ENERGY EQUIVALENT R-VALUE: Part 1 - Development Of Integrated Evaluation Methodology For Building Enclosures

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The paper is submitted to the Journal of Building Physics; and the extended abstract is presented here:

As a result of global increase in environmental awareness and the strive for reduction in energy consumption, it is only natural to look towards buildings as areas that need significant improvement to meet the society demand on reducing the energy use. After all, buildings consume more energy than cars. Yet the procedures that are used to define the thermal performance of, for example a wall, are based on indicators established under testing performed on dry materials, without consideration of effects caused by air or moisture movements. With other words these tests represent arbitrary rating conditions because we know that energy performance of materials and building assemblies is affected by moisture and air flows.

This paper, in part 1, explains why the traditional testing with calibrated boxes is limited to comparative measurements of heat flow and proposes a new test procedure, which, through a series of steps, bridges the gap between the currently used R-value rating and the energy performance rating. In the second part of the paper, this integrated testing and modeling methodology is applied to interacting effects of heat, air and moisture flows.

In this way, these two papers report a key part of a project sponsored by an industrial consortium[2] and aiming in a development of performance indicator that closer reflects the thermal performance of an assembly under service conditions. In doing so, the current R-value serves as a baseline to which R-values measured in later steps are compared. These steps include R-value measured under two levels of air infiltration and wetting by infiltration of warm, moist air followed by a subsequent drying.

2. Evaluation of existing measurement technologies

Methodology for determination of thermal resistance (R-value) for a building assembly is described in ASTM C236 and ASTM C 976 standards. Typically one tests a wall section, 8 ft by 8 ft (2.4m x 2.4m) or larger in either a guarded or a calibrated hot box. The wall separates the room and weather chambers. During the experiment, heat from the hot box flows in all directions: through the wall to the weather chamber, through the wall to the surroundings of the wall, and through the five sides of the hot box to the warm chamber. To perform a guarded hot box measurement one must maintain a zero balance on all five sides of the box. If this is not possible, a correction factor is determined as a function of temperature distribution and heat flux through the tested wall. This correction is applied to the measured heat production inside the box and therefore the name of the calibrated hot box.

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[2] Members of the consortium were: (1) Honeywell Corporation, (2) Huntsman Corporation, (3) Jeld-Wen Corp, (4) Greenfiber Corp., (5) Huber Engineering Wood Inc and (6) Centria Corporation.

2.1 Evaluation of hot box measurements

The hot box methods have been developed and used for testing of wall assemblies that are affected neither by the presence or movement of moisture nor by movement of air in the assembly. This fact was known for many years; Wilkes (1982) discussing block and frame walls stated that un-insulated block walls showed 15 to 19% lower performance than predicted. Greason (1989) stated that while good agreement was found for all solid walls, walls with air spaces showed lower performance than predicted.

It is, therefore, important to consider what would happen to the hot box method if one wanted to use it for measuring simultaneous heat, air and moisture transports. To measure three different flows through the building assemblies such a box would need to establish three different balances, namely that of heat, air and moisture. It means one would have to measure the difference between entering and leaving the box for each of heat, air and moisture flows while requesting that all sides of the box are both impermeable for air and moisture and highly insulated to minimize heat losses and gains.

To solve three simultaneous and interacting balance equations one need to measure the following inputs:

(a) the quantity of heat produced inside the box,

(b) the quantity of heat lost through the sides of the calibrated box,

(c) the quantity of heat carried by air flowing through the wall,

(d) the quantity of heat carried in or out of the box by air flows

(e) the quantity of air entering to the calibrated box,

(f) the quantity of air leaving the calibrated box,

(g) the amount of air transmitted through the wall,

(h) the amount of moisture delivered to the box by air flow

(i) the amount of moisture leaving the calibrated box with air

(k) the amount of moisture that is transmitted through the wall with the air infiltration

(l) the amount of moisture that is transmitted through the wall through diffusion

Even if adding two factors (k) and (l) together one obtains 10 separate measurements.

Since the most of air ingress takes place at the perimeter of the wall, the size of the hot box for measuring air flow must be larger than the wall assembly (this eliminates application of the guarded hot box method). With such a construction of calibrated box, correcting for the flanking heat transmission (effect of thermal short on the perimeter of the wall) becomes very difficult and control system becomes very complex. Obviously these 10 parameters can be measured in a sequence of three different tests, each aiming at one effect, e.g., het, air or moisture. Yet, in such a test series one cannot measure the interaction between these three transport phenomena.

There is, however, another major obstacle when using this approach. If the influence of exterior air pressure field causes a convective loop either in the air gap or in the porous thermal insulation, the distribution of temperature on the wall surface changes. In such a case, the previously established correction for the calibrated box requires a new adjustment. Yet, as the boundary conditions affect the hygrothermal response of the test wall, it becomes an iterative process introducing excessive period of testing before the correction is established and prevents testing of transient processes.

Effectively, this approach would require building three different calibrated boxes[3], as two different boxes are used today in laboratories testing both heat or air transmission. One must remember, however, that a calibrated box is restricted to measuring an average value of thermal resistance. The average rating does not allow on separation between various flow mechanisms i.e., one cannot measure how thermal performance changes as an effect of air flow or moisture movement. Effectively, this approach is neither suitable for academic research, nor for industrial R/D when one wants to optimize materials used for heat, air and moisture performance of walls.

Another solution, R-value measurements based on heat flux transducers need to be used in this project (see: Hedlin et al, 1980).

2.3 Evaluation of heat flux measurements

Measuring heat flux by means of heat flux transducers (HFT), in addition to the questions related to the measuring technology *such as a required minimum sensitivity of the HFT,* brings forth two considerations:

1) Would the transducer modify the flow of heat or moisture and how can we estimate such an effect
2) How to calculate the *average thermal resistance* of the assembly (as this is our ultimate goal for energy rating) when we only measure selected local values of heat flux.

To avoid dealing with the first concern (at least during the method development) we have selected an approach called for simplicity "calibrated boundary layer" (CBL). This approach, originally introduced by Henka (1923)[4], includes a uniform and continuous layer of the known insulation placed on the warm side. An improvement over the original concept of Henka is that the calibrated boundary layer contains several specimens that were previously tested in the heat flow meter (HFM) apparatus. In this manner the approach can be as precise as the thermal conductivity measurements performed with ASTM C518 test method. Furthermore, as the discussed later in this project, the use of CBL will enhance our possibility of estimating effects of moisture transfer on heat flow through the wall.

Medium density mineral fiber boards were used in the first series of tests. Historically, convection was supposed to affect only the low density mineral fiber products and this material was assumed to be non-convective while having a high permeability for air and vapor. With other words, it did not create a vapor barrier similar to that of a standard HFT. Yet, during the pilot tests a substantial difference between thermocouples and thermopile used in the HFT were observed.

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[3] One could also use only one calibrated box for heat flow measurements and acquire other information from sensors placed in and outside of the test specimen. Yet, this approach is limited to heat and air interactions.

[4] Referred to by Schmidt and others in history of heat flow transducer developments (see ASTM STP 885, Building Applications of HFT, Bales, Bomberg, Courville editors)

The CBL approach was applied during several years of field testing at NRCC (Bomberg and Kumaran,1994; Bomberg et al 1994) and was proven effective, yet there were no air flows involved in those tests. When finding out that thermal performance of the medium density, semi-rigid mineral fiber board was affected by air movement, the construction of HFT was modified and finally a a EPS laminated with paper was used. MS thesis of Shetty (2007) reports the improved the design of HFT that eliminated effects of radiation by covering the sensor with Kraft paper. By doing so the calibration of HFT exposed to air and that in HFT apparatus (sandwiched between black plates) became practically identical. Finally the design of Shetty (2007) with improved and (4) new design of thermopile was used. Only results obtained with HFT (4) are presented here.

3. Development of a new testing methodology

The objective of this work has been formulated as follows:

- Develop a method to determine thermal performance ***under reference conditions for wall assemblies***
- Develop verification of HAM models for a given assembly under reference conditions that involve air and moisture movement

This pilot study highlighted presence of several critical factors. The same wall assembly when installed with and without perimeter sealing showed very different thermal performance. One may say that the effect was expected. Yet, the significance of this effect was much higher than expected and forced us to re-consider the basic approach to this project.

3.1. Separating wall performance from its dependence on the rest of the building

Integrated testing and modeling approach was found necessary to allow performing local measurements of heat flux and calculate the average R-values for the building component from 2-D HAM models. Yet, the validity of HAM models is generally questioned[5] unless it is compared with measurements or verified by other means. This implies that tests involving air movement must also provide verification of HAM model. Finding that the current testing methodology is not suitable for simultaneous evaluation of heat, air and moisture flows one must resort to use of Heat Flow Transducers (HFT). Measuring local heat flows allows us better evaluation of materials and systems but also requires using HAM models[6].

We need to evaluate the contribution of different thermal insulating materials because some of these materials can deliver the nominal thermal resistance only when they are fully protected from the effects of air and moisture. Others can be used for partial or total control of heat and air flows or there are even thermal insulating materials that can control of water ingress. Since the current R-value concept considers only the heat transfer, all other contributions of thermal insulation cannot be recognized. Therefore, the scope of the test method proposed in this project should enable all these aspects to be fully recognized.

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[5] In this research results of 2 different 2-D codes out of 3 used for comparisons, namely (multi-physics by Comsol, WUFI, CHAMPS / Delphin) are compared each with other.

[6] One must use combined heat and moisture transport model because phase change of moisture affects temperature and change in temperature affects relative humidity in the material. Calculations of heat transfer without consideration of moisture can only be considered as first approximation.

It was noted that wall airtightness under field conditions depends also on the history of moisture content and that one must account for shrinkage of wood and changes in wall airtightness caused by wetting and drying of wood-based materials. To address these concerns one must introduce a specific sequence of testing.

3.2. Sequence of testing selected for evaluation

The proposed procedure introduces a stepwise approach. Step 1 aims at determination of the steady state R-value for the tested walls. This step will compare the test results with the current state-of-the art as developed by the ORNL – so called “clear wall R-value” (cf. Syed and Kosny, 2006). This test is performed under standard boundary conditions, yet, it is performed with a new testing methodology. This step is used as a reference and benchmark for a wall with dry and newly installed insulation (no moisture or airflows). This R-values will later be used as the basis for comparing changes in R-value that occur as in effect of introducing air flow thought the wall (step 2) or hot and humid conditions (step 3) or drying of the wall after the exposed to moisture (step 4).

Step 2 continues with the same RH and T conditions but employs air pressure on the weather side. Air pressure gradient of 50 Pa is excessive when comparing to the practical air pressure variations in the field conditions but it is a standard value used for field evaluation of houses. Applied pressure gradient will now be maintained constant though all stages of the test. The second step is to evaluate the effect of air flows. The pilot research led us to understanding of the interaction between external and internal air pressure conditions affecting the air flows. Any attempt to characterize wall with regard to factors that affect transfer from external pressure field i.e. degree of connectivity between wall and environment while trying to measure resistance to air flow inside the wall leads to circular dependencies i.e., one cannot generalize the measured results. One needs to characterize internal flow path (see Derome, 2005) because the difference between short and long path has been highlighted by Ojnanen and Kumaran (1996) in context of moisture deposition. Yet, significance the internal path depends on many effects such as construction workmanship and moisture history.

To permit generalization of the test results one must separate all issues into two components:

1) All conditions related to the construction and past history of the construction as they affect the boundary of the tested enclosure component
2) A test procedure that would focus on hygrothermal response of the studied wall system.

This leads to an apparent contradiction. While effects of construction workmanship and history of moisture in the wall must be excluded from the actual test leaving the focus on the contribution of the actual air and thermal control systems on the HAM performance of the wall, yet these effects must be included in the test program. To avoid this contradiction we must be able to control the external effects and perform the test under a specified level of “construction quality”.

With other words, we need to use at least two different sets of external conditions of specified inflow and outflow from the top and the bottom of the test wall. By doing so, we provide the capability of generalization of the measured results. Since the overall leakage of the wall is quantified in relation to the external pressure difference, these two series can be performed under one set of pressure conditions. Review of available published (Onysko, 1989; Hui, 2007) and unpublished information were used to define two levels of wall airtightness used in the test.

Finally, steps 3 and 4 in the test procedure include changing the direction of thermal gradient[7] and changing the exterior climate to be either source of moisture (step 3) or sink of moisture (step 4). While moisture is introduced we move to the transient measurements and must rely more on the modeling capability. To reduce the time of wall exposure and to better assess the effect of moisture carried by air, during step 3 extreme weather conditions are used for a specified period of time. In step 4 we revert to the stage 2 and the same conditions as applied in the stage 2 are reinstated to see if drying of the moisture introduced during step 3 is effective.

Now, having developed methods of verification for material characteristics for hygrothermal model and having measured the assembly performance under four different sets of climatic conditions one can use the HAM model for calculation of the average R-values for the building component under the actual field conditions. The conditions of exposure are presented in Table 4 below.

Table 4: Steps in the test program and nominal conditions during the tests

Stage	Pressure drop across the wall	Temp on outside.	RH outside	Nominal temp. inside	Nominal relative humidity inside
1	0 Pa	-20 °C	N/A	25 °C	50 %
2	50 Pa	-20 °C	N/A	25 °C	50 %
3	50 Pa	40 °C	85 %	25 °C	50 %
4	50 Pa	-20 °C	N/A	25 °C	50 %

In addition to the main test series several additional airtightness tests are performed before step 1 and after completion of the step 4 to characterize the wall assembly.

The characterization of the wall airtightness is discussed in part 2 of this paper, which presents application of the new integrated testing and modeling methodology to selected wall assemblies.

Conclusions

This paper reviewed why the traditional testing with calibrated boxes is not suitable for energy performance rating. The aim of this project (sponsored by an industrial consortium) was twofold:

1) to create a performance indicator that will more closely reflect the actual thermal performance of an assembly. This performance test determines the traditional R-value as the base line to which values measured in later steps are compared.
2) To provide a verification opportunity for advance heat, air moisture (HAM) so that they can be used for addressing effects of moisture

The proposed test procedure uses a series of steps that bridge the gap between the currently used R-value rating and energy performance R-value rating. In addition to the standard measurements of air pressure, temperature and relative humidity in various locations characterize performance of the wall under exposure to simultaneous heat, air and moisture transports. All these measurements are necessary

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[7] Note that we do not change the gradients of air pressure to avoid discussion on wall durability aspects, and if so is needed we would use another, mid-scale testing equipment available in the laboratory.

for the second objective i.e., verification of HAM models. The second part of this paper will demonstrate application of the proposed test methodology.

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Mechanical & Aerospace Engineering

Energy equivalent R-value

Part 1: Integrated evaluation methodology for BE

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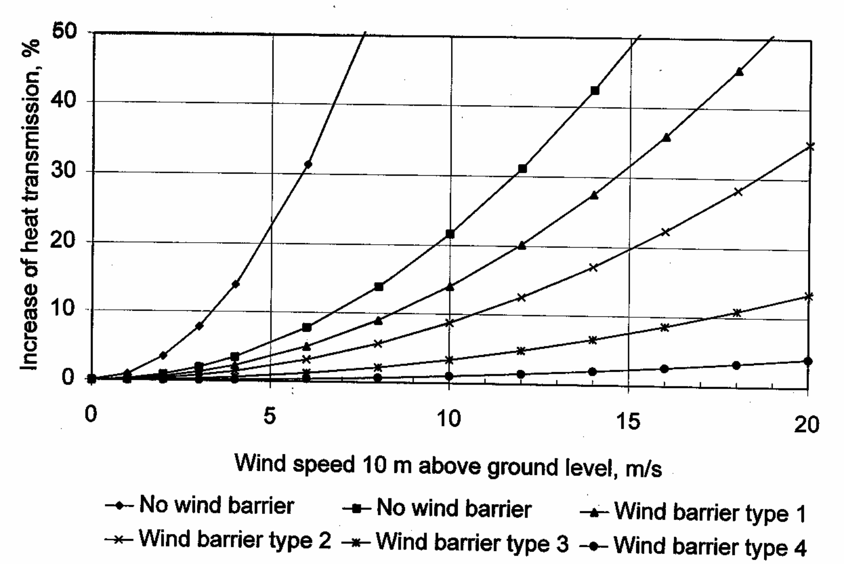
Outline

- ***R-value is a material not a system indicator***
- ***A measure of energy performance for an assembly is needed***
- ***Factors affecting energy performance of assembly under field conditions***
- ***Why verification of HAM models on material and system level is required***
- ***Proposed methodology for testing and verification of HAM models***

Wind reduces R-value of wood-frame wall with MFI and AB (Uvslokk 1996)



Fasteners and gaps between boards al reduce R-value, in % (Petrie et al 2000)

Mean temp. ^{o} C (^{o} F)	Mechanical fasteners in 4” PIR boards	Gaps between two 2 “ PIR boards	Gaps between 2” PIR boards
-1 (30)	8.6	14.5	16.7
24 (75)	7.0	12.2	15.3
51 (123)	5.6	10.2	14.0

Factors affecting the R-value of low sloped roofs (Bomberg & Pazera 2006)

- ***Mean temperature of insulation varies***
- ***Aging of gas-filled foams***
- ***Thermal bridges = mechanical fasteners used for insulation boards***
- ***Air gaps & air flow between boards***
- ***Moisture contained in the roof***
- ***Moisture carried by air or condensation caused by air movement***
- ***Reflective coatings may lower surface temperature (cool roofs)***

To measure heat, air and moisture at the same time with hot box we need:

(a) the quantity of heat produced inside the box,

(b) the quantity of heat lost through the sides of the calibrated box,

(c) the quantity of heat carried by air flowing through the wall,

(d) the quantity of heat carried in or out of the box by air flows

(e) the quantity of air entering to the calibrated box,

We need to measure HAM simultaneously we need : -2-

(f) Mass of air leaving the calibrated box,

(g) Mass of air transmitted across the wall,

(h) Air borne moisture delivered to the box

(i) Air borne moisture leaving the box

(k) Mass of moisture transmitted through the wall by the air infiltration

(l) Mass of moisture transmitted through the wall through diffusion

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Measurement contradictions

- 10 or 11 individual measurements
- Air flows are affected by a perimeter so air-box larger than the test wall
- To calibrate flanking heat loss the box must be smaller than the wall
- Even if moisture effects were tested in the lab, the field effect need to be calculated for the actual field climate

Integrated testing and computer modeling must have three objectives

1. Characterize effect of air flow on R-value through the assembly as built
2. R-value under reference conditions of air flow through the assembly
3. Method for verification of HAM models for a given assembly under reference conditions that involve simultaneous ingress of air and moisture

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Proposed approach involve a sequence of 4 steps

- **Step 1:** measure nominal and several local R-values, no air or moisture effects
- We measure temperature differences across the assembly and heat fluxes: minimum (insulation), maximum (thermal bridge) and intermediate on three levels (9 local measurements)
- We use 2-D heat flow model to calculate mean R-value for the test wall

Understanding air flow measurements

- To evaluate the effect of air flows on R-value when air pressure fields outside and inside the wall interact each with other, we need to measure separately:

1. Connectivity between wall and environment
2. Resistance to air flow inside the wall

- In the latter case: (a) what is the internal path, (b) what is caused by construction workmanship and moisture effects?

Step 2: Add 50 Pa on the weather side

- We measure on the wall as built:

(1)isothermal conditions, connectivity

(2)Under thermal and pressure gradients we characterize the assembly.

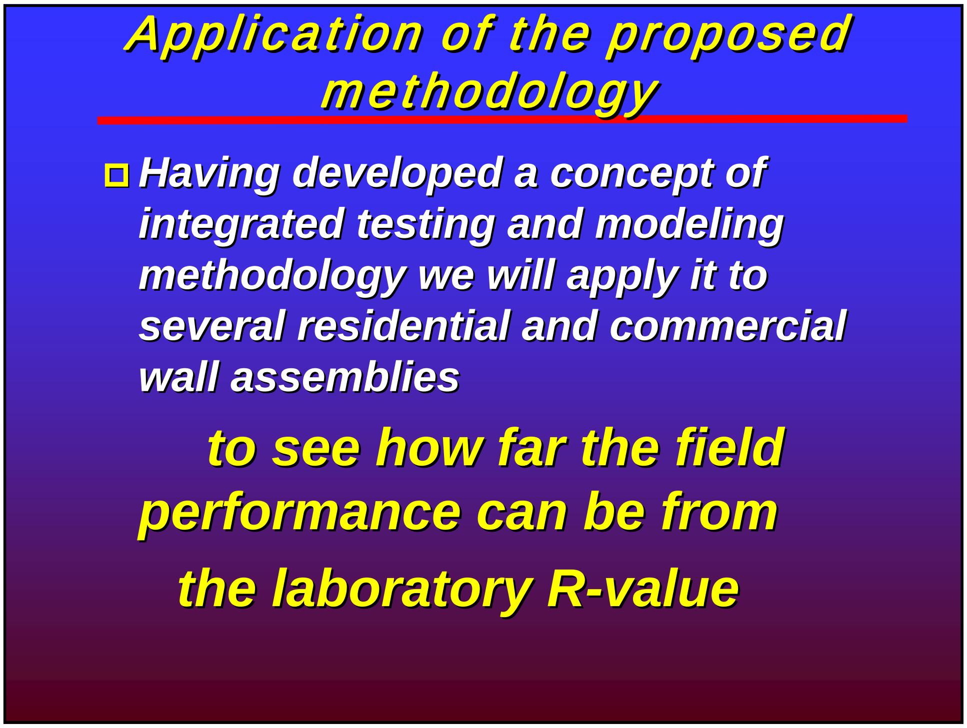
- To this end we use calibrated inlet and outlets and 2 levels of flow to examine air flow - pressure relations
- Two points permit estimating variation in results measured for only one case of connectivity.

Step 3: HAM verification - moisture carried by air enters the test wall

- We apply hot and humid conditions for 3 days. Moist air is driven into the wall by (1) air pressure and (2) thermal gradient
- Initially, a longer period was used but some walls even though protected with WRB got so wet that drywall was soaked and thermal tests on inner surface had to be stopped.

Step 4: HAM verification, reverse to standard conditions of step 2

- Stages 3 and 4 are used for only for verification of HAM models.
- At this stage energy equivalent R-value expands the R-value concept only to standardized measurements of thermal bridges and air ingress.



Application of the proposed methodology

- Having developed a concept of integrated testing and modeling methodology we will apply it to several residential and commercial wall assemblies

to see how far the field performance can be from

the laboratory R-value