DETERMINING TOTAL ASSEMBLY R-VALUES

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ABSTRACT

Standards such as ASHRAE 90.1 (ASHRAE, 2010-2016) and NECB (NRCC, 2011) are referenced in national Building Codes, and both require total-assembly R-values. ASHRAE 90.1 prescribes specific calculation methods for specific types of assemblies, and the NECB requires a hybrid of parallel-path and isothermal-planes methods; but both approaches are, strictly speaking, incorrect. Separate from the requirement to use the calculation methods stipulated in these standards, practitioners may wish to determine the thermal performance of assemblies for their own interest, or for use in projects where the national codes and standards are not applied.

This presentation explains how and why various calculation methods work, and describes some ground-breaking (but historical) research comparing hot-box tests, computer simulation, and various hand calculation methods, and the recommendations coming out of that research.

Methods discussed include physical testing, 2D and 3D computer simulation, parallel-path and isothermal-planes methods, zone method, modified zone method, ISO/DIS 6946, BRANZ method, and the methods required by ASHRAE 90.1 and NECB. These approaches will be assessed for accuracy, ease of use, and repeatability of results (which would ensure consistent answers and remove operator expertise as a variable).

R-VALUE REQUIREMENTS

Table 1 presents prescriptive requirements for the most recent versions of ASHRAE 90.1 and NECB standards for steel-framed walls, expressed as R-values. In the ASHRAE standard, insulation levels are presented as the minimum amount of insulation required to be placed in the stud cavity, plus the amount required to be placed as "continuous insulation", or "ci", defined as insulation that is only breached by fasteners or by intentional service penetrations such as electrical conduit, plumbing, or mechanical ducts. Both ASHRAE and NECB also define prescriptive requirements for total-assembly U-value, here presented as the equivalent R-values for direct comparison (and because the focus of this paper is R-values). One can see the intent of the standard by examining Table 1: in Climate Zone 5, for example (i.e., the site of the 2017 CCBST conference), the requirement for R13 in the stud cavity and an additional R10 continuous is considered to be the same as a total-assembly R18.2, because the latter includes thermal bridging effects.

Proving that a design contains appropriate insulation levels only requires documenting the thermal

resistance printed on the insulation package. Proving a total-assembly U-value (or R-value) is a little more involved, and is the reason for this paper. Acceptable methods for determining total-assembly R-values include physical testing, computer simulation, or a variety of calculation methods, but some expertise is required for any of these methods.

Table 1: Thermal Resistance Requirements for ASHRAE or NECB

Standard	Climate Zone	Non-Residential		Residential	
		Insulation R Value, h·ft²·°F/Btu (m²·K/W)	Assembly R Value, h·ft²·°F/ Btu (m²·K/W)	Insulation R Value, h·ft²·°F/Btu (m²·K/W)	Assembly R Value, h·ft²·°F/ Btu (m²·K/W)
ANSI/ASHRAE/IES 90.1- 2013 or 2016 (requirements unchanged in 2016)	4	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)
	5	R13+10 ci (2.3 + 1.8 ci)	R18.2 (RSI 3.3)	R13+10 ci (2.3 + 1.8 ci)	R18.2 (RSI 3.3)
	6	R13+R12.5 ci (2.3 + 2.2 ci)	R20.4 (RSI 3.6)	R13+R12.5 ci (2.3 + 2.2 ci)	R20.4 (RSI 3.6)
	7	R13+R12.5 ci (2.3 + 2.2 ci)	R20.4 (RSI 3.6)	R13+15.6 ci (2.3 + 2.7 ci)	R23.8 (RSI 4.2)
	8	R13+18.8 ci (2.3 + 3.3 ci)	R27.0 (RSI 4.75)	R13+18.8 ci (2.3 + 3.3 ci)	R27.0 (RSI 4.75)
ANSI/ASHRAE/IES 90.1- 2010	4	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)
	5	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)
	6	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)
	7	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+15.6 ci (2.3 + 2.7 ci)	R23.8 (RSI 4.2)
	8	R13+7.5 ci (2.3 + 1.3 ci)	R15.6 (RSI 2.7)	R13+18.8 ci (2.3 + 3.3 ci)	R27.0 (RSI 4.75)
National Energy Code of Canada For Buildings (NECB) 2011 or 2015	4	Not Applicable	R18 (RSI 3.2)	Not Applicable	
	5		R20.4 (RSI 3.6)		
	6		R23 (RSI 4.1)		
	7		R27 (RSI 4.75)		
	8		R31 (RSI 5.46)		

EVALUATION METHODS

Physical measurement

Physical testing has long been considered the gold standard for evaluating the thermal performance of assemblies. The process is complex, and requires specialized equipment (e.g., a calibrated hot box), thoroughly trained technicians, and rigorous adherence to appropriate standards (e.g., ASTM, 2011). Testing laboratories are supposed to conduct precision and bias exercises to determine the accuracy of their facilities: typical accuracy is in the order of ±5%. Figure 1 shows a test specimen (in this case, a steel-skin emergency exit door) in the test chamber with thermocouple leads and thermocouples taped in specified locations. In this case, the resulting temperature readings have been superimposed on the image. Figure 2 shows a more complex specimen, indicating the range of assemblies that can be tested (see also Table 2).

The test procedure is generally limited to specimens of a testable size. For most test facilities, this means assemblies that are not much larger than 3m x 3m (10 feet x 10 feet). Also, the results are tested at steady-state, and great pains are taken to ensure that the as-tested conditions remain constant and controlled, and that humidity is controlled so that it does not affect temperature measurements – especially on the cold side of the specimen, which is typically held at -18 °C.

Computer-based Simulation

Since 1988, computer simulation has been a popular adjunct (or some cases, a substitute) for physical testing of fenestration (e.g., ASHRAE, 1993) or opaque assemblies (ASHRAE, 1996). This approach provides a relatively quick and inexpensive way to evaluate the thermal performance (i.e., U-factors or R-values) of assemblies, and forms the basis of international standards for evaluating the thermal performance of

windows (ANSI/NFRC 2013; CSA 2014). Guides have been developed (e.g., Enermodal, 1996) to show how to create three-dimensional results using two-dimensional models, and these have proven to be reasonably accurate. The fact that the results are generated by computer has, unfortunately, led to some confusion due to the misunderstanding of the difference between accuracy and precision: computers can provide results that are precise to many decimal places, but are only as accurate as the input data, which is typically limited by the thermal conductivity of the materials (known, at best, to two decimal places). The accuracy of the model is also limited by the expertise of the modeler, which is not always reliable – and may not even be known, depending on the source of the simulation report or the reported result.

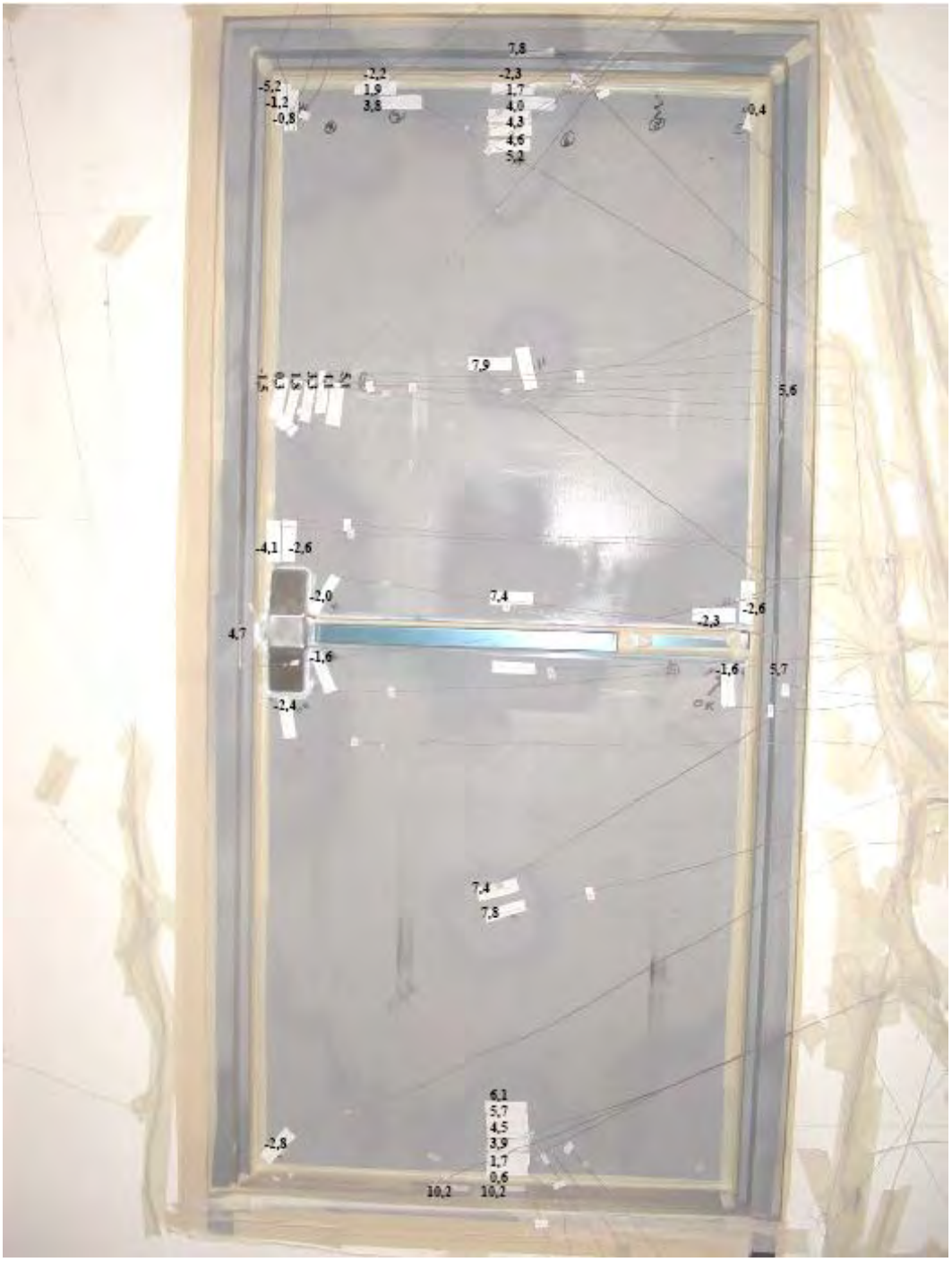

Figure 1: Test specimen instrumented for ASTM C1363 hot-box test (temperature results superimposed)

Figure 2: Revolving door in a calibrated hot-box test facility, showing complex specimens can be tested

More recently, three-dimensional computer models have been promoted as "state-of-the-art". While such models can provide more accuracy and can capture some thermal effects that are truly three-dimensional and significant, they are not always justifiable in providing additional accuracy in terms of the additional cost. Three-dimensional computer models are purported to accurately predict interstitial temperatures in complex assemblies; but such models would have to include explicit models for air movement (if such movement were suspected to bridge thermal barriers), and would have to model variable room-side film coefficient and transient effects to be truly representative. Guidance for the latter is provided in the literature (e.g., McGowan 1995), but this approach has not been widely used. Figure 3 presents a comparison of physical test results and two-dimensional computer simulation for a range of window assemblies.

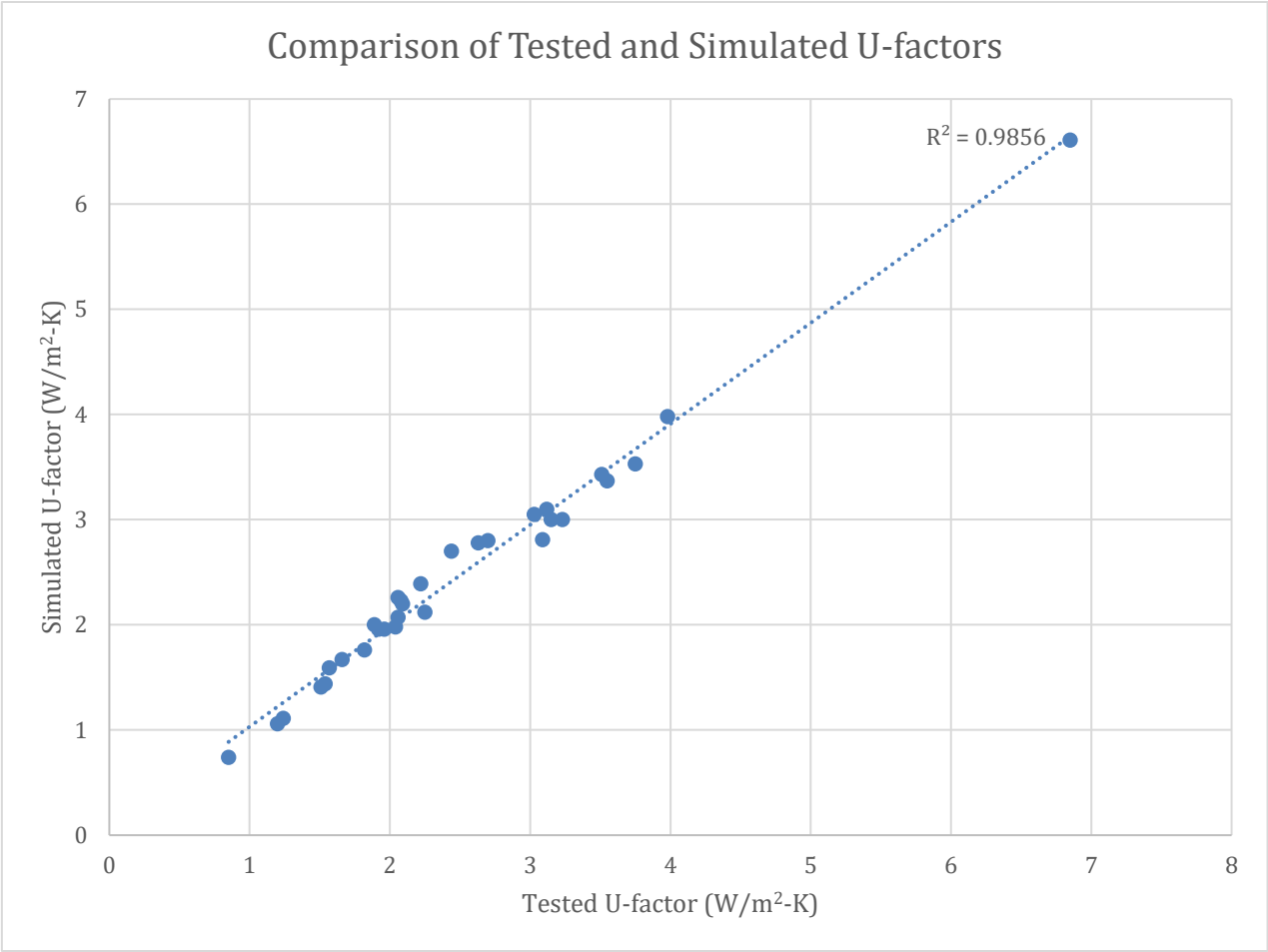

Figure 3: Comparison of Test and Simulated U-factors (after Carpenter, 1992)

Two-dimensional models have been developed for very complex assemblies, including pyramidal and hip-ridge skylights, barrel vault skylights, revolving glazed doors, and aircraft hangar doors. In all cases evaluated in the technical literature, the simulation results were within the stated error margin of the test facility (ASHRAE, 1993; ASHRAE, 1996; ASHRAE, 1988).

Hand Calculation Methods

Over 20 years ago, a ground-breaking research project compared computer simulation and simplified calculation methods against test results for a range of steel-framed and masonry wall assemblies (ASHRAE, 1996). This section of the paper summarizes the simplified calculation methods evaluated in that study, and provides recommendations for best use in the context of modern standards.

ASHRAE 90.1 requires testing or using the parallel path calculation method for steel- or wood-framed walls, and testing or the isothermal planes method for mass walls. The parallel path method (PPM) assumes that heat flows from the warm side to the cold side of the assembly in parallel paths, with no lateral conduction between the paths (hence the name of the method). Thus, each path is separated into its constituent layers, and the resistances of those layers are added to produce an overall resistance for each path, which is then area-weighted to produce a total-assembly value.

The method of isothermal planes (IPM), which some sources call the "series-parallel method", first splits the assembly into layers and determines an area-weighted resistance for each layer. The underlying assumption is that each layer experiences complete lateral conduction, and is therefore at a common uniform temperature (in other words, each layer or "plane" of the assembly is at the same temperature: hence the name "method of isothermal planes").

The actual thermal characteristics of any real assembly will lie somewhere between these two methods, because real heat transfer exhibits some amount lateral conduction (but not as much as IPM implies). Therefore, IPM will always produce a lower R-value than the truth – but the R-value determined with PPM will always be too high. The engineering judgment required to predict an accurate value is based on evaluating the degree of lateral conduction that is likely to occur in a given assembly. As the ASHRAE Handbook of Fundamentals (ASHRAE, 2017) puts it, "The actual resistance generally is some value between the two calculated values. In the absence of test values, examination of the construction usually reveals whether a value closer to the higher or lower calculated R-value should be used."

ISO 6946 (ISO, 2007) recommends using the arithmetic mean of both methods, and the ASHRAE research project (ASHRAE, 1993) recommended this approach, in the absence of any other information.

The Zone method used a geometric approach to determining the split between PPM and IPM, in considering the "shape" of the heat flow associated with a thermal anomaly (or thermal bridging element). The imposition of parallel heat flow paths implicit in PPM suggests that the effective area of a thermal anomaly is the projected area of the anomaly itself, whereas the IPM "smears" the effect of a thermal anomaly over the entire assembly. The Zone method suggested that the effective area of a thermal anomaly could be projected on a 45° line on either side of the anomaly until the inner or outer surface of the assembly was encountered: the resulting area would be the effective area of the anomaly, and the IPM and PPM results could be combined accordingly.

A modified zone method (Barbour et al., 1994; Kosny and Christian, 1995) was developed, that adjusted the effective area of the thermal anomaly according to the relative conductivity of the sheathing layer. This was a reasonable approach, as a more conductive sheathing layer would exhibit more lateral conduction, and thus look more like an IPM result. This method was distributed online by Oak Ridge National Laboratories (ORNL), in the form of correlations for various types of sheathing and assemblies, but ORNL determined that users were applying the modified zone method to assemblies far beyond the scope and intent of the online application, so they pulled down the tool rather than see it being continually misapplied.

The Building Research Association of New Zealand developed a method to analyze steel-stud framing, in which the C-channel stud is replaced with an equivalent conductivity using IPM, and the assembly then analyzed with PPM. This is similar to the method required by the NECB, in which the layer of a wall assembly that includes the framing is converted to an equivalent resistance with IPM, and then PPM is used to finish the calculation. A refinement of the BRANZ method (Trethowen, 1995) included the contact resistance between the steel stud and the sheathing, which produced more accurate results. The contact resistance concept was shown (ASHRAE, 1993) to improve the accuracy of the calculation (when compared to test results), and was used in more recent research (ASHRAE, 2011) involving two- and three-dimensional computer models.

CONCLUSION

Ultimately, the most cost-effective result remains simplified computer models or hand calculation methods that incorporate a combination of PPM and IPM, especially the ISO method. The methods stipulated in ASHRAE 90.1 (either PPM or IPM, depending on the assembly type) or NECB (a hybrid of IPM and PPM) should only be used when it is necessary to demonstrate that the calculation procedure has met the requirements of those standards for code compliance. For more accurate and representative results, ISO 6946 provides a more consistent methodology that is easily adaptable to a spreadsheet application.

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