	18.56	37.41
2199	18.56	37.41	18.56	37.41
2200	18.56	37.41	18.56	37.41
2201	18.56	37.41	18.57	37.41
2202	18.56	37.41	18.57	37.42
2203	18.57	37.42	18.57	37.42
2204	18.57	37.42	18.57	37.42
2205	18.57	37.42	18.57	37.42
2206	18.57	37.42	18.57	37.42
2207	18.57	37.42	18.57	37.42
2208	18.57	37.42	18.57	37.42
2209	18.57	37.42	18.57	37.42
2210	18.57	37.42	18.57	37.42
2211	18.57	37.42	18.57	37.42
2212	18.57	37.42	18.57	37.42
2213	18.57	37.42	18.57	37.42
2214	18.57	37.42	18.58	37.42
2215	18.57	37.42	18.58	37.42
2216	18.57	37.42	18.58	37.42
2217	18.58	37.42	18.58	37.42
2218	18.58	37.42	18.58	37.42
2219	18.58	37.42	18.58	37.42
2220	18.58	37.42	18.58	37.42
2221	18.58	37.42	18.58	37.42
2222	18.58	37.42	18.58	37.42
2223	18.58	37.42	18.58	37.42
2224	18.58	37.42	18.58	37.42
2225	18.58	37.42	18.58	37.42
2226	18.58	37.42	18.58	37.42
2227	18.58	37.42	18.58	37.42
2228	18.58	37.42	18.58	37.42
2229	18.58	37.42	18.58	37.42
2230	18.58	37.42	18.58	37.42

2231	18.58	37.42	18.58	37.42
2232	18.58	37.42	18.58	37.42
2233	18.58	37.42	18.58	37.42
2234	18.58	37.42	18.58	37.42
2235	18.58	37.42	18.58	37.42
2236	18.58	37.42	18.58	37.42
2237	18.58	37.42	18.58	37.42
2238	18.58	37.42	18.58	37.42
2239	18.58	37.42	18.58	37.42
2240	18.58	37.42	18.58	37.42
2241	18.58	37.42	18.58	37.42
2242	18.58	37.42	18.58	37.42
2243	18.58	37.42	18.58	37.42
2244	18.58	37.42	18.58	37.42
2245	18.58	37.42	18.58	37.42
2246	18.58	37.42	18.58	37.42
2247	18.58	37.42	18.58	37.42
2248	18.58	37.42	18.58	37.42
2249	18.58	37.42	18.58	37.42
2250	18.58	37.42	18.58	37.42
2251	18.58	37.42	18.58	37.42
2252	18.58	37.42	18.58	37.42
2253	18.58	37.42	18.58	37.42
2254	18.58	37.42	18.58	37.42
2255	18.58	37.42	18.58	37.42
2256	18.58	37.42	18.58	37.42
2257	18.58	37.42	18.58	37.42
2258	18.58	37.42	18.58	37.42
2259	18.58	37.42	18.58	37.42
2260	18.58	37.42	18.58	37.42

Tabulated results: Second step

	EnergyPlus		Analytical	
Time	Internal surface temp.	External surface temp.	Internal surface temp.	External surface temp.
(hour)	(C)	(C)	(C)	(C)
4321	18.42	-3.32	18.56	-2.95
4322	17.63	-7.64	17.98	-7.71
4323	16.13	-9.97	16.45	-10.10
4324	14.34	-11.49	14.53	-11.62
4325	12.56	-12.57	12.63	-12.70
4326	10.93	-13.40	10.90	-13.53
4327	9.49	-14.07	9.40	-14.18
4328	8.25	-14.61	8.12	-14.72
4329	7.19	-15.06	7.04	-15.16
4330	6.30	-15.43	6.13	-15.53

4331	5.54	-15.74	5.36	-15.84
4332	4.89	-16.01	4.72	-16.10
4333	4.35	-16.23	4.19	-16.31
4334	3.89	-16.41	3.74	-16.49
4335	3.51	-16.57	3.36	-16.64
4336	3.18	-16.70	3.05	-16.77
4337	2.90	-16.82	2.78	-16.88
4338	2.67	-16.91	2.56	-16.96
4339	2.48	-16.99	2.38	-17.04
4340	2.31	-17.06	2.22	-17.10
4341	2.17	-17.11	2.09	-17.15
4342	2.06	-17.16	1.98	-17.20
4343	1.96	-17.20	1.89	-17.23
4344	1.87	-17.24	1.82	-17.26
4345	1.80	-17.26	1.75	-17.29
4346	1.74	-17.29	1.70	-17.31
4347	1.69	-17.31	1.65	-17.33
4348	1.65	-17.33	1.62	-17.34
4349	1.62	-17.34	1.58	-17.35
4350	1.59	-17.35	1.56	-17.36
4351	1.56	-17.36	1.54	-17.37
4352	1.54	-17.37	1.52	-17.38
4353	1.52	-17.38	1.50	-17.39
4354	1.51	-17.39	1.49	-17.39
4355	1.49	-17.39	1.48	-17.40
4356	1.48	-17.39	1.47	-17.40
4357	1.47	-17.40	1.46	-17.40
4358	1.47	-17.40	1.46	-17.41
4359	1.46	-17.40	1.45	-17.41
4360	1.45	-17.41	1.45	-17.41
4361	1.45	-17.41	1.44	-17.41
4362	1.45	-17.41	1.44	-17.41
4363	1.44	-17.41	1.44	-17.41
4364	1.44	-17.41	1.44	-17.41
4365	1.44	-17.41	1.43	-17.42
4366	1.44	-17.41	1.43	-17.42
4367	1.43	-17.42	1.43	-17.42
4368	1.43	-17.42	1.43	-17.42
4369	1.43	-17.42	1.43	-17.42
4370	1.43	-17.42	1.43	-17.42
4371	1.43	-17.42	1.43	-17.42
4372	1.43	-17.42	1.43	-17.42
4373	1.43	-17.42	1.43	-17.42
4374	1.43	-17.42	1.43	-17.42
4375	1.43	-17.42	1.43	-17.42
4376	1.43	-17.42	1.43	-17.42
4377	1.43	-17.42	1.43	-17.42
4378	1.43	-17.42	1.42	-17.42

4379	1.43	-17.42	1.42	-17.42
4380	1.43	-17.42	1.42	-17.42
4381	1.42	-17.42	1.42	-17.42
4382	1.42	-17.42	1.42	-17.42
4383	1.42	-17.42	1.42	-17.42
4384	1.42	-17.42	1.42	-17.42
4385	1.42	-17.42	1.42	-17.42
4386	1.42	-17.42	1.42	-17.42
4387	1.42	-17.42	1.42	-17.42
4388	1.42	-17.42	1.42	-17.42
4389	1.42	-17.42	1.42	-17.42
4390	1.42	-17.42	1.42	-17.42
4391	1.42	-17.42	1.42	-17.42
4392	1.42	-17.42	1.42	-17.42
4393	1.42	-17.42	1.42	-17.42
4394	1.42	-17.42	1.42	-17.42
4395	1.42	-17.42	1.42	-17.42
4396	1.42	-17.42	1.42	-17.42
4397	1.42	-17.42	1.42	-17.42
4398	1.42	-17.42	1.42	-17.42
4399	1.42	-17.42	1.42	-17.42
4400	1.42	-17.42	1.42	-17.42
4401	1.42	-17.42	1.42	-17.42
4402	1.42	-17.42	1.42	-17.42
4403	1.42	-17.42	1.42	-17.42
4404	1.42	-17.42	1.42	-17.42
4405	1.42	-17.42	1.42	-17.42
4406	1.42	-17.42	1.42	-17.42
4407	1.42	-17.42	1.42	-17.42
4408	1.42	-17.42	1.42	-17.42
4409	1.42	-17.42	1.42	-17.42
4410	1.42	-17.42	1.42	-17.42
4411	1.42	-17.42	1.42	-17.42
4412	1.42	-17.42	1.42	-17.42
4413	1.42	-17.42	1.42	-17.42
4414	1.42	-17.42	1.42	-17.42
4415	1.42	-17.42	1.42	-17.42
4416	1.42	-17.42	1.42	-17.42
4417	1.42	-17.42	1.42	-17.42
4418	1.42	-17.42	1.42	-17.42
4419	1.42	-17.42	1.42	-17.42
4420	1.42	-17.42	1.42	-17.42

Comment: The EnergyPlus result shows response to step changes in zone dry bulb temperature in approximately the same way as the analytical solution. In the first step, the maximum difference in internal surface temperature is 0.18 ^{o}C, with 97 hours out of 100 hours have an difference within ±0.1 ^{o}C. The maximum difference in external surface temperature is 0.19 ^oC, with 93 hours out of 100 hours have an difference within ±0.05 ^oC. In the second step, the maximum difference in internal surface temperature is -0.35 ^oC, with 85 hours out of 100 hours have an difference within ±0.1 ^oC. The maximum difference in external surface temperature is -0.37 ^oC, with 88 hours out of 100 hours have an difference within ±0.05 ^oC.

EnergyPlus single zone comparison results: Test ExtSolRad

Test parameters (Layer 1 is outside, layer 3 is inside)

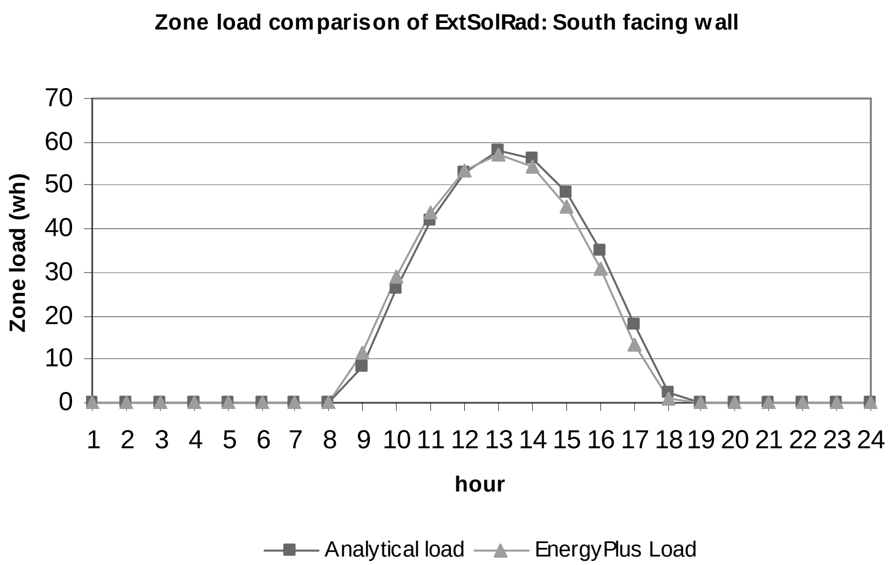
Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Solar absorption of the surface 'α'	0.9	-
Number of layers: 'N'	3	-
Thermal conductivity: layer 1 'K_1'	0.15	W/mK
Thickness: layer 1 'L_1'	0.1	m
Thermal conductivity: layer 2 'K_2'	0.05	W/mK
Thickness: layer 2 'L_2'	0.1	m
Thermal conductivity: layer 3 'K_3'	0.15	W/mK
Thickness: layer 3 'L_3'	0.1	m
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	12.49	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.0	-
Inside correlation coefficient 'A'	3.076	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.0	-

Tabulated results

Hour	Analytical load (wh)	EnergyPlus Load (wh)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	8.4124	11.3486
10	26.3177	29.0282

11	41.8726	43.7973
12	52.8181	53.4791
13	57.8145	57.1234
14	56.2308	54.3279
15	48.4330	45.2366
16	35.1659	30.9429
17	18.0858	13.5726
18	2.3190	0.7719
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000

Plotted results



Comment: EnergyPlus result shows it responds to exterior solar beam radiation in approximately the same way as analytical solution does in the condition of ExtSolRad case. The maximum difference between the loads calculated by EnergyPlus and the analytical solution is 4.51 W, which is about 7.81% of the peak analytical load.

The reflectance of the ground needs to be set to zero so that no radiation will be reflected from the ground to the external surface. Also the view factors between the walls and the ground are set to zero for the same reason.

EnergyPlus single zone comparison results: Test SolRadGlazing

Test parameters

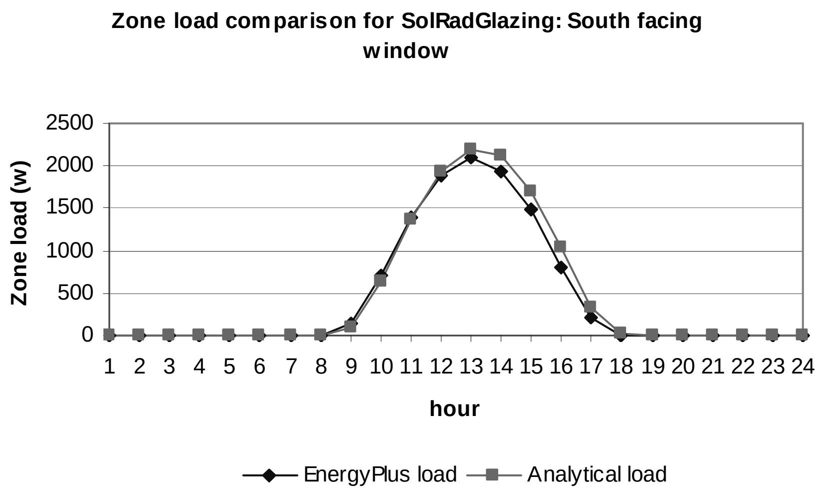
Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Thickness of the surface 'L'	0.0023	m
Extinction coefficient of the surface 'K'	10.0	m^{-1}
Refractive index of the surface 'n_g'	1.526	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.23	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.0	-
Inside correlation coefficient 'A'	3.076	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.0	-

Tabulated results

Hour	EnergyPlus load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	148.0409	100.0184
10	712.7608	641.0149
11	1391.1281	1360.4352
12	1894.2342	1931.6661
13	2090.6538	2200.8446
14	1941.8611	2115.1078
15	1476.9389	1699.2282
16	811.7562	1032.6289
17	211.0956	341.5271
18	2.9217	15.0076

19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000

Plotted results



Comment: EnergyPlus result shows it responds to exterior solar beam radiation in approximately the same way as analytical solution does in the condition of SolRadGlazing case. The maximum difference between the loads calculated by EnergyPlus and the analytical solution is 222.29 W, which is about 10.10% of the peak analytical load.

As in the ExtSolRad test, the reflectance of the ground needs to be set to zero so that no radiation will be reflected from the ground to the external surface. Also the view factors between the walls and the ground are set to zero for the same reason.

EnergyPlus single zone comparison results: Test SolRadShade

Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle 'ε'	90	Degree
Surface azimuth 'ψ'	180	Degree
Thickness of the surface 'L'	0.0023	m
Extinction coefficient of the surface 'K'	10.0	m^{-1}
Refractive index of the surface 'n_g'	1.526	-
Depth of the horizontal fin 'P_h'*	0.6	m
Depth of the vertical fin'P_v'*	0.6	m
Vertical fin is on which side of the window*	Right/Left	-
External air temperature '$T_{a,o}$'	20	C
Internal air temperature '$T_{a,i}$'	20	C
Outside correlation coefficient 'A'	8.23	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.0	-
Inside correlation coefficient 'A'	3.076	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.0	-

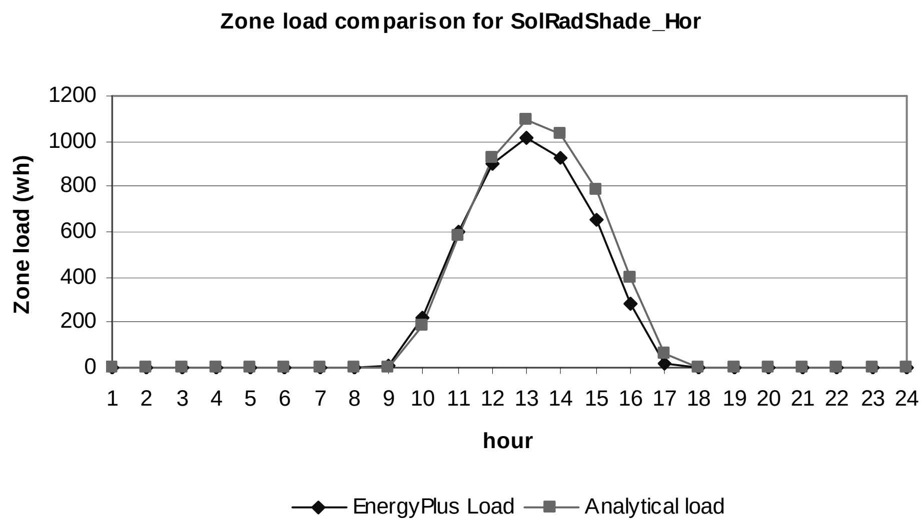
* Combinations of these parameter values are used as noted in the results

Tabulated and plotted results

1. South facing window with horizontal shade

Hour	EnergyPlus Load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	6.4950	1.5560
10	221.3399	188.1192
11	596.0258	580.5106
12	896.6843	922.8312

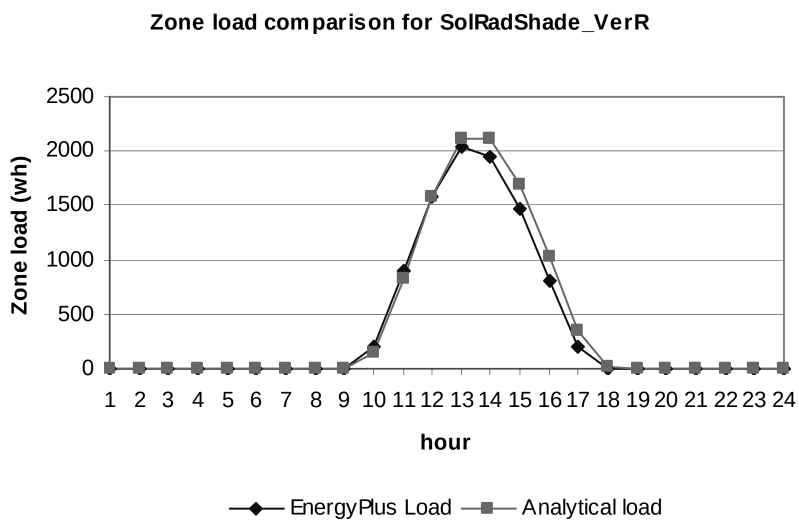
13	1018.2919	1090.4571
14	928.7629	1036.3453
15	651.7380	782.5699
16	280.4373	396.8906
17	22.0013	60.1683
18	0.0000	0.0000
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000



2. Vertical fin on right side of south facing window

Hour	EnergyPlus Load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	0.0000	0.0000
10	211.1596	150.7421
11	895.5201	827.4395
12	1587.7969	1572.2631
13	2038.2731	2112.6204
14	1941.8611	2115.1078

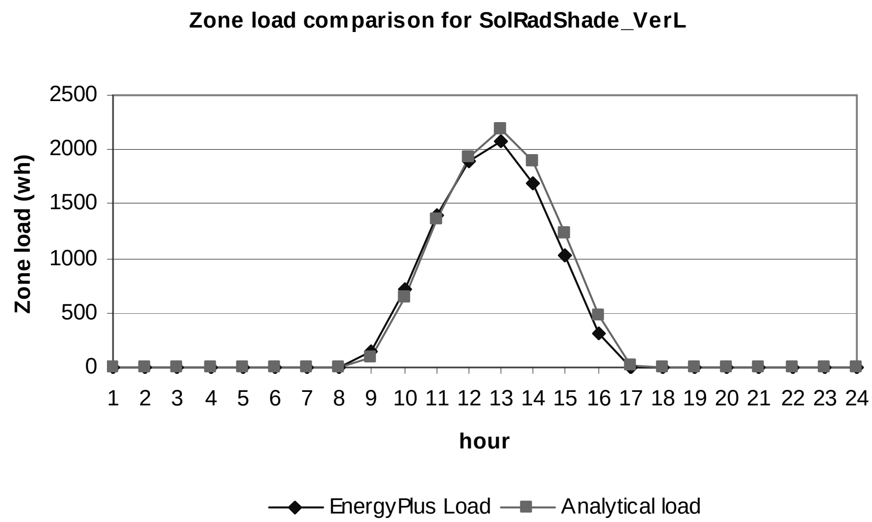
15	1476.9389	1699.2282
16	811.7562	1032.6289
17	211.0956	341.5271
18	2.9217	15.0076
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000



3. Vertical fin on left side of south facing window

Hour	EnergyPlus Load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	148.0409	100.0184
10	712.7607	641.0149
11	1391.1281	1360.4352
12	1894.2342	1931.6661
13	2070.0188	2192.9176
14	1695.7515	1895.3568
15	1024.0144	1238.3097

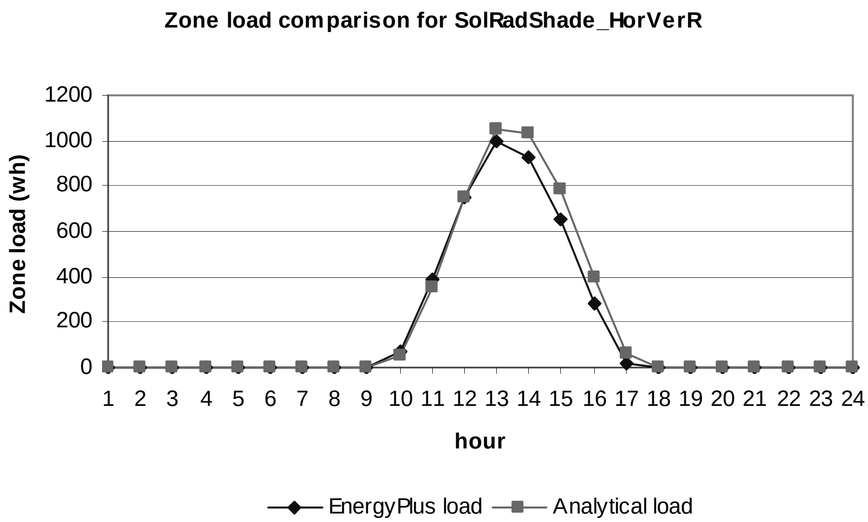
16	318.3779	480.3507
17	0.0000	18.2679
18	0.0000	0.0000
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000



4. South facing window with horizontal shade and right side vertical fin

Hour	EnergyPlus load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	0.0000	0.0000
10	71.8735	50.6418
11	385.6438	355.4659
12	752.2835	751.9689
13	992.8145	1046.8828
14	928.7659	1036.3453
15	651.7427	782.5699
16	280.4484	396.8906
17	22.0030	60.1683

18	0.0000	0.0000
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000



Comment:
The EnergyPlus results show approximately the same shading effects for exterior solar beam radiation as that of the analytical solution. The errors follow the same trend as in the SolRadGlazing case. The differences between predicted loads and the analytical solution are as follows:

- In the test case of south facing window with horizontal shade, the maximum zone load difference (130.83 Wh) is 12.00% of the analytical peak load.
- In the test case of south facing window with vertical fin on right side, the maximum zone load difference (222.29 Wh) is 10.51% of the analytical peak load.
- In the test case of south facing window with vertical fin on left side, the maximum zone load difference (214.30 Wh) is 9.77% of the analytical peak load.
- In the test case of south facing window with horizontal shade and right side vertical fin, the maximum zone load difference (130.83Wh) is 12.50% of the analytical peak load.

Since the input files for EnergyPlus were translated from the corresponding BLAST input files, a problem was found with the BLAST translator of EnergyPlus. The vertical shading translated from BLAST did not show any shading effect because of the different order of the shading surface vertexes the translator put in the EnergyPlus input file. After changing the vertex order, the shading works.

EnergyPlus single zone comparison results: Test WinReveal

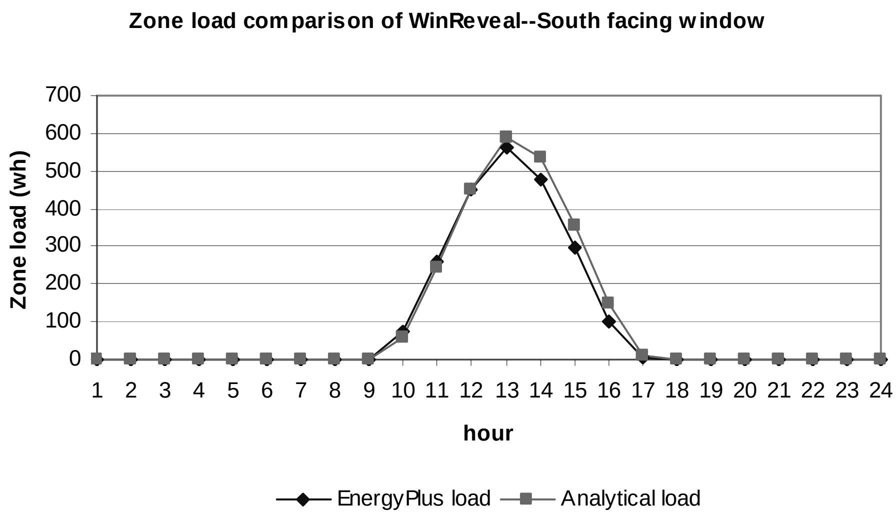
Test parameters

Test parameters	**Value**	**Units**
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle ‘ε’	90	Degree
Surface azimuth ‘ψ’	180	Degree
Thickness of the window surface	0.0023	m
Depth of the window reveal ‘R’	0.3	m
Length of the window ‘B’	2.0	m
Height of the window ‘H’	2.0	m
Extinction coefficient of the window surface ‘K’	10.0	m^{-1}
Refractive index of the window surface ‘n_g’	1.526	-
External air temperature ‘$T_{a,o}$’	20	C
Internal air temperature ‘$T_{a,i}$’	20	C
Outside correlation coefficient ‘A’	8.23	W/m^2K
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	W/m^2K
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated and plotted results

Hour	EnergyPlus load (W)	Analytical load (W)
1	0.0000	0.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	0.0000	0.0000
6	0.0000	0.0000
7	0.0000	0.0000
8	0.0000	0.0000
9	0.6900	0.0000
10	74.4732	56.8706
11	262.0570	242.9290
12	452.0161	448.2255
13	561.1581	586.6180
14	478.6307	533.8867

15	296.0436	357.2700
16	102.0148	148.1089
17	4.1161	13.0173
18	0.0000	0.0000
19	0.0000	0.0000
20	0.0000	0.0000
21	0.0000	0.0000
22	0.0000	0.0000
23	0.0000	0.0000
24	0.0000	0.0000



Comment: EnergyPlus result shows similar shading effects for exterior solar beam irradiation as that of the analytical solution under the condition of WinReveal case. The maximum zone load difference (61.23 W) reaches 10.44% of the analytical peak load, with an average difference of 5.06% of the analytical peak load.

EnergyPlus comparison results: Test IntSolarDist

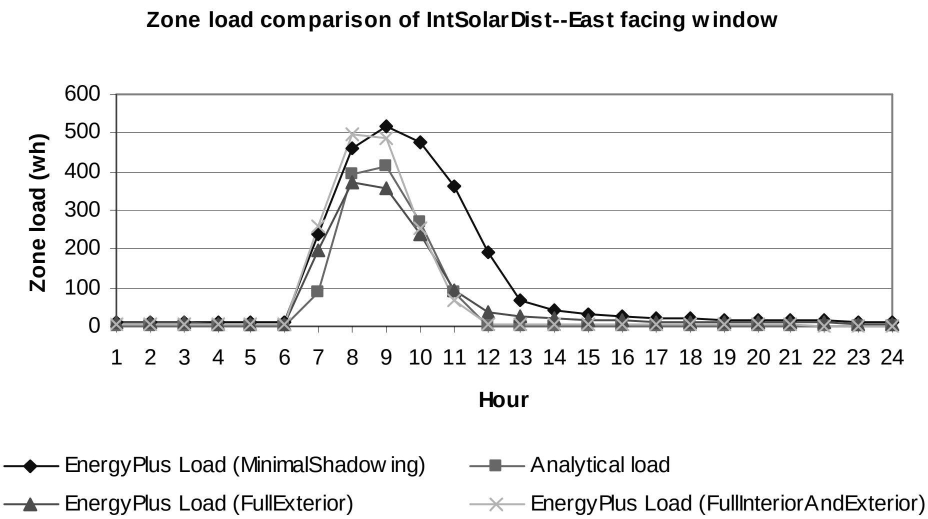
Test parameters

Test parameters	Value	Units
Location	Atlanta	-
Test date	08/21/1999	-
Surface tilt angle ‘ε’	90	Degree
Surface azimuth ‘ψ’	90	Degree
Thickness of the window surface	.0023	m
Depth of the horizontal fin ‘P_h’	0.5	m
Depth of the vertical fin‘P_v’	0.5	m
Extinction coefficient of the window surface ‘K’	10.0	m^{-1}
Refractive index of the window surface ‘n_g’	1.526	-
Solar absorption of the internal surfaces	1.0	-
External air temperature ‘$T_{a,o}$’	20	C
Internal air temperature ‘$T_{a,i}$’	20	C
Outside correlation coefficient ‘A’	8.23	W/m^2K
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	W/m^2K
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated and plotted results

Hour	EnergyPlus Load (MinimalShadowing) (W)	EnergyPlus Load (FullInteriorAndExterior) (W)	EnergyPlus Load (FullExterior) (W)	Analytical load (W)
1	12.4747	4.1399	8.4399	0.0000
2	11.8903	4.0143	8.0944	0.0000
3	11.3704	3.8939	7.7788	0.0000
4	10.9037	3.7781	7.4878	0.0000
5	10.4801	3.6665	7.2188	0.0000
6	10.0907	3.5588	6.9679	0.0000
7	235.4713	258.8226	199.0094	88.6987
8	458.5522	495.9518	371.9866	393.1928
9	518.9806	487.8422	355.9175	413.7012
10	478.1529	250.9073	237.0668	266.6587
11	360.8240	65.8552	95.1564	85.8311
12	192.8964	5.1890	36.9742	0.0000

13	68.7388	4.4357	26.2730	0.0000
14	43.0618	3.9564	20.2938	0.0000
15	32.8642	3.6261	16.6372	0.0000
16	26.6648	3.3729	14.1642	0.0000
17	22.5201	3.1721	12.3887	0.0000
18	19.5791	3.0083	11.0658	0.0000
19	17.3939	2.8705	10.0435	0.0000
20	15.7231	2.7495	9.2363	0.0000
21	14.4067	2.6390	8.5836	0.0000
22	13.3394	2.5389	8.0429	0.0000
23	12.4608	2.4472	7.5856	0.0000
24	11.7247	2.3623	7.1940	0.0000



Comment: The IntSolarDist test is designed to be able to detect whether any solar energy is being redistributed within the zone. EnergyPlus is able to redistribute the transmitted solar irradiation differently according to how a ‘solar distribution flag’ is set. According to the EnergyPlus input/output reference the meaning of the flags is as follows:

(i) Solar Distribution = MinimalShadowing: Detached shading devices on zone walls are not taken into account. All transmitted solar is assumed incident on the floor.

(ii) Solar Distribution = FullExterior: All transmitted solar is assumed incident on the floor.

(iii) Solar Distribution = FullInteriorAndExterior: Transmitted solar is distributed according to the position of the sun patch.

The resulting hourly zone loads (see plot above) with the different solar distribution options verify the operation of the solar distribution flag noted above. The result with a flag of MinimalShadowing has a relatively high value of zone load since no shading effect by the detached sub-surfaces is accounted for in this option. The result with flag of FullExterior, that assume transmitted solar incident on the floor (which is heavyweight), show a reduction in the peak load and storage of some of the energy until later hours. Only a flag value of FullInteriorAndExterior, where the distribution is explicitly calculated and the energy is distributed to the massless rear wall of the zone, results in loads matching the analytical solution.

The differences between the predicted and analytical loads are as follows:

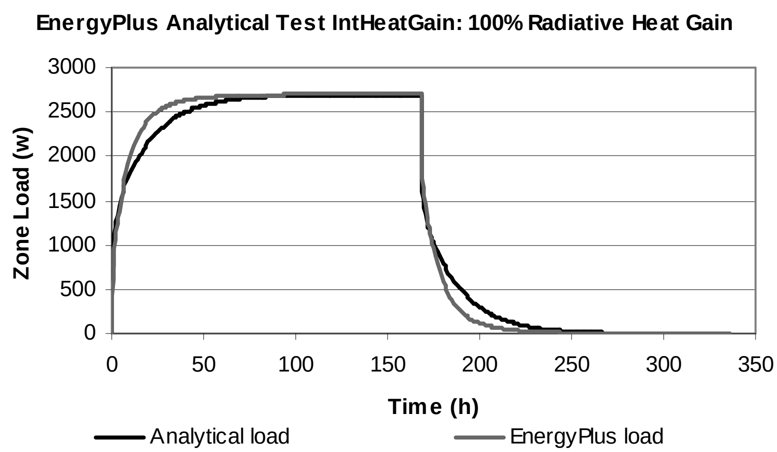
- When solar distribution was specified as MinimalShadowing, the maximum zone load difference (275.00 W) is 66.47% of the analytical peak load.
- When solar distribution was specified as FullExterior, the maximum zone load difference (110.31 Wh) becomes 26.66% of the analytical peak load.
- When solar distribution was specified as FullInteriorAndExterior, the maximum zone load difference (170.12 Wh) becomes 41.12% of the analytical peak load.

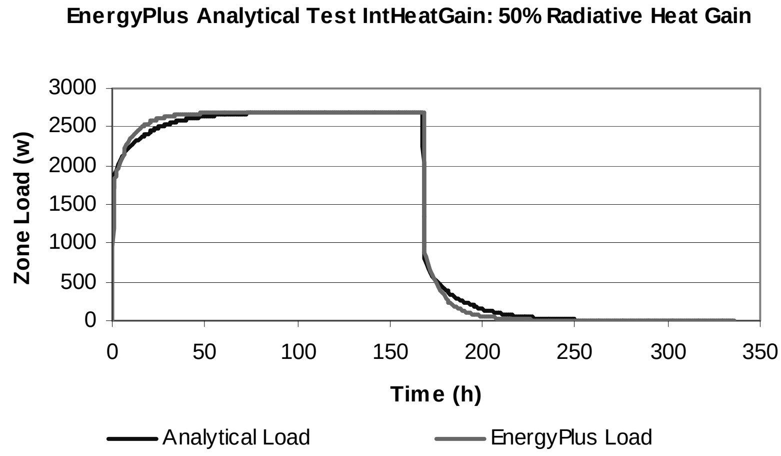
EnergyPlus single zone comparison results: Test IntHeatGain

Test parameters

Test parameters	Value	Units
Thermal conductivity	0.14	W/mK
Thickness	0.1	m
Density	500	Kg/m^3
Specific heat capacity	2500	J/kgK
Internal air temperature	20.0	C
Internal convection coefficient	3.076	W/m^{2}K
Step size of the internal heat gain	2700	W
Radiative fraction of the internal heat gain	0.5 and 1.0	-

Plotted results: 100% & 50% radiative heat gain





Note: Before hour zero, there is no internal heat gain

Tabulated results: 100% & 50% radiative heat gain

	100% RADIATIVE		50% RADIATIVE	
Time	Analytical load	EnergyPlus load	Analytical Load	EnergyPlus Load
Hour	(W)	(W)	(W)	(W)
0	0	0	1350	0
1	948	767	1823	1734
2	1191	1055	1945	1878
3	1341	1234	2019	1967
4	1449	1383	2073	2041
5	1533	1514	2116	2107
6	1603	1632	2150	2166
7	1663	1736	2181	2218
8	1718	1829	2208	2265
9	1767	1912	2233	2306
10	1813	1986	2256	2343
11	1857	2052	2277	2376
12	1898	2111	2298	2406
13	1936	2164	2317	2432
14	1973	2212	2336	2456
15	2008	2254	2353	2477
16	2041	2293	2369	2496
17	2072	2327	2385	2514
18	2102	2358	2400	2529
19	2131	2386	2414	2543
20	2158	2411	2428	2556
21	2184	2434	2441	2567
22	2208	2455	2453	2577

23	2232	2473	2465	2587
24	2254	2490	2476	2595
25	2275	2506	2487	2603
26	2295	2520	2497	2610
27	2315	2533	2506	2616
28	2333	2544	2516	2622
29	2350	2555	2524	2627
30	2367	2565	2533	2632
31	2383	2574	2540	2637
32	2398	2582	2548	2641
33	2412	2590	2555	2645
34	2426	2597	2562	2648
35	2439	2603	2568	2651
36	2451	2609	2575	2654
37	2463	2615	2580	2657
38	2474	2620	2586	2660
39	2485	2624	2591	2662
40	2495	2629	2596	2664
41	2504	2633	2601	2666
42	2513	2637	2606	2668
43	2522	2640	2610	2670
44	2531	2644	2614	2672
45	2538	2647	2618	2673
46	2546	2650	2622	2675
47	2553	2652	2626	2676
48	2560	2655	2629	2677
49	2567	2657	2632	2679
50	2573	2659	2635	2680
51	2579	2662	2638	2681
52	2584	2664	2641	2682
53	2590	2665	2644	2683
54	2595	2667	2646	2684
55	2600	2669	2649	2684
56	2604	2670	2651	2685
57	2609	2672	2653	2686
58	2613	2673	2655	2687
59	2617	2675	2657	2687
60	2620	2676	2659	2688
61	2624	2677	2661	2689
62	2628	2678	2663	2689
63	2631	2679	2664	2690
64	2634	2680	2666	2690
65	2637	2681	2668	2691
66	2640	2682	2669	2691
67	2642	2683	2670	2691
68	2645	2684	2672	2692
69	2647	2685	2673	2692
70	2650	2685	2674	2693

71	2652	2686	2675	2693
72	2654	2687	2676	2693
73	2656	2687	2677	2694
74	2658	2688	2678	2694
75	2660	2689	2679	2694
76	2661	2689	2680	2695
77	2663	2690	2681	2695
78	2665	2690	2681	2695
79	2666	2691	2682	2695
80	2668	2691	2683	2695
81	2669	2691	2684	2696
82	2670	2692	2684	2696
83	2671	2692	2685	2696
84	2673	2693	2685	2696
85	2674	2693	2686	2696
86	2675	2693	2686	2697
87	2676	2694	2687	2697
88	2677	2694	2687	2697
89	2678	2694	2688	2697
90	2678	2694	2688	2697
91	2679	2695	2689	2697
92	2680	2695	2689	2697
93	2681	2695	2689	2698
94	2681	2695	2690	2698
95	2682	2696	2690	2698
96	2683	2696	2690	2698
97	2683	2696	2691	2698
98	2684	2696	2691	2698
99	2685	2696	2691	2698
100	2685	2697	2692	2698
101	2686	2697	2692	2698
102	2686	2697	2692	2698
103	2687	2697	2692	2698
104	2687	2697	2693	2699
105	2687	2697	2693	2699
106	2688	2697	2693	2699
107	2688	2698	2693	2699
108	2688	2698	2693	2699
109	2689	2698	2693	2699
110	2689	2698	2694	2699
111	2689	2698	2694	2699
112	2690	2698	2694	2699
113	2690	2698	2694	2699
114	2690	2698	2694	2699
115	2691	2698	2694	2699
116	2691	2698	2694	2699
117	2691	2698	2695	2699
118	2691	2699	2695	2699

119	2691	2699	2695	2699
120	2692	2699	2695	2699
121	2692	2699	2695	2699
122	2692	2699	2695	2699
123	2692	2699	2695	2699
124	2692	2699	2695	2699
125	2692	2699	2695	2699
126	2693	2699	2695	2699
127	2693	2699	2695	2699
128	2693	2699	2696	2700
129	2693	2699	2696	2700
130	2693	2699	2696	2700
131	2693	2699	2696	2700
132	2693	2699	2696	2700
133	2693	2699	2696	2700
134	2694	2699	2696	2700
135	2694	2699	2696	2700
136	2694	2699	2696	2700
137	2694	2699	2696	2700
138	2694	2699	2696	2700
139	2694	2699	2696	2700
140	2694	2699	2696	2700
141	2694	2699	2696	2700
142	2694	2700	2696	2700
143	2694	2700	2696	2700
144	2694	2700	2696	2700
145	2694	2700	2696	2700
146	2694	2700	2696	2700
147	2695	2700	2696	2700
148	2695	2700	2696	2700
149	2695	2700	2696	2700
150	2695	2700	2696	2700
151	2695	2700	2696	2700
152	2695	2700	2696	2700
153	2695	2700	2696	2700
154	2695	2700	2696	2700
155	2695	2700	2697	2700
156	2695	2700	2697	2700
157	2695	2700	2697	2700
158	2695	2700	2697	2700
159	2695	2700	2697	2700
160	2695	2700	2697	2700
161	2695	2700	2697	2700
162	2695	2700	2697	2700
163	2695	2700	2697	2700
164	2695	2700	2697	2700
165	2695	2700	2697	2700
166	2695	2700	2697	2700

167	2695	2700	2697	2700
168	2695	2700	1347	2700
169	1747	1921	873	961
170	1504	1647	752	824
171	1354	1468	677	734
172	1247	1319	623	659
173	1162	1187	581	593
174	1093	1069	546	535
175	1032	965	516	483
176	978	872	489	436
177	928	789	464	394
178	882	715	441	357
179	839	648	419	324
180	798	589	399	295
181	759	536	380	268
182	723	488	361	244
183	688	446	344	223
184	655	407	327	204
185	623	373	312	187
186	593	342	297	171
187	565	314	282	157
188	538	289	269	144
189	512	266	256	133
190	487	245	244	123
191	464	227	232	113
192	441	210	221	105
193	420	194	210	97
194	400	180	200	90
195	381	167	190	84
196	363	156	181	78
197	345	145	173	73
198	329	135	164	68
199	313	126	156	63
200	298	118	149	59
201	283	110	142	55
202	270	103	135	52
203	257	97	128	49
204	245	91	122	46
205	233	85	116	43
206	222	80	111	40
207	211	76	105	38
208	201	71	100	36
209	191	67	96	34
210	182	63	91	32
211	173	60	87	30
212	165	56	82	28
213	157	53	79	27
214	150	50	75	25

215	142	48	71	24
216	135	45	68	23
217	129	43	64	21
218	123	41	61	20
219	117	38	58	19
220	111	36	56	18
221	106	35	53	17
222	101	33	50	16
223	96	31	48	16
224	91	30	46	15
225	87	28	44	14
226	83	27	41	13
227	79	25	39	13
228	75	24	38	12
229	71	23	36	11
230	68	22	34	11
231	65	21	32	10
232	62	20	31	10
233	59	19	29	9
234	56	18	28	9
235	53	17	27	9
236	51	16	25	8
237	48	15	24	8
238	46	15	23	7
239	44	14	22	7
240	42	13	21	7
241	40	13	20	6
242	38	12	19	6
243	36	11	18	6
244	34	11	17	6
245	33	10	16	5
246	31	10	15	5
247	29	9	15	5
248	28	9	14	5
249	27	9	13	4
250	25	8	13	4
251	24	8	12	4
252	23	7	12	4
253	22	7	11	4
254	21	7	10	3
255	20	6	10	3
256	19	6	9	3
257	18	6	9	3
258	17	6	9	3
259	16	5	8	3
260	16	5	8	3
261	15	5	7	2
262	14	5	7	2

263	13	4	7	2
264	13	4	6	2
265	12	4	6	2
266	12	4	6	2
267	11	4	6	2
268	10	3	5	2
269	10	3	5	2
270	9	3	5	2
271	9	3	5	2
272	9	3	4	1
273	8	3	4	1
274	8	3	4	1
275	7	2	4	1
276	7	2	4	1
277	7	2	3	1
278	6	2	3	1
279	6	2	3	1
280	6	2	3	1
281	6	2	3	1
282	5	2	3	1
283	5	2	3	1
284	5	2	2	1
285	5	2	2	1
286	4	2	2	1
287	4	1	2	1
288	4	1	2	1
289	4	1	2	1
290	4	1	2	1
291	3	1	2	1
292	3	1	2	1
293	3	1	2	1
294	3	1	1	1
295	3	1	1	0
296	3	1	1	0
297	3	1	1	0
298	2	1	1	0
299	2	1	1	0
300	2	1	1	0
301	2	1	1	0
302	2	1	1	0
303	2	1	1	0
304	2	1	1	0
305	2	1	1	0
306	2	1	1	0
307	2	1	1	0
308	1	1	1	0
309	1	0	1	0
310	1	0	1	0

311	1	0	1	0
312	1	0	1	0
313	1	0	1	0
314	1	0	1	0
315	1	0	1	0
316	1	0	0	0
317	1	0	0	0
318	1	0	0	0
319	1	0	0	0
320	1	0	0	0
321	1	0	0	0
322	1	0	0	0
323	1	0	0	0
324	1	0	0	0
325	1	0	0	0
326	1	0	0	0
327	1	0	0	0
328	1	0	0	0
329	1	0	0	0
330	0	0	0	0
331	0	0	0	0
332	0	0	0	0
333	0	0	0	0
334	0	0	0	0
335	0	0	0	0
336	0	0	0	0

Comment:

The EnergyPlus results show a relatively slower response to a step change in internal convective and/or radiative heat gain in the Internal Heat Gain case. Most difference occurs in the first 40 hours and after 168 hours (with error percentage up to 5-10% of the peak analytical zone load, the internal heat gain occurs during the period of 0-168 hours). During the period of 41-168 hours the results matches well (with error percentage within ±5% and most less than 2%). In addition, the percentage error for the case of 50% radiative heat gain is relatively less than that for the case of 100% radiative heat gain, which might be expected.

Possible reason for the difference is that EnergyPlus uses different internal surface convection coefficients for different surfaces (vertical walls, floor and ceiling are treated differently). While in the analytical solution, same convection coefficient is assumed for all the six internal surfaces in the test zone.

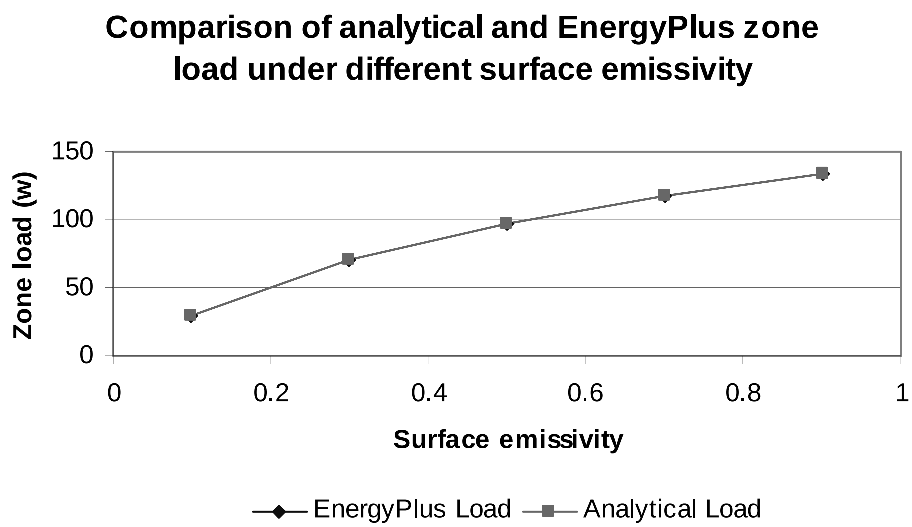
EnergyPlus single zone comparison results: Test ExtLWRad

Test parameters

Test parameters	Value	Units
Emissivity of the external surface	0.1 - 0.9	-
Thermal conductivity of the external surface	1.0	W/mK
Thickness of the external surface	0.1	m
Sky temperature	7.552	C
External air temperature	20	C
Internal air temperature	20	C
Outside correlation coefficient 'A'	See the result table	W/m^2K
Outside correlation coefficient 'C'	0.0	-
Outside correlation exponent 'n'	0.0	-
Inside correlation coefficient 'A'	See the result table	W/m^2K
Inside correlation coefficient 'C'	0.0	-
Inside correlation exponent 'n'	0.0	-

Tabulated and plotted results:

Emissivity of the external surface	Inside convection correlation coefficient 'A'	Outside convection correlation coefficient 'A'	EnergyPlus Load	Analytical Load
0.1	1.8410	0.9810	30.1122	30.1066
0.3	2.2753	1.2266	70.1830	70.1802
0.5	2.4700	1.3400	97.5446	97.5117
0.7	2.5900	1.4100	117.8708	117.8314
0.9	2.6730	1.4570	133.7085	133.6903



Comment: The EnergyPlus results are approximately the same as analytical solution in the external long wave radiation case, with a maximum difference of 0.034% for the emissivities tested. The sky temperature used in EnergyPlus was reported and used in the analytical tests. Also the inside and outside convection coefficients obtained from the EnergyPlus output was used in the analytical solution.

EnergyPlus single zone comparison results: Test IntRad

Test parameters

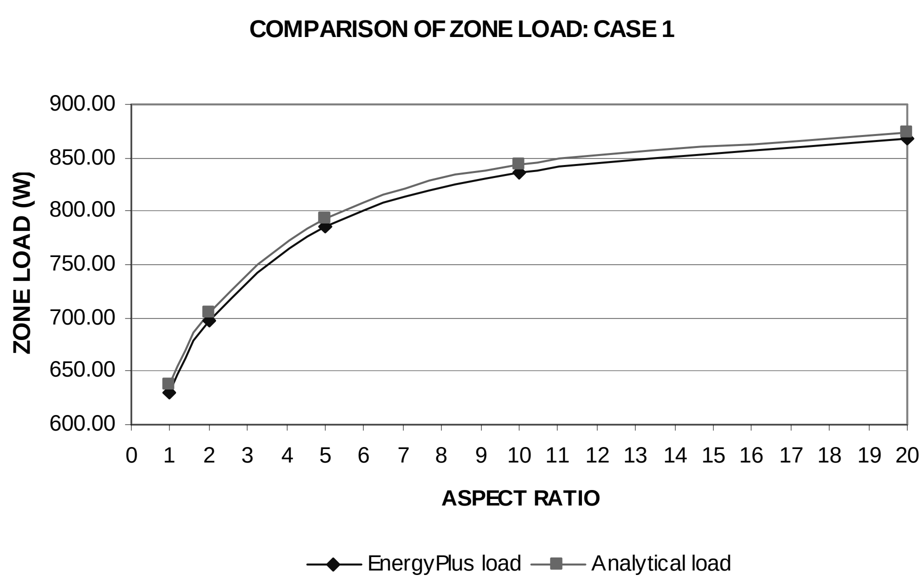
Test parameters	Value	Units
Width of the cuboid	3.0	m
Outside air temperature	40	C
Inside air temperature	20	C
External convection coefficient	12.49	W/m^2K
Internal convection coefficient	3.076	W/m^2K

(Note: Emissivities of the surfaces as listed in different cases.)

Tabulated and plotted results:

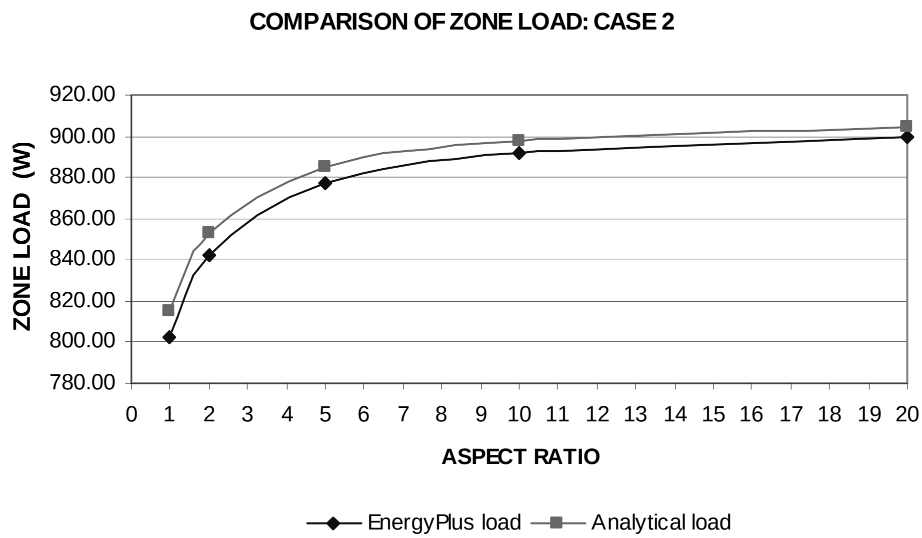
Case 1: *EMISSIVITY of the EXTERIOR SURFACE =0.9*
EMISSIVITY of OTHER SURFACES =0.1

Aspect ratio	EnergyPlus load (W)	Analytical load (W)	Zone load difference (%)
1	629.86	636.89	1.11
2	696.82	705.07	1.17
5	785.44	793.39	1.00
10	835.94	842.82	0.82
20	868.56	874.43	0.67



Case 2: *EMISSIVITY of ALL THE SURFACES =0.9*

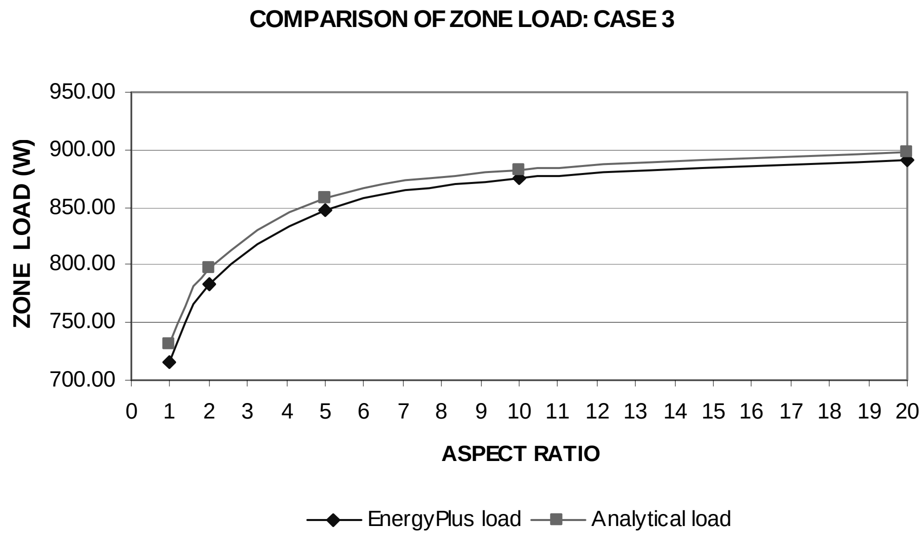
Aspect ratio	EnergyPlus load (W)	Analytical load (W)	Zone load difference (%)
1	802.31	814.71	1.52
2	842.31	852.59	1.21
5	877.39	884.78	0.84
10	891.89	897.87	0.67
20	899.80	904.92	0.57



Case 3:

EMISSIVITY of the EXTERIOR SURFACE =0.9
EMISSIVITY of the SURFACE OPPOSITE to the EXTERIOR SURFACE =0.1
EMISSIVITY of OTHER SURFACES =0.3

Aspect ratio	EnergyPlus load (W)	Analytical load (W)	Zone load difference (%)
1	716.47	730.55	1.93
2	783.64	796.90	1.66
5	847.45	857.15	1.13
10	875.43	883.01	0.86
20	891.15	897.39	0.70



Comment:

4. It was found that in case 1, the EnergyPlus results match with analytical solution better (with maximum error percentage of 1.17%) than in the other two cases (with maximum error percentage of 1.52% for case 1 and 1.93% for case 3).
5. The EnergyPlus results match with analytical solution better under larger aspect ratio than under smaller aspect ratio.
6. The EnergyPlus resultant zone loads are all lower than the analytical zone loads.

EnergyPlus single zone comparison results: Test Infiltration-1

Test parameters

Test parameters	Value	Units
Outside air temperature	10	C
Inside air temperature	20	C
Outside humidity ratio	0.0046	-
Infiltration rate	0.5	m^3/s

Tabulated results:

EnergyPlus Infiltration Load (W)	Analytical Infiltration Load (W)
6270.95	6304.72

Note: Atmospheric pressure = 101325 pa

Comment:

4. A difference of 0.54% in the test zone infiltration loads was found between EnergyPlus result and the analytical result in the Infiltration-1 case.

EnergyPlus inter-zone comparison results: Test Infiltration-1

Test parameters

Test parameters	Value		Units
	Case 1	Case 2	
Outside air temperature	10	18	C
Inside air temperature	20	28	C
Outside humidity ratio	0.0046	0.0046	-
Infiltration rate	0.5	0.5	m^3/s

Tabulated results:

Test case	EnergyPlus Zone Load (W)		Analytical Zone Load (W)	
	Cooling zone	Heating zone	Cooling zone	Heating zone
Case 1	-5842.10	5842.10	-6304.72	6304.72
Case 2	-5530.65	5530.65	-6131.48	6131.48

Note: Atmospheric pressure = 101325 pa

Comment:

5. A difference of 7.34% and 9.80% respectively for each case in the test zone loads was found between EnergyPlus result and the analytical result.
6. By looking through the source code of EnergyPlus, it appears this deviation comes from the different way used by EnergyPlus to calculate the inter-zone airflow load. Similar to BLAST, EnergyPlus supplies a way of specifying simple inter-zone airflow by scheduling the cross zone mixing in volume flow rate (m^3/s). The following lines appear in the CalcHeatBalanceAir subroutine (HeatBalanceAirManager.f90) of EnergyPlus:

```
!                 COMPUTE CROSS ZONE
!                 AIR MIXING
^
^
        MCPxN=MVFC(J)*   &
          cpairfn(ZoneAirHumRat(n),REAL(tzn))*rhoairfn(OutBaroPress,REAL(tzn),ZoneAirHumRat(n))
        MCPM(N)=MCPM(N)+MCPxN
        MCPxM=MVFC(J)*   &
            cpairfn(ZoneAirHumRat(m),REAL(tzm))*rhoairfn(OutBaroPress,REAL(tzm),ZoneAirHumRat(m))
        MCPM(M)=MCPM(M)+MCPxM
        MCPTM(N)=MCPTM(N)+MCPxM*TZM
        MCPTM(M)=MCPTM(M)+MCPxN*TZN
```

Where MVFC is defined in HeatBalanceAirManager.f90 of EnergyPlus as:

```
REAL, ALLOCATABLE, DIMENSION(:) :: MVFC      !DESIGN MIXING FLOW RATE (M**3/SEC) (CROSS ZONE
MIXING)
```

MCPM and MCPTM is defined in DataHeatBalFanSys.f90 of EnergyPlus as:

```
Real, Allocatable, Dimension(:)  :: MCPM       !Mixing MASS FLOW * AIR SPECIFIC HEAT
Real, Allocatable, Dimension(:)  :: MCPTM      !Mixing MASS FLOW * AIR CP * AIR TEMPERATURE
```

Cpairfn is the function in EnergyPlus to calculate air specific heat.
rhoairfn is the function in EnergyPlus to calculate air density.

Following the way showed in these source code and the corresponding psychrometric functions to compute the air specific heat and density, hand calculation of the inter-zone airflow load caused by cross mixing matches the EnergyPlus output very well. The following table shows the hand calculation results:

Test case	Zone	Zone air temperature (C)	Zone air humidity ratio	Air specific heat (J/kgk)	Zone air density (kg/m^3)	Inter-zone airflow load (W)
Case 1	Heating zone	20	0.0046	1013.3912	1.1952	5842.25
	Cooling zone	10	0.0046	1013.3912	1.2374	
Case 2	Heating zone	28	0.0046	1013.3912	1.1634	5530.65
	Cooling zone	18	0.0046	1013.3912	1.2034	

There is at least one problem in this calculation process. It uses the same cross mixing volume flow rate for both the heating and cooling zone, which means an equal air volume flow instead of an equal air mass flow. In the analytical solution, it is the mass flow balance assumed.

Another factor accounts for the difference between the analytical solution and EnergyPlus method is the treatment of the air specific heat. EnergyPlus uses a function to calculate the air specific heat based on the air dry bulb temperature and humidity ratio, while the air specific heat is assumed as a constant value of 1006 J/kgk in the analytical implementation. EnergyPlus treats more accurately on this aspect.

7. The EnergyPlus output shows that the scheduled cross mixing flow volume (should be 1800 m^3 hourly) is not correct (1738.62 m^3 for case 1 and 1692.43 m^3 for case 2 in the output file). This is caused by an error in the subroutine ReportAirHeatBalance written to “updates the report variables for the AirHeatBalance” in EnergyPlus. The following lines appear in this subroutine:

```
   AirDensity        = rhoairfn(OutBaroPress,OutDryBulbTemp,OutHumRat)
   CpAir             = cpairfn(OutHumRat,OutDryBulbTemp)
   ZnRPT(ZoneLoop)%InfilVolume=(MCPI(ZoneLoop)/CpAir/AirDensity)*TimeStepZone*3600.0
   ZnRPT(ZoneLoop)%InfilMass=(MCPI(ZoneLoop)/CpAir)*TimeStepZone*3600.0
!????    ZnRPT(ZoneLoop)%InfilMass=OAMFL(ZoneLoop)*TimeStepZone*3600.0
   ZnRpt(ZoneLoop)%MixVolume=(MCPM(ZoneLoop)/CpAir/AirDensity)*TimeStepZone*3600.0
   ZnRPT(ZoneLoop)%MixMass=(MCPM(ZoneLoop)/CPAir)*TimeStepZone*3600.0
```

Note that the air density and specific heat is calculated using the outside conditions and then used in updating the air volume and mass both for the infiltration and inter-zone airflow mixing. But the air density and specific heat should be in zone inside conditions in case of cross mixing. Using the outside air density and specific heat to calculate the mixing air volume and mass from MCPM verifies the values output in the EnergyPlus output file.

EnergyPlus inter-zone comparison results: Test SSCond

Test parameters

Test Parameter	Value	Units
Number of fabric layers	3	-
Thermal conductivity: Layer 1	0.1	W/m.K
Thickness: Layer 1	0.1	m
Thermal conductivity: Layer 2	0.05	W/m.K
Thickness: Layer 2	0.05	m
Thermal conductivity: Layer 3	0.25	W/m.K
Thickness: Layer 3	0.01	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	3.076	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated results

EnergyPlus result load in one hour	**Analytical solution load in one hour**
wh	**wh**
100.40	100.36

Comment: The EnergyPlus result matches well with the analytical solution for the Steady State Conduction case with the maximum difference of 0.04% for zone load in one hour.

EnergyPlus inter-zone comparison results: Test SSConv

Test parameters

Test Parameter	Value	Units
Thermal conductivity	1.0	W/m.K
Thickness	0.1	m
Inside temperature	10.0	^oC
Outside Temperature	40.0	^oC
Outside correlation coefficient ‘A’	3.076	$W/m^2.K$
Outside correlation coefficient ‘C’	0.0	-
Outside correlation exponent ‘n’	0.0	-
Inside correlation coefficient ‘A’	3.076	$W/m^2.K$
Inside correlation coefficient ‘C’	0.0	-
Inside correlation exponent ‘n’	0.0	-

Tabulated results

EnergyPlus result load in one hour (wh)	Analytical solution load in one hour (wh)
360.42	359.91

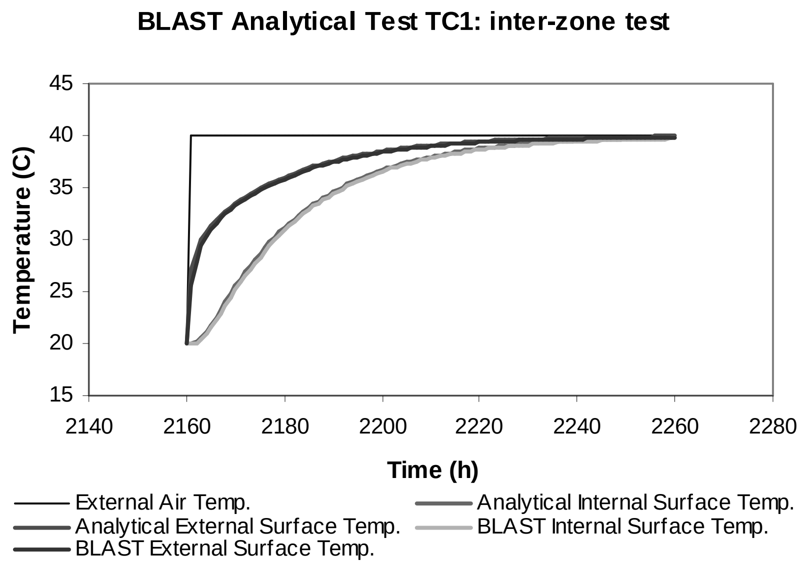
Comment: The EnergyPlus result matches well with the analytical solution for the Steady State Convection case with the maximum difference of 0.14% for zone load in one hour.

BLAST inter-zone comparison results: Test Tc1

Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	20.0	^oC
Temperature step (ΔT)	20.0	^oC
External convection coefficient	3.076	$W/m^2.K$

Plotted result



Tabulated results

Note: the internal surface temperature in the BLAST test corresponds to the surface of the inter-zone structure facing to the salve zone, and the external surface temperature corresponds to the surface facing to the master zone.

Time (hour)	External Air Temp. (C)	Analytical		BLAST	
		Internal Surface Temp. (C)	External Surface Temp. (C)	Internal Surface Temp. (C)	External Surface Temp. (C)
2160	20.00	20.00	20.00	20.00	20.00
2161	40.00	20.00	27.06	20.00	25.60

2162	40.00	20.12	28.85	20.08	27.96
2163	40.00	20.49	29.96	20.38	29.34
2164	40.00	21.07	30.76	20.88	30.29
2165	40.00	21.77	31.39	21.52	31.01
2166	40.00	22.53	31.91	22.23	31.59
2167	40.00	23.30	32.35	22.98	32.08
2168	40.00	24.06	32.76	23.73	32.51
2169	40.00	24.80	33.12	24.47	32.90
2170	40.00	25.52	33.47	25.18	33.25
2171	40.00	26.21	33.79	25.87	33.58
2172	40.00	26.86	34.09	26.54	33.89
2173	40.00	27.49	34.38	27.17	34.19
2174	40.00	28.09	34.65	27.78	34.46
2175	40.00	28.66	34.90	28.36	34.72
2176	40.00	29.21	35.15	28.91	34.97
2177	40.00	29.72	35.38	29.44	35.21
2178	40.00	30.22	35.60	29.94	35.44
2179	40.00	30.69	35.82	30.41	35.65
2180	40.00	31.13	36.02	30.87	35.85
2181	40.00	31.56	36.21	31.30	36.05
2182	40.00	31.97	36.39	31.71	36.23
2183	40.00	32.35	36.56	32.11	36.41
2184	40.00	32.72	36.73	32.48	36.58
2185	40.00	33.07	36.89	32.83	36.74
2186	40.00	33.40	37.04	33.17	36.89
2187	40.00	33.72	37.18	33.50	37.03
2188	40.00	34.02	37.31	33.80	37.17
2189	40.00	34.31	37.44	34.10	37.30
2190	40.00	34.58	37.57	34.37	37.43
2191	40.00	34.84	37.68	34.64	37.55
2192	40.00	35.09	37.79	34.89	37.66
2193	40.00	35.32	37.90	35.13	37.77
2194	40.00	35.55	38.00	35.36	37.87
2195	40.00	35.76	38.10	35.58	37.97
2196	40.00	35.97	38.19	35.78	38.06
2197	40.00	36.16	38.27	35.98	38.15
2198	40.00	36.34	38.36	36.17	38.23
2199	40.00	36.52	38.44	36.35	38.31
2200	40.00	36.69	38.51	36.52	38.39
2201	40.00	36.85	38.58	36.68	38.46
2202	40.00	37.00	38.65	36.84	38.53
2203	40.00	37.14	38.72	36.98	38.60
2204	40.00	37.28	38.78	37.12	38.66
2205	40.00	37.41	38.84	37.26	38.72
2206	40.00	37.53	38.89	37.38	38.78
2207	40.00	37.65	38.95	37.50	38.83
2208	40.00	37.77	39.00	37.62	38.88
2209	40.00	37.87	39.04	37.73	38.93

2210	40.00	37.97	39.09	37.83	38.98
2211	40.00	38.07	39.13	37.93	39.02
2212	40.00	38.16	39.18	38.03	39.07
2213	40.00	38.25	39.22	38.12	39.11
2214	40.00	38.34	39.25	38.20	39.14
2215	40.00	38.42	39.29	38.28	39.18
2216	40.00	38.49	39.32	38.36	39.22
2217	40.00	38.57	39.36	38.44	39.25
2218	40.00	38.63	39.39	38.51	39.28
2219	40.00	38.70	39.42	38.57	39.31
2220	40.00	38.76	39.44	38.64	39.34
2221	40.00	38.82	39.47	38.70	39.37
2222	40.00	38.88	39.50	38.76	39.39
2223	40.00	38.93	39.52	38.81	39.42
2224	40.00	38.98	39.54	38.86	39.44
2225	40.00	39.03	39.57	38.91	39.46
2226	40.00	39.08	39.59	38.96	39.48
2227	40.00	39.12	39.61	39.01	39.51
2228	40.00	39.17	39.62	39.05	39.52
2229	40.00	39.21	39.64	39.09	39.54
2230	40.00	39.24	39.66	39.13	39.56
2231	40.00	39.28	39.68	39.17	39.58
2232	40.00	39.31	39.69	39.20	39.59
2233	40.00	39.35	39.71	39.24	39.61
2234	40.00	39.38	39.72	39.27	39.62
2235	40.00	39.41	39.73	39.30	39.64
2236	40.00	39.44	39.75	39.33	39.65
2237	40.00	39.46	39.76	39.36	39.66
2238	40.00	39.49	39.77	39.38	39.67
2239	40.00	39.51	39.78	39.41	39.69
2240	40.00	39.54	39.79	39.43	39.70
2241	40.00	39.56	39.80	39.45	39.71
2242	40.00	39.58	39.81	39.48	39.72
2243	40.00	39.60	39.82	39.50	39.73
2244	40.00	39.62	39.83	39.52	39.73
2245	40.00	39.64	39.84	39.54	39.74
2246	40.00	39.66	39.85	39.55	39.75
2247	40.00	39.67	39.85	39.57	39.76
2248	40.00	39.69	39.86	39.59	39.77
2249	40.00	39.70	39.87	39.60	39.77
2250	40.00	39.72	39.87	39.62	39.78
2251	40.00	39.73	39.88	39.63	39.78
2252	40.00	39.74	39.88	39.64	39.79
2253	40.00	39.76	39.89	39.66	39.80
2254	40.00	39.77	39.90	39.67	39.80
2255	40.00	39.78	39.90	39.68	39.81
2256	40.00	39.79	39.91	39.69	39.81
2257	40.00	39.80	39.91	39.70	39.82

2258	40.00	39.81	39.91	39.71	39.82
2259	40.00	39.82	39.92	39.72	39.83
2260	40.00	39.83	39.92	39.73	39.83

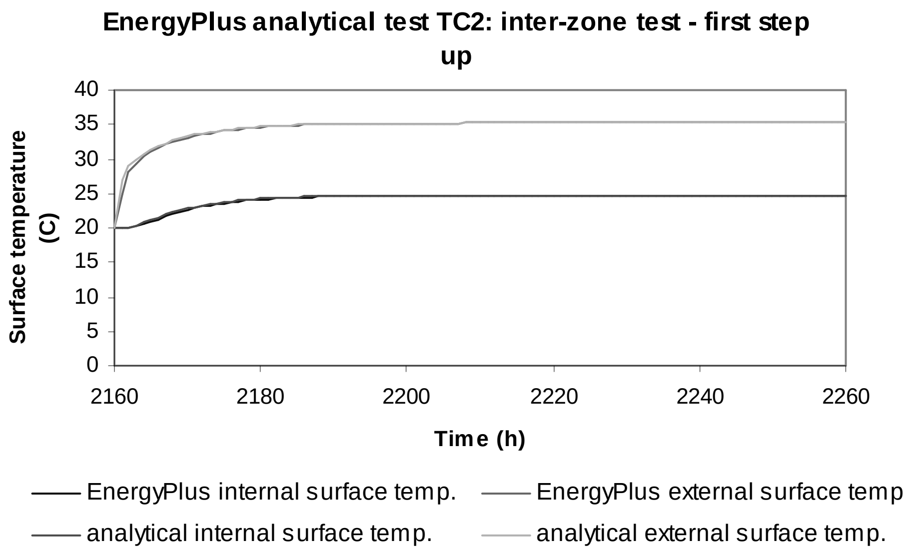
Comment: BLAST responds to step changes in external dry bulb temperature in approximately the same way as the analytical solution. Except the first hour of the step change occurs, the maximum difference in external surface temperature was -1.45 ^{o}C, with 90 hours out of 100 hours having a difference within 0.2 ^{o}C. The maximum difference in internal surface temperature was -0.34 ^{o}C, with 84 hours out of 100 hours having a difference within 0.25 ^{o}C.

EnergyPlus inter-zone comparison results: Test Tc2

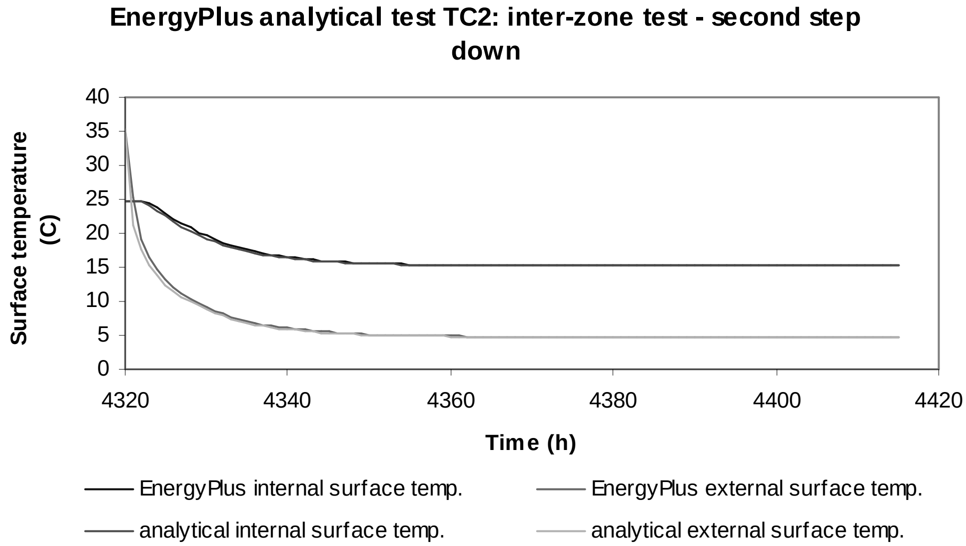
Test parameters

Test Parameter	Value	Units
Thermal conductivity	0.14	W/m.K
Density	500	Kg/m^3
Specific heat capacity	2500	J/kg.K
Thickness	0.1	m
Initial temperature (T_0)	20.0	^{o}C
Temperature step (ΔT)	20.0	^{o}C
External convection coefficient	3.076	W/m^2.K
Internal convection coefficient	3.076	W/m^2.K

Plotted results: First step change



Plotted results: Second step change



Tabulated results: First step

Note: the internal surface temperature in the EnergyPlus test corresponds to the surface of the inter-zone structure facing to the salve zone, and the external surface temperature corresponds to the surface facing to the master zone.

Time	EnergyPlus		Analytical	
	Internal surface temp.	External surface temp.	Internal surface temp.	External surface temp.
(hour)	(C)	(C)	(C)	(C)
2160	20.00	20.00	20.00	20.00
2161	20.00	24.98	20.00	27.06
2162	20.04	28.08	20.09	28.85
2163	20.22	29.41	20.35	29.96
2164	20.53	30.32	20.73	30.76
2165	20.90	31.02	21.13	31.38
2166	21.29	31.57	21.52	31.88
2167	21.65	32.03	21.89	32.31
2168	22.00	32.42	22.23	32.67
2169	22.31	32.76	22.53	32.98
2170	22.59	33.05	22.79	33.25
2171	22.84	33.31	23.03	33.49
2172	23.06	33.53	23.23	33.70
2173	23.26	33.73	23.42	33.89
2174	23.43	33.91	23.58	34.05
2175	23.58	34.06	23.72	34.19

2176	23.72	34.20	23.85	34.32
2177	23.84	34.32	23.96	34.43
2178	23.95	34.43	24.05	34.52
2179	24.04	34.52	24.14	34.61
2180	24.13	34.60	24.21	34.68
2181	24.20	34.68	24.28	34.75
2182	24.26	34.74	24.34	34.81
2183	24.32	34.80	24.39	34.86
2184	24.37	34.85	24.43	34.90
2185	24.42	34.90	24.47	34.94
2186	24.46	34.94	24.51	34.98
2187	24.49	34.97	24.54	35.01
2188	24.52	35.00	24.57	35.04
2189	24.55	35.03	24.59	35.06
2190	24.58	35.05	24.61	35.08
2191	24.60	35.08	24.63	35.10
2192	24.62	35.09	24.65	35.12
2193	24.63	35.11	24.66	35.13
2194	24.65	35.13	24.67	35.14
2195	24.66	35.14	24.68	35.15
2196	24.67	35.15	24.69	35.16
2197	24.68	35.16	24.70	35.17
2198	24.69	35.17	24.71	35.18
2199	24.70	35.18	24.72	35.19
2200	24.71	35.18	24.72	35.19
2201	24.71	35.19	24.73	35.20
2202	24.72	35.20	24.73	35.20
2203	24.72	35.20	24.74	35.21
2204	24.73	35.21	24.74	35.21
2205	24.73	35.21	24.74	35.21
2206	24.73	35.21	24.75	35.21
2207	24.74	35.22	24.75	35.22
2208	24.74	35.22	24.75	35.22
2209	24.74	35.22	24.75	35.22
2210	24.74	35.22	24.75	35.22
2211	24.75	35.22	24.75	35.22
2212	24.75	35.23	24.76	35.23
2213	24.75	35.23	24.76	35.23
2214	24.75	35.23	24.76	35.23
2215	24.75	35.23	24.76	35.23
2216	24.75	35.23	24.76	35.23
2217	24.75	35.23	24.76	35.23
2218	24.76	35.23	24.76	35.23
2219	24.76	35.23	24.76	35.23
2220	24.76	35.23	24.76	35.23
2221	24.76	35.24	24.76	35.23
2222	24.76	35.24	24.76	35.23
2223	24.76	35.24	24.76	35.23

2224	24.76	35.24	24.76	35.23
2225	24.76	35.24	24.76	35.23
2226	24.76	35.24	24.76	35.23
2227	24.76	35.24	24.76	35.23
2228	24.76	35.24	24.76	35.23
2229	24.76	35.24	24.76	35.23
2230	24.76	35.24	24.76	35.23
2231	24.76	35.24	24.76	35.23
2232	24.76	35.24	24.76	35.23
2233	24.76	35.24	24.76	35.23
2234	24.76	35.24	24.76	35.23
2235	24.76	35.24	24.76	35.23
2236	24.76	35.24	24.76	35.23
2237	24.76	35.24	24.76	35.23
2238	24.76	35.24	24.76	35.23
2239	24.76	35.24	24.76	35.23
2240	24.76	35.24	24.76	35.23
2241	24.76	35.24	24.76	35.23
2242	24.76	35.24	24.76	35.23
2243	24.76	35.24	24.76	35.23
2244	24.76	35.24	24.76	35.23
2245	24.76	35.24	24.77	35.23
2246	24.76	35.24	24.77	35.23
2247	24.76	35.24	24.77	35.23
2248	24.76	35.24	24.77	35.23
2249	24.76	35.24	24.77	35.23
2250	24.76	35.24	24.77	35.23
2251	24.76	35.24	24.77	35.23
2252	24.76	35.24	24.77	35.23
2253	24.76	35.24	24.77	35.23
2254	24.76	35.24	24.77	35.23
2255	24.76	35.24	24.77	35.23
2256	24.76	35.24	24.77	35.23
2257	24.76	35.24	24.77	35.23
2258	24.76	35.24	24.77	35.23
2259	24.76	35.24	24.77	35.23
2260	24.76	35.24	24.77	35.23

Tabulated results: Second step

	EnergyPlus		Analytical	
Time	Internal surface temp.	External surface temp.	Internal surface temp.	External surface temp.
(hour)	(C)	(C)	(C)	(C)
4320	24.76	35.24	24.77	35.23
4321	24.76	25.29	24.76	21.12
4322	24.68	19.09	24.58	17.53

4323	24.33	16.43	24.06	15.31
4324	23.71	14.60	23.31	13.71
4325	22.96	13.21	22.51	12.47
4326	22.19	12.10	21.72	11.47
4327	21.45	11.18	20.98	10.62
4328	20.77	10.40	20.31	9.90
4329	20.15	9.73	19.71	9.27
4330	19.59	9.14	19.18	8.73
4331	19.09	8.63	18.71	8.25
4332	18.64	8.17	18.30	7.83
4333	18.25	7.78	17.93	7.46
4334	17.90	7.43	17.61	7.14
4335	17.59	7.12	17.32	6.85
4336	17.32	6.84	17.07	6.60
4337	17.08	6.60	16.85	6.38
4338	16.86	6.39	16.66	6.19
4339	16.68	6.20	16.49	6.02
4340	16.51	6.03	16.34	5.87
4341	16.36	5.89	16.21	5.74
4342	16.23	5.76	16.09	5.62
4343	16.12	5.64	15.99	5.52
4344	16.02	5.54	15.90	5.43
4345	15.93	5.45	15.82	5.35
4346	15.85	5.37	15.75	5.28
4347	15.78	5.30	15.69	5.22
4348	15.71	5.24	15.63	5.16
4349	15.66	5.18	15.58	5.11
4350	15.61	5.13	15.54	5.07
4351	15.57	5.09	15.51	5.04
4352	15.53	5.05	15.47	5.00
4353	15.50	5.02	15.44	4.97
4354	15.47	4.99	15.42	4.95
4355	15.44	4.96	15.40	4.93
4356	15.42	4.94	15.38	4.91
4357	15.40	4.92	15.36	4.89
4358	15.38	4.90	15.35	4.88
4359	15.36	4.89	15.33	4.86
4360	15.35	4.87	15.32	4.85
4361	15.34	4.86	15.31	4.84
4362	15.33	4.85	15.30	4.83
4363	15.32	4.84	15.29	4.82
4364	15.31	4.83	15.29	4.82
4365	15.30	4.82	15.28	4.81
4366	15.29	4.82	15.27	4.80
4367	15.29	4.81	15.27	4.80
4368	15.28	4.80	15.27	4.80
4369	15.28	4.80	15.26	4.79
4370	15.27	4.80	15.26	4.79

4371	15.27	4.79	15.26	4.79
4372	15.26	4.79	15.25	4.78
4373	15.26	4.79	15.25	4.78
4374	15.26	4.78	15.25	4.78
4375	15.26	4.78	15.25	4.78
4376	15.25	4.78	15.25	4.78
4377	15.25	4.78	15.24	4.77
4378	15.25	4.77	15.24	4.77
4379	15.25	4.77	15.24	4.77
4380	15.25	4.77	15.24	4.77
4381	15.25	4.77	15.24	4.77
4382	15.25	4.77	15.24	4.77
4383	15.25	4.77	15.24	4.77
4384	15.24	4.77	15.24	4.77
4385	15.24	4.77	15.24	4.77
4386	15.24	4.77	15.24	4.77
4387	15.24	4.77	15.24	4.77
4388	15.24	4.77	15.24	4.77
4389	15.24	4.77	15.24	4.77
4390	15.24	4.77	15.24	4.77
4391	15.24	4.76	15.24	4.77
4392	15.24	4.76	15.24	4.77
4393	15.24	4.76	15.24	4.77
4394	15.24	4.76	15.24	4.77
4395	15.24	4.76	15.24	4.77
4396	15.24	4.76	15.24	4.77
4397	15.24	4.76	15.24	4.77
4398	15.24	4.76	15.24	4.77
4399	15.24	4.76	15.24	4.77
4400	15.24	4.76	15.24	4.77
4401	15.24	4.76	15.24	4.77
4402	15.24	4.76	15.24	4.77
4403	15.24	4.76	15.24	4.77
4404	15.24	4.76	15.24	4.77
4405	15.24	4.76	15.24	4.77
4406	15.24	4.76	15.24	4.77
4407	15.24	4.76	15.24	4.77
4408	15.24	4.76	15.24	4.77
4409	15.24	4.76	15.24	4.77
4410	15.24	4.76	15.23	4.77
4411	15.24	4.76	15.23	4.77
4412	15.24	4.76	15.23	4.77
4413	15.24	4.76	15.23	4.77
4414	15.24	4.76	15.23	4.77
4415	15.24	4.76	15.23	4.77

Comment: The EnergyPlus result shows response to step changes in master zone dry bulb temperature in approximately the same way as the analytical solution. In the first step, the maximum difference in internal surface temperature is -0.24 ^{o}C, with 84 hours out of 100 hours have an difference within ±0.1 ^{o}C. In the second step, the maximum difference in internal surface temperature is 0.48 ^{o}C, with 72 hours out of 95 hours have an difference within ±0.1 ^{o}C. In both steps, there are 3-4 hours when the differences in external surface temperature are relatively large, but the temperature difference quickly reduces to within ±0.2 ^{o}C after that.