ADVANCES IN MODELLING THERMAL BRIDGES IN BUILDING ENVELOPES

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ABSTRACT

This paper describes recent techniques developed to simplify the analysis and improve the accuracy of modeling thermal bridges. Two techniques are presented for determining the overall wall thermal resistance. The first is a hand technique using weighting factors between the isothermal planes and parallel path results. The second is a MS-WINDOWS finite-volume computer program. A technique is presented that accounts for the impact of thermal bridges on the transient response of wall systems. The equivalent wall model involves creating a fictitious multi-layer wall with properties selected so that its dynamic response to the transient conditions is the same as the real wall with two- and three-dimensional effects.

INTRODUCTION

Most building envelopes have thermal bridging: locations where the thermal resistance of the assembly is comprised for structural or framing reasons. Common thermal bridges include steel or wood studs in cavity walls, junctions between floors and walls, balconies and other structural protrusions, corners and extra framing around doors and walls. These thermal anomalies increase heat transfer to the outdoors and can be a site for condensation. Despite their common nature, many building simulation programs and program users ignore the impact of thermal bridging or attempt to account for thermal bridging with a simple correction factor to the R-value. This paper describes recent techniques developed to simplify the analysis and improve the accuracy of modeling thermal bridges. These techniques account for the impact of thermal bridges on thermal resistance and transient response of the wall system.

BUILDING ENVELOPE THERMAL RESISTANCE

Traditional Approach

The negative impact of thermal bridges has been known for a long time. Most building designers are aware of the reduction in wall R-value due to wood and steel framing. The traditional analysis technique to determine this reduction has been the “Parallel Path” method as described in the ASHRAE Handbook of Fundamentals. The resistances of each layer are added together to get a total path R-value. If there is more than one path through the wall (e.g., through the wood stud and through the cavity insulation), the total resistance of each path is calculated. The U-value (reciprocal of R-value) of each path are area-weighted to determine the total wall R-value.

This approach implies that the heat flows in parallel paths and does not adjust its direction to find an easier route through the wall. The reality of course is that heat takes the path of least resistance, and as such the parallel path method always over-predicts the actual R-value.

Table 1 lists the R-value over-prediction of the parallel path method for two common wood and steel frame wall systems. The over-prediction was calculated by comparing the results of the parallel path method to the results from 2-D finite volume analysis (see Section 2). The over prediction is most severe with steel frame walls but also has an effect in wood frame walls.

Table 1: Parallel-Path R-value Over-Prediction (%)

Wall Type	Wood Frame	Steel Frame
38 X 89 @ 400 mm centers with 25 mm ins. Sheathing	2.2 %	54 %
38 X 140 @ 400 mm centers with 25 mm ins. sheathing	2.2 %	86 %

Hand Calculation Correction Factors

The ASHRAE Handbook of Fundamentals recommends that both the parallel path method and the isothermal planes method be used to determine wall R-value. The correct wall R-value will be somewhere between these two results. In the isothermal planes method, the effective R-value of each layer is added together. If a layer is made up of more than one material, the material thermal conductivites are area-weighted.

Unfortunately, the two methods give very different results and some information is needed to determine where between these two extremes the correct answer lies. The results from the two methods can be weighted as follows:

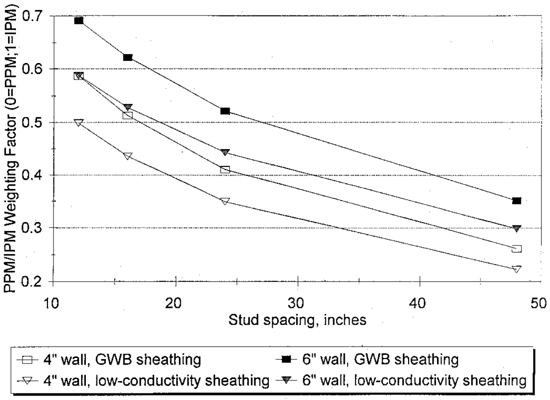
$$R_{wall}=R_{isothermal\ planes}*K+R_{parallel\ path}*(1-K)$$

Where K is a weighting factor between 0 and 1

Figure 1 shows the weighting factor (K) for a variety of steel and wood stud assemblies [Enermodal, 1996]. A value of 1.0 means that the isothermal-planes result is correct and a value of 0.0 means that the parallel-path result is correct. The lower the value K is, the higher the R-value will be. As the studs are placed closer together, thermal bridging is more significant and a higher weighting factor is required. Similarly, deeper studs cause more thermal bridging.

The above approach is useful for assessing thermal bridging in simple stud walls, however, it does have three major limitations. First, the weighting factors are limited to the wall systems studied. Second, the method cannot be easily applied to non-parallel geometries such as corners and wall/floor junctions. Third, the method does not account for lateral heat transfer caused by highly conductive layers. Two-dimensional finite-volume heat transfer overcomes all of these limitations.

Figure 1: Weighting Factor between Isothermal Planes and Parallel Path Results



Two-Dimensional Heat Transfer

Several two-dimensional computer programs (such as FRAMEplus, Enermodal, 2001a) are available to analyze more complicated wall assemblies. The speed of analysis and ease of use of these programs means that practitioners can use them on a daily basis as part of their design practice.

The latest version of FRAMEplus (5.0) allows users to draw and analyse wall and window sections in a MS-WINDOWS environment. The program has a comprehensive materials library and automatically assigns environmental boundary conditions, meshes the geometry and performs the calculations (usually within a few seconds). For complex walls and windows, the program area-weights individual results to obtain total wall (including corners etc) and window results.

Figure 2 shows the FRAMEplus screen of an insulated concrete block drawing. Figure 3 shows the main screen where the component area-weighting is performed.

This and similar computer programs provide a simple and accurate means of determining total wall properties to account for the thermal resistance impact of thermal bridging. However, these thermal anomalies can also have an impact on the thermal or transient response of wall assemblies. The time-lag benefits of a thermal massive wall system can be partially negated by thermal bridging. This speeds up the thermal response of the wall. A different approach is needed to account for transient effects.

Figure 2: FRAMEplus Model of an Insulated Concrete Block

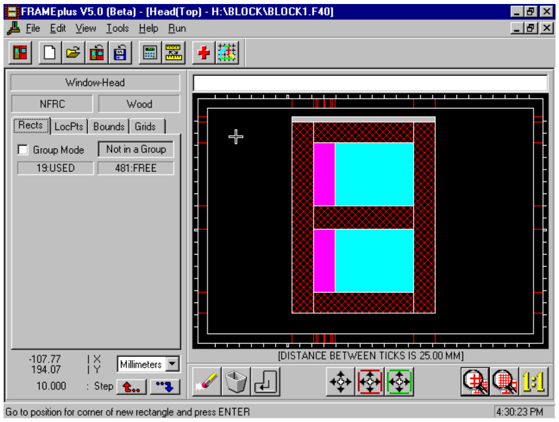
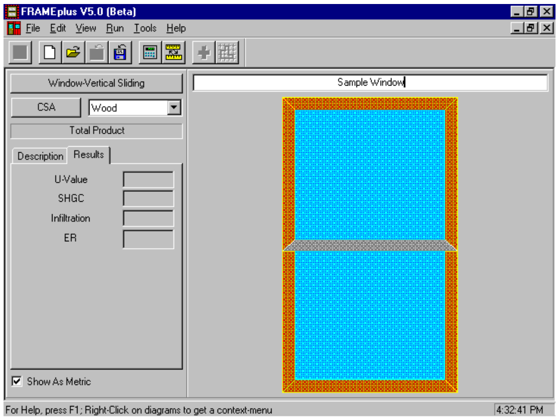


Figure 3: FRAMEplus Screen for Displaying Total Window/Wall Results



BUILDING ENVELOPE TRANSIENT RESPONSE

Equivalent Wall Model

Most building energy analysis programs model the transient response of walls as a series of one-dimensional layers, ignoring the impact that thermal bridges have on the transient response of the assembly. A recent ASHRAE project developed the concept of equivalent wall layers to account for this impact [Enermodal, 2001b]. The equivalent wall technique is a relatively simple way to model complex building assemblies in whole-building energy programs that use a nodal network or require input of thermo-physical properties of wall layers.

The equivalent wall model involves creating a fictitious multi-layer wall with properties selected so that its dynamic response to the transient conditions is the same as the real wall with two- and three-dimensional effects. Thus, for example, a homogenous wall layers could be defined with specific conductivities, densities, specific heats, etc., to give the same dynamic (and steady-state) response as a steel-framed wall with gypsum wallboard sheathing.

The equivalent wall method, developed by Kossecka and Kosny [1996, 1997], is incorporated into a specialized version of HEATING 7.2 [Childs, 1993], called

EQV_WALL. This computer tool aids in the modeling of dynamic thermal performance of complex wall systems with significant thermal mass, and is utilized for these simulations.

The equivalent wall method uses, as its mathematical basis, conditions imposed on the response factors and z-transfer function coefficients by thermal structure factors. Thermal structure factors are dimensionless quantities representing the fractions of heat stored in the wall volume, in transition between two different states of steady heat flow, which are transferred across each wall surface.

Structure factors φ_{ii} and φ_{ie} for a wall composed of n plane homogeneous layers, numbered from 1 to n with layer 1 at the interior surface, are given as follows:

$$\varphi_{ii} = \frac{1}{R^2 C} \sum_{m=1}^{n} C_m \left[\frac{R_m^2}{3} + R_m R_{m-e} + R_{m-e}^2 \right]$$

$$\varphi_{ie} = \frac{1}{R^2 C} \sum_{m=1}^{n} C_m \left[-\frac{R_m^2}{3} + \frac{R_m R}{2} + R_{i-m} R_{m-e} \right]$$

where R is the total thermal resistance per unit cross section area, R_m and C_m denote the thermal resistance and capacity of the m-th layer, whereas R_{i-m} and R_{m-e} denote the resistance for heat transfer from surfaces of the m-th layer to inner and outer surroundings, respectively.

There are several ways the equivalent wall technique may generate a simple one-dimensional multi-layer structure with the same thermal properties and dynamic behaviour as the actual wall. The first step is to assume some number of 'equivalent' layers for the wall structure. Experience has shown that three-layer equivalent wall models provide the best results. A simple way to solve for equivalent layer properties is to first generate, randomly or with some logic, a set of capacitances C_n (or resistances R_n) for each layer. Then seek the resistances R_n (or capacitances C_n) to satisfy the above equations. The thermal structure factors and overall R-value must match those for the 3-D wall assembly. Thermo-physical properties of the layers may then be established, if necessary, to match R_n and C_n values and total thickness of the wall.

The development of the equivalent wall model is an iterative procedure. By adjusting the number and capacitances of equivalent wall layers, the equivalent wall model can generate results that more closely resemble those of the 3-D model. The equivalent wall model results are not unique; however, different equivalent wall models have, in general, very similar dynamic thermal properties. If desired, one may examine several generated models to choose the best one.

Equivalent Wall Model Example

A comparison was made between the thermal response of the three-dimensional computer model and the equivalent wall model for an insulated concrete block wall (as shown in Figure 2). The equivalent wall layers are shown in Table 2. The comparison was made for a one-day period shown in Figure 4. The quantity Te is the exterior air temperature and Tes is the exterior sol-air temperature. The indoor air temperature was held constant at 68 F (20 C).

The results of the comparison are shown in Figure 5. There is very good agreement between the 3-D and the equivalent wall model. For reference, the response assuming instantaneous heat flow (i.e., no thermal lag) is also shown, labeled "steady-state". The 3-D transient analysis results in a 4-hour shift in peak load and a considerably smoother daily response.

A tabulation of equivalent wall properties for 20 common wall systems is contained in Enermodal, 2001b.

Table 2: Equivalent Wall Layers for an Insulated Concrete Block Wall

WALL DESCRIPTION

Components	*Total R-Value* ft^2-°F-h/ Btu
11.625 in. 2 Core Concrete Block 0.375 in. Mortar 1.875 in. Foam inserts	2.3

EQUIVALENT WALL THERMOPHYSICAL PROPERTIES

N	R_n ft^2-°F h/Btu	C_n Btu/ft^2-°F	l_n in	k_n Btu-in/h-ft^2-°F	ρ_n lb/ft^3	c_{pn} Btu/lb-°F
1	0.51	5.78	3.13	6.1	111	0.2
2	1.26	1.81	5	4.0	21.7	0.2
3	0.52	6.79	3.5	6.7	116	0.2
Total	2.3					

Figure 4: Daily Profile of the Exterior Air (Te) and Sol-Air (Tes) Temperatures

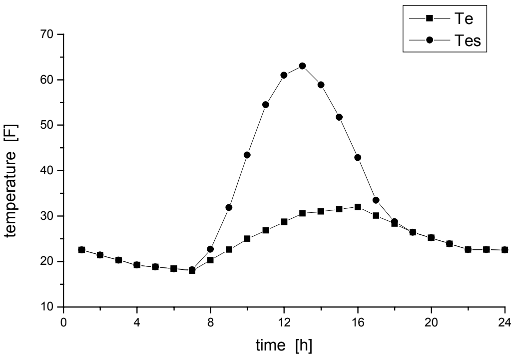
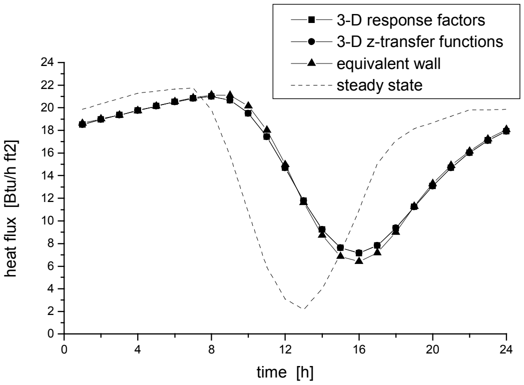


Figure 5: Comparison of Results for 3-D Transient Model and Equivalent Wall Model



CONCLUSIONS

The conventional parallel-path method can significantly over-predict the R-values of walls with thermal bridging. This over-prediction can be corrected using one of two simple techniques. First, a weighting factor between the isothermal planes and parallel-path methods is the easiest technique for simple wall assemblies. Second, user-friendly 2-D computer simulation tools can be used for more accurate assessment and for more complex assemblies.

Thermal bridging can also impact the transient response of walls. An "equivalent wall" model is a simple way of accounting for the transient response. This technique shows excellent agreement with detailed 3-D heat transfer models.

REFERENCES

Childs K.W. 1993. HEATING 7.2 User's Manual". ORNL/TM-12262. Oak Ridge National Laboratory, Oak Ridge, TN.

Enermodal, 1996. Building Insulation System Thermal Anomalies – 785-RP, report prepared for ASHRAE, Atlanta, GA

Enermodal, 2001a. FRAMEplus Computer Program Version 5.0 (www.frameplus.net) developed for Natural Resources Canada, Kitchener, ON

Enermodal, 2001b. Modeling Two- and Three-Dimensional Heat Transfer Through Composite Wall and Roof Assemblies in Hourly Energy Simulation Programs (1145-RP), report prepared for ASHRAE, Atlanta, GA

Kossecka E. and J. Kośny. 1996. Relations between structural and dynamic thermal characteristics of building walls. Proceedings of 1996 International Symposium of CIB W67 *Energy and Mass Flows in the Life Cycle of Buildings"*, Vienna, 4-10 August, pp. 627-632.

Kossecka E. and J. Kośny. 1997. Equivalent wall as a dynamic model of the complex thermal structure. *Journ. of Thermal Insulation and Building Envelopes,* Vol. **20**, 249-268.

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