Thermal Bridging Calculation of Three Steel Stud Wall Assemblies with Benchmarking

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Introduction

The Pan-Canadian framework [1] on clean growth and climate change was adopted in December 2016 by the current Canadian government. The Pan-Canadian framework is a collective plan to grow the economy while reducing emissions and deploying measures to makes changes to the National Building Code that will help ensure building resilience when adapting to climate change. The federal government has an important role to play in both setting ambitious emission reduction targets and taking steps to achieve those goals. To support the 2030 target of reducing GHG emissions from federal operations by at least 40 per cent below 2005 levels, the 2017 budget proposed resources for NRCan to provide expertise to other federal departments for determining the best approaches to implement energy efficiency and clean energy technologies. Of Canada's total GHG emissions, 17% comes from homes and buildings whereas 12% are from direct emissions (e.g., combustion of natural gas for heating) and an additional 5% are emissions associated with electricity generation that is consumed in the built environment [1].

In this context, it is generally recognized that the thermal performance of building envelopes can be significantly affected by thermal bridging. Thermal bridges are localized areas of high heat flow through walls, roofs and other insulated building envelope components. Thermal bridging is caused by highly conductive elements that penetrate the thermal insulation or may also be caused by misaligned planes of thermal insulation. These paths allow heat flow to bypass the insulating layer thereby reducing the effectiveness of the insulation in providing resistance to heat loss to the building exterior.

In this project the COMSOL Multiphysics Heat Transfer Module was used to model the steady state and transient thermal performance of three steel stud wall assemblies from which the thermal bridging effects were calculated.

Laboratory thermal tests were conducted on these wall assemblies in NRC's Guarded Hot Box (GHB) following the test procedures given in ASTM C1363 [2]. The results from thermal tests were used to benchmark the steady state results derived from simulation. The benchmarking procedure demonstrated that the techniques and procedures used to produce R and RSI values can accurately reproduce test measurements using measured (or typical) material properties and consistent boundary conditions. The interior side of the wall assemblies was always exposed to 21 °C, whereas exterior wall temperatures of -5, -20 and -35 °C were used for the parametric sweep in the steady state condition. For the transient study, the exterior temperature was ramped up and down linearly in 24 hours and varied from -5 °C to -29 °C. The amount of energy to keep the interior warm was measured and compared with the steady state condition.

Experimental Set-up

The basic wall construction shared by all three wall assemblies consisted of an interior gypsum drywall board, measuring 13 mm (0.5 in.) thick; 6 mm polyethylene vapour barrier; 20 gauge steel studs having a depth of 92 mm (3.625 in.) and 41 mm (1.625 in.) in width, and spaced 406 mm (16 in.) on centre; fiberglass batt R-12 insulation, 89 mm (3.50 in.) in depth; and an exterior layer of OSB sheathing measuring 16 mm (0.625 in.) in thickness. Wall assemblies W2 and W3 had an additional layer of XPS exterior insulation attached to the OSB sheathing. The insulation layers were 25 mm (1 in.) and 50 mm (2 in.) thick for W2 and W3 respectively. Schematics of each wall assembly are presented in an exploded view in Figure 1 and **Error! Reference source not found.**.

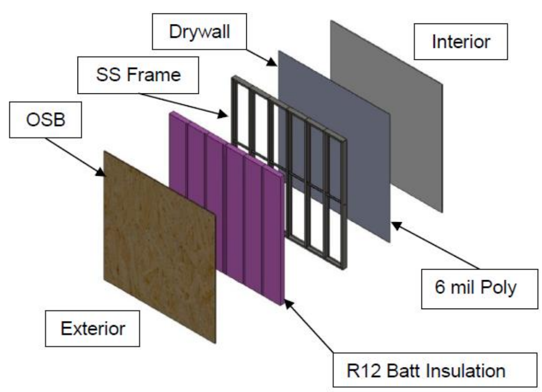

Figure 1. Schematic of wall assembly W1

The NRC GHB test facility, for which a schematic is given in **Error! Reference source not found.**, is a test apparatus specifically designed to determine the thermal resistance of building envelope assemblies and components by subjecting a test specimen to a temperature difference and measuring the amount of energy required to maintain interior set point conditions; i.e., the amount of heat the test specimen consumes to maintain the imposed temperature difference is measured and the thermal resistance is determined on the basis of the rate of heat transfer across the specimen, and as function of the unit area of the test specimen.

To determine the overall thermal resistance of the test specimen, measurements were taken of the interior (room-side) and exterior (weather-side) air temperature at the surface of the test specimen, as well as the heat input to the calorimeter thereby allowing the air temperature within the guard to be maintained to that of the room-side (interior) temperature. The thermal resistance can then be calculated using:

$$RSI = \frac{A * \Delta T}{Q}$$

Where:

- Q = heat input to the calorimeter (W)
- A = specimen area normal to the direction of heat transfer (m^2)
- ΔT = absolute temperature difference between the interior and exterior air (°C)

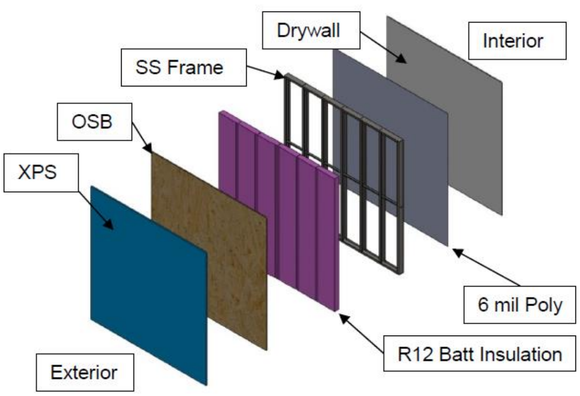

Figure 2. Schematic of wall assembly W2 and W3. Styrofoam (XPS – Extruded Polystyrene) panel was 25 mm (1 in.) thick for W2 & 50 mm (2 in.) thick for W3

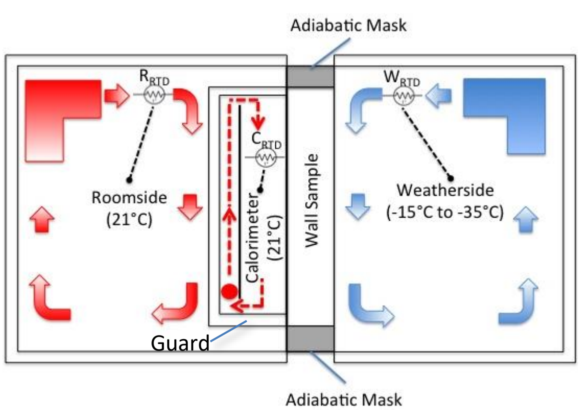

Figure 3. Schematic of GHB set-up & primary facility elements showing: room-side (interior) and weather-side (exterior) chambers, wall test specimen (sample), adiabatic mask, calorimeter and guard

In addition to the parameters mentioned previously, the interior and exterior surface temperatures of the wall assemblies were measured using thermocouples.

Numerical Simulation

Numerical simulations were completed on the wall assemblies in three dimensions. The modeling sequence for both series consisted of: (i) selecting and creating the geometry to be modelled; (ii) selecting the material properties; (iii) determining and applying the boundary conditions; (iv) performing mesh verification; (v) conducting the numerical simulations, and; (vi) comparing the results to those obtained from laboratory tests.

The 3-D geometries were imported in COMSOL Multiphysics and material properties were assigned to the corresponding domains. Mesh verification was conducted on one of the wall assemblies to determine the effect of changes in mesh sizing. Temperature dependent thermal conductivities for the insulation materials were measured using a Guarded Hot Plate (GHP) in accordance with ASTM C519 [4]; these results were used in the simulations. Parametric sweeps of the thermal conductivities were conducted to capture the different boundary conditions to which the wall assemblies were exposed when subjected to different climate zones. The results for fiberglass insulation batt and extruded polystyrene (XPS) as follow:

$K_{Fibergalss} = 0.03438+0.000212T_{mean}$
$K_{XPS} = 0.0271+0.0001129T_{mean}$

For the steady state condition, three different boundary conditions were applied on the wall assemblies. The temperatures and convective heat transfer coefficients used for the two sides of the wall assemblies are shown in In the transient scenarios, the thermal mass of the wall (the left hand side of the equation) could either reduce or increase the required energy to keep the interior at 21 °C. When the exterior temperature is increasing, and extra amount of energy is required to warm up the wall assembly components and that creates a false lower R-value. Whereas, when the exterior temperature is decreasing, the heat reservoir in the wall assembly can reduce the required energy to keep the wall warm and that creates a false higher R-value for the wall assemblies.

Table 1. A parametric sweep of the cold side temperature was conducted for these simulations. The average surface temperatures and the total heat flux passing through wall were measured and the thermal resistance was calculated using the correlation stated in the experimental section.

Contact thermal resistances were also considered in modelling the wall assemblies that were tested. The 2009 ASHRAE Handbook – Fundamentals [3] states that the contact resistances in buildings are too small to be of concern in many cases, but might be important for steel framing. Furthermore, contact resistance has previously been shown to be important for accurately simulating the thermal performance of steel stud assemblies [4]. To better model the thermal performance of the wall assemblies, contact resistances were also considered when undertaking simulations. For these purposes a value for contact resistance of 0.057 hr.ft^2. ^{o}F/Btu (0.010 m^2 ^{o}C/W) was modeled at insulation interfaces, whereas a value of 0.011 hr.ft^2. ^{o}F/Btu (0.0020 m^2 ^{o}C/W) was used in the model configuration at steel to steel connections.

Different scenarios of ramping up and down the exterior temperature from -5 °C to -29 °C on the steel stud wall assemblies were studied. Corresponding R-values and energy consumption to keep the interior warm were analyzed. Here is the conduction heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$

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Table 1. Exterior and interior boundary conditions

$T_{cold\ air}$ (°C)	$T_{hot\ air}$ (°C)	$T_{cold\ surface}$ (°C)	$T_{hot\ surface}$ (°C)	h_{cold} ($\frac{W}{m^2K}$)	h_{hot} ($\frac{W}{m^2K}$)
-5	21	-4.6818	19.824	32.7	9.2
-20	21	-19.513	19.19	34.0	8.9
-35	21	-34.355	18.589	34.0	8.9

Results

The wall assemblies that were described before were tested in the NRC GHB facility. The results were used to benchmark the COMSOL simulations. Surface to surface (S-t-S) R values were measured and compared for three outdoor temperatures: -5 °C, -20 °C and -35 °C.

The S-t-S R and RSI values derived from COMOSL for wall assemblies W1, W2, and W3 are provided, respectively, in In the transient scenarios, the thermal mass of the wall (the left hand side of the equation) could either reduce or increase the required energy to keep the interior at 21 °C. When the exterior temperature is increasing, and extra amount of energy is required to warm up the wall assembly components and that creates a false lower R-value. Whereas, when the exterior temperature is decreasing, the heat reservoir in the wall assembly can reduce the required energy to keep the wall warm and that creates a false higher R-value for the wall assemblies.

Table 1. These have been benchmarked against the GHB results. For W1, an outdoor temperature of -35 °C could not be achieved in the cold side of GHB because the calorimeter heater could not compensate for the heat flow through the wall and the mask at that temperature. It can be seen that the difference between the calculated R values for W1 is 4.34% on average which is below the ± 8% uncertainty reported for the NRC GHB. The average difference is 1.42% for W2 and 4.80% for W3.

The effect of thermal bridging has also been studied numerically. The R-values were calculated for the WAs supposing the steel studs had been replaced with the glass-fiber insulation from which the increase in R-value was then calculated. Average increases in R-value were found to be 115% for W1, 61% for W2 and 38% for W3. It can be seen that the effect of thermal bridging becomes less significant by applying additional exterior insulation to the WA. To normalize the temperature results for different outside temperatures, temperatures are non-dimensionalized using the temperature index approach. The temperature index is the ratio of a surface temperature to the overall temperature difference between indoor and outdoor. A value of 0 is the outdoor air temperature and 1 is the indoor air temperature.

$$T_i = \frac{T_{surface} - T_{outdoor}}{T_{indoor} - T_{outdoor}}$$

The results for the steady state can be found in our last year COMSOL Conference paper [5].

For the transient simulations, we ramped up the temperature from -29 °C to -5 °C in 24 hours and ramped down the temperature from -5 °C to -29 °C in 24 hours linearly, 1 °C every hour. Figure 4 illustrates the equivalent R-values and the heat fluxes on the interior and exterior surfaces for W1 when the exterior temperature is increased from -29 °C to -5 °C. It can be seen that because the wall components are colder, an extra heating is energy on the interior surface is required to overcome the thermal inertia of wall assembly components. We are using the interior heat flux to calculate the R-value, since that is the required energy to maintain the interior of an enclosure at a desirable temperature. The interior heat flux would not reduce proportionally to the temperature differences on the exterior and interior surfaces. Hence, increasing the exterior temperature would lead to false reduced R-values.

Figure 5 shows the R-value and heat flux results for W2 when the exterior temperature is decreased from -5 °C to -29 °C. In this scenario, the initial temperature gradient in the wall assembly is warmer than its upcoming temperature profile and therefore, the heat reservoir in the wall assembly can create a delay in cooling down the wall assembly and reduces the interior heat flux in comparison to the exterior heat flux. This would create false higher R-values during cooling down the exterior temperature. Figure 6 depicts the results for W3 when the exterior temperature is increased from -29 °C to -5 °C. Similar behavior for all three WAs was observed when we increased or decreased the exterior temperature and to avoid repetitive results, we don't include the other combinations.

As stated earlier, the interior heat flux is very important, since it determines the required energy to keep the interior warm. In order to determine how the exterior temperature change can affect the energy consumption. We averaged the heat fluxes during the ramp up and down phases and compared the values with the steady condition with exterior temperatures of -5 °C, -29 °C and the average temperature of -17 °C. These results for the WAs are depicted in Figure 7, Figure 8 and Figure 9. It can be seen that there is a significant difference between the cases with the exterior temperature of -5 °C and -29 °C. We also modeled the case at the average temperature in the steady state condition and the energy flux is the average of two values. It can also be seen that the for all three WAs, ramping down the temperature requires less energy due to the stored heat in the wall and ramping up the exterior temperature required more energy since an extra energy is required to warm up the wall components.

Conclusions

This project consisted in conducting Guarded Hot Box (GHB) tests and COMSOL Multiphysics simulations. In the first phase of this project, three wall assemblies were fabricated and tested in the NRC GHB in the steady state condition. The results from the tests were used to benchmark the results derived from numerical simulations. Different outdoor temperatures were also studied to reflect different climate zones in Canada. For the second phase which is the main purpose of this paper, we increased and decreased the exterior temperature linearly in 24 hours. The following outcomes have been derived from the study:

- Three steel stud wall assemblies tested in NRC's GHB test facilities and another series of simulations were conducted and benchmarked against these results. Average differences of 4.34%, 1.42% and 4.80% were observed between numerical results obtained in this study and the reported GHB results.
- Another series of simulations was also conducted in which the thermal bridging material (steel) was replaced with the embedded insulation (glass-fiber) and the R value calculated. Average R value increases of 115%, 61% and 38% were obtained for the wall assemblies considered. It has been shown that the effects of thermal bridging become less important by adding exterior insulation.
- It has been shown that when the exterior temperature is getting colder, the wall components can help to reduce the energy consumption in the enclosures and create false higher R-values.
- It has been shown that when the exterior temperature is getting warmer, the wall components cause an increase in the energy consumption in the enclosures and create false lower R-values.

This is an ongoing project and additional wall assemblies have been or will be tested and benchmarked against results obtained from numerical simulation. This project has demonstrated that the results derived from the COMSOL Multiphysics software are capable of predicting the thermal performance of steel stud wall assemblies with a high precision.

Table 2. Benchmarking results for Wall 1, Wall 2 and Wall 3

	COMSOL results		GHB Results			No Thermal Bridging		
T_o (°C)	RSI S-t-S	R S-t-S	RSI S-t-S	R S-t-S	Difference	RSI S-t-S	R S-t-S	Increase
Wall 1								
-5	1.36	7.77	1.43	8.17	**5.13%**	2.82	16.02	**106%**
-20	1.37	7.73	1.42	8.30	**3.55%**	3.03	17.20	**122%**
-35	1.45	8.14				3.14	17.82	**119%**
Wall 2								

-5	2.26	12.86	2.35	13.34	**3.66%**	3.59	20.40	**59%**
-20	2.39	13.60	2.40	13.63	**0.21%**	3.87	21.96	**61%**
-35	2.46	13.97	2.45	13.91	**0.39%**	3.98	22.59	**62%**
Wall 3								
-5	3.27	18.57	3.15	17.89	**3.84%**	4.62	26.22	**41%**
-20	3.37	19.14	3.23	18.34	**4.37%**	4.89	27.77	**45%**
-35	3.43	19.48	3.23	18.34	**6.21%**	5.02	28.51	**46%**

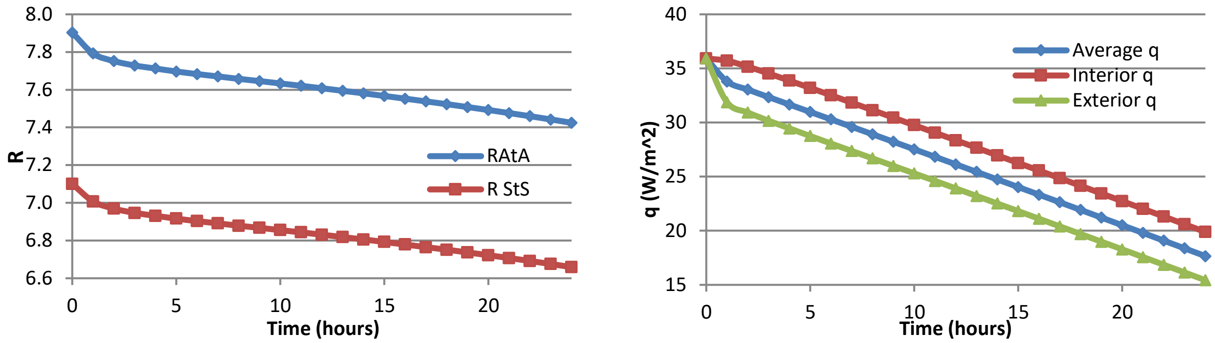

Figure 4: Transient R-value (left) and surface heat fluxes (right) for ramping up the temperature from -29 °C to -5 °C for Wall 1

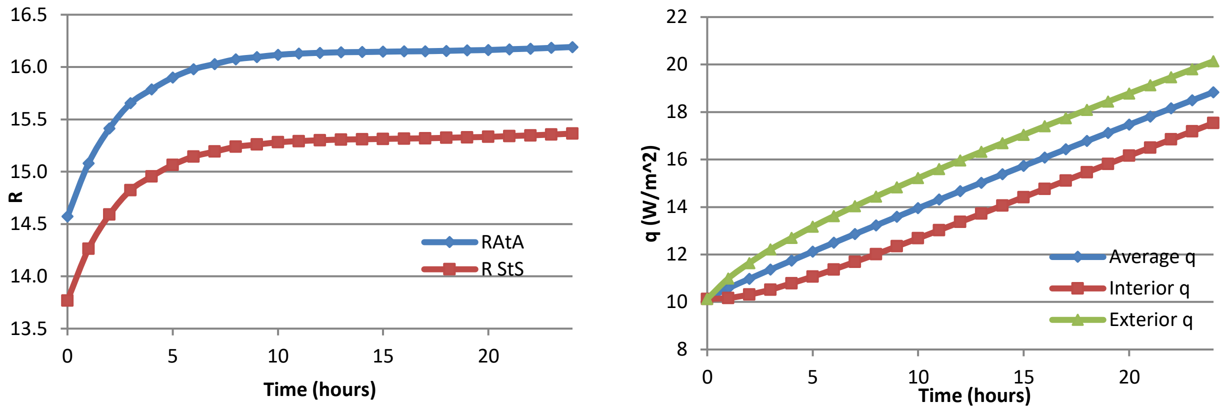

Figure 5: Transient R-value (left) and surface heat fluxes (right) for ramping up the temperature from -5 °C to -29 °C for Wall 2

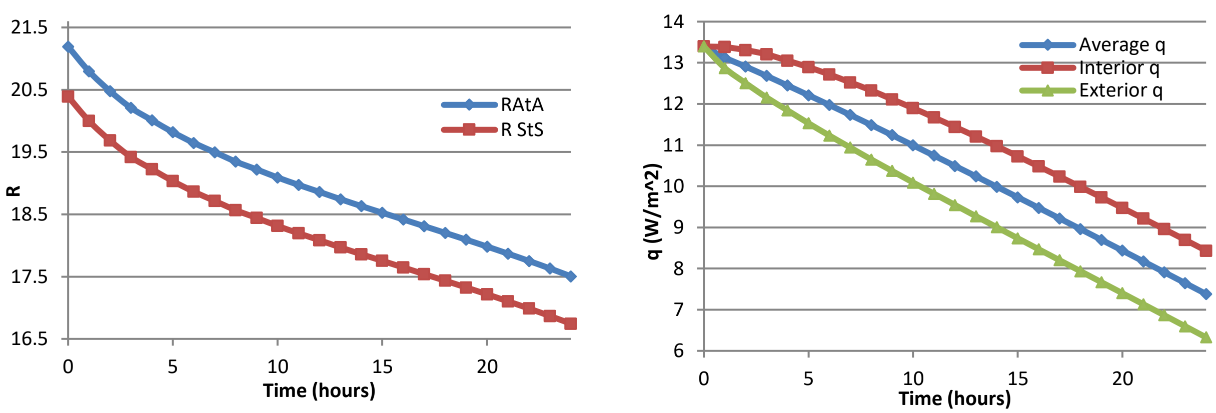

Figure 6: Transient R-value (left) and surface heat fluxes (right) for ramping up the temperature from -29 °C to -5 °C for Wall 3

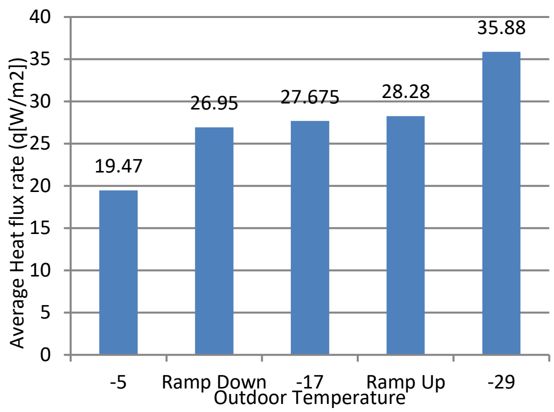

Figure 7. Energy consumption comparison for W1

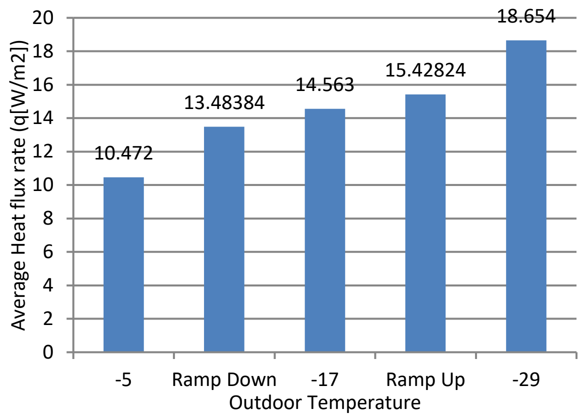

Figure 8. Energy consumption comparison for W2

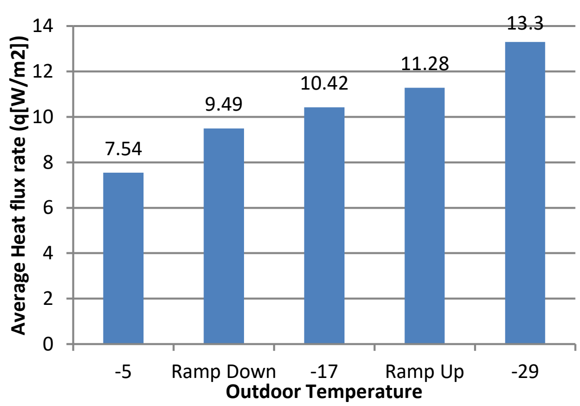

Figure 9. Energy consumption comparison for W2

References

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3. *American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2009). 2009 ASHRAE handbook: Fundamentals. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.*
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