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# Effect of Natural Convection on the Thermal Transmittance of Exterior Walls with Air-Permeable Insulation

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## ABSTRACT

*In the past few years, the Finnish building code's demands for energy efficiency has increased the thickness of insulation layers in building envelopes. Natural convection is considered in the building code by not allowing structures whose modified Rayleigh's numbers exceed the limit values. However, it has been unclear how considerably the natural convection can affect the heat loss through envelope in instantaneous or annual level. The aim of this study was to inspect the actual effect of natural convection in relatively thick, air-permeable vertical insulation layers by laboratory measurements and computational modeling.*

*Several U-factor measurements by calibrated hot box method were carried out to wood frame test walls with mineral wool or cellulose insulation. Attributes presumably affecting the convection process were varied. Poor workmanship's effect was studied with intentionally sloppy installation work and with intentional horizontal air gaps in the insulation layer. Careful installation with the convection barrier was used as a reference where the effect of convection was supposed to be negligible. Measured U-factors were compared to numerically calculated U-factors and to simplified U-factor calculations. Permeabilities and thermal conductivities of the used materials were measured for the calculations' initial data.*

*Measured and calculated results were in relatively good agreement. Results showed that during cold periods natural convection can slightly increase the actual U-factors of exterior walls. The convection barrier can be used effectively to restrict natural convection as demanded by the building code. However, the quality of workmanship should not be forgotten when pursuing a very low U-factor by increasing insulation thickness.*

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## INTRODUCTION

Heat losses through the building envelope play a significant part in the overall energy consumption of small buildings in countries with cold climates. Such countries have typically developed long traditions in the use of thick insulation layers. In addition, during recent decades the growing demands in energy efficiency have led to efforts to save energy by using over 400 mm thick insulation layers in roofs and exterior walls. Also, Finnish building code's instructions for thermal insulation were revised in 2010, reducing the reference U-factor for exterior walls from 0.042 to 0.030 Btu/(h·ft<sup>2</sup>·°F) (0.24 to 0.17 W/[m<sup>2</sup>·K]).

A Finnish wood-frame house is typically insulated with mineral wool batts, but the cellulose insulation has also gained

popularity due to its low price and also because it can be installed into vertical structures by wet-spraying. Manufacturers have managed to develop the thermal conductivities of both materials to competitive levels. However, both of these types of materials remain air-permeable, which has raised questions about the role of convection in the total heat transfer through envelope structures with even thicker insulation layers.

Currently pending building code revision will restrict the modified Rayleigh number ( $Ra_m$ ) of prescribed exterior walls by not allowing wall structures with  $Ra_m$  exceeding the value of 2.5 when the temperature difference between indoors and outdoors is 90°F (50 K). Conformity of structures shall be

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**Figure 1** (a) The hot box of the research equipment and (b) the monitoring room.

proved by calculating  $Ra_m$  in accordance with international standard EN ISO 10456 (ISO 2007):

$$Ra_m = 3 \times 10^6 \frac{d \cdot k \cdot \Delta T}{\lambda} \quad (1)$$

In theory, for vertical structures heated from the side there is no critical value of  $Ra_m$  determining the onset of natural convection, but the convection may start as soon as the temperature difference is introduced. The purpose of this research was to investigate the effect of natural convection on the U-factor of typical wood frame wall structures in average winter outdoor temperatures and to evaluate the adequacy of the limit value of  $Ra_m$ . A goal was also to clarify the actual influence of poor workmanship, air gaps and convection barrier (CB) on the thermal resistance.

## RESEARCH ARRANGEMENT

Evaluations of natural convection's magnitude were based on comparisons of U-factor measurements and software simulations. Convection's proportion of the total heat transfer through a structure can be described with Nusselt number (Nu) which is here defined as:

$$Nu = \frac{\phi_{cd} + \phi_{conv}}{\phi_{cd}} \quad (2)$$

Experimental Nusselt numbers were determined by assuming that the effect of natural convection is negligible when examining the U-factor of a test wall with convection barrier. Thus, the increment in total heat flux due to removal of convection barrier is assumed to be entirely due to natural convection and the Nusselt number can be calculated from two measurements:

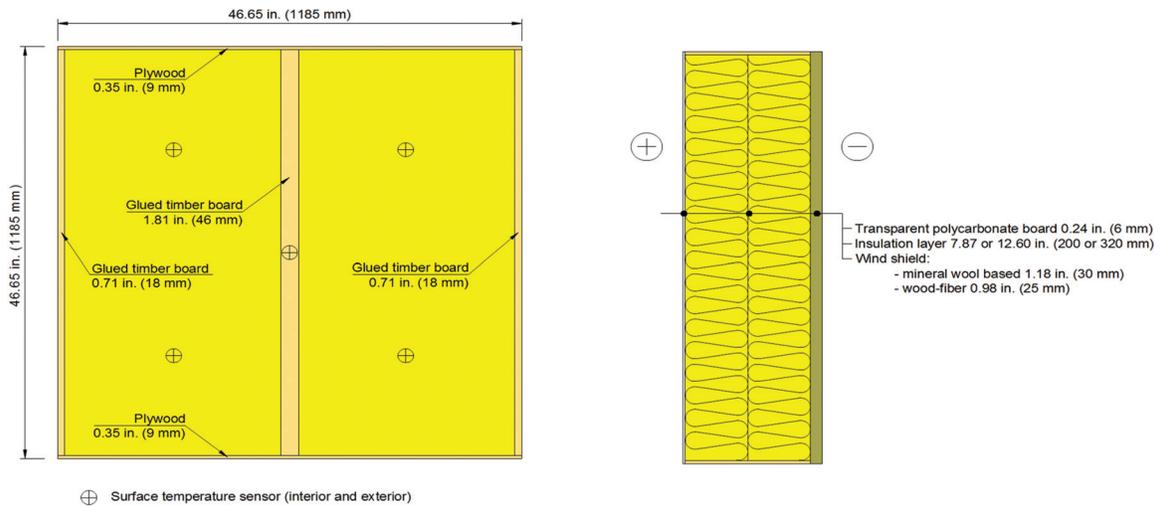
$$Nu = \frac{U_{noCB}}{U_{CB}} \quad (3)$$

The laboratory equipment used in this research is called Building Physical Research Equipment and it is located in the

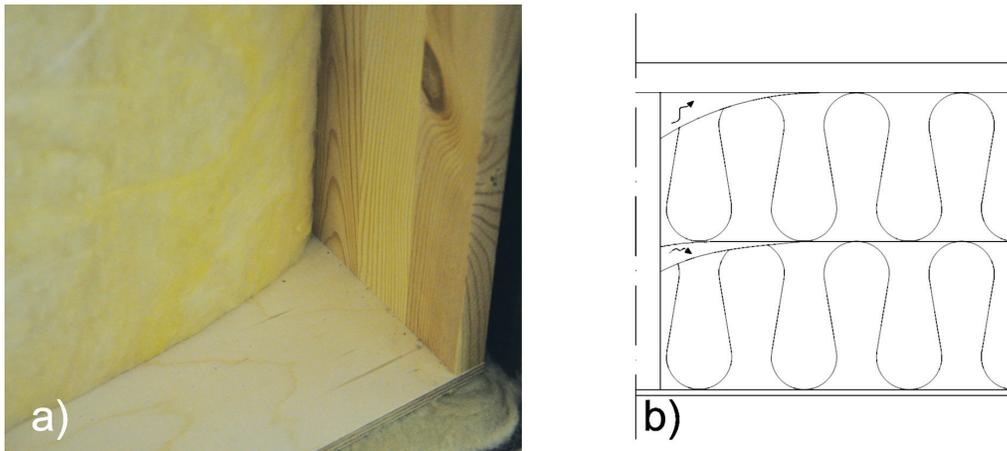
building laboratory of Tampere University of Technology. The operational principle of the U-factor determination is calibrated hot box (CHB) method and the equipment can be used to carry out the standard U-factor test in accordance to international standard EN ISO 8990 (Vinha 1998). In addition, the equipment can be used to conduct building physically more comprehensive experiments where indoor and outdoor humidity conditions together with pressure difference are adjusted. However, only thermal adjustments and measurements necessary in U-factor determination were utilized in this research.

## Test Walls

Due to limitations of dimensions of the equipment, the height of the test walls was 46.65 in. (1185 mm), which is less than half of the height of typical actual walls and the height-thickness ratio is known to be a major determinant of the natural convection process in finite vertical cavity. However, the test wall dimensions in this research represent critical circumstances which occur in actual building envelopes, for example, under or above a window. Test walls were insulated with either mineral wool batts or wet-sprayed cellulose insulation. Two insulation thicknesses were investigated: 7.67 in. and 12.60 in. (200 mm and 320 mm). Current reference U-factor 0.030 Btu/(h·ft<sup>2</sup>·°F) [0.17 W/(m<sup>2</sup>·K)] can be achieved with approximately 7.87 in. (200 mm) thick mineral wool or cellulose insulation layer when the structure has also a heat insulating wind shield. Modern low-energy houses may have over 15.75 in. (400 mm) thick insulation layers but the dimensions of the equipment ruled out test walls with overall thickness over 15 in. (380 mm). Therefore, the maximum insulation thickness of a test wall with wind shield was 12.60 in. (320 mm). Dimensioned drawing of the test walls is shown in Figure 2. Convection barriers were made of vapor permeable plastic sheets which were tightened and fixed with staples and duct tape as shown in Figure 4a. Temperature difference between indoors and outdoors was 63°F (35°C) ( $T_{in} = 68^\circ\text{F}$  (20°C),  $T_{out} = 5^\circ\text{F}$  [15°C]) in all measurements. To prevent the effect of small deviations in the actual surface resistances



**Figure 2** Dimensioned drawing of the test walls. Surface temperature sensor positions are also illustrated.



**Figure 3** (a) Rounded wool batt in a test wall and (b) an illustration of air gaps formed due to sloppy installation.

between separate experiments, the U-factors used in comparative calculations were calculated from surface-to-surface thermal resistances measured in experiments and surface resistances according to standard EN ISO 6946 (2007).

Poor workmanship was introduced in part of the test walls by intentionally sloppy installation of the mineral wool batts. As a result of sloppy installation, the edges of batts may become rounded forming vertical air gaps as shown in Figure 3. Because these types of air gaps are normally hard to see after the installation, the inner surface of the test walls was made of transparent polycarbonate board. As reference for the sloppy installation, ideal test walls were built by extremely carefully installing the batts from the outside against the polycarbonate board and getting visual confirmation of the installations' quality and the absence of air gaps.

Negligent installation may also cause horizontal air gaps at upper or lower edges of wall insulation. In case of wet-sprayed cellulose insulation these may form due to creep of the material.

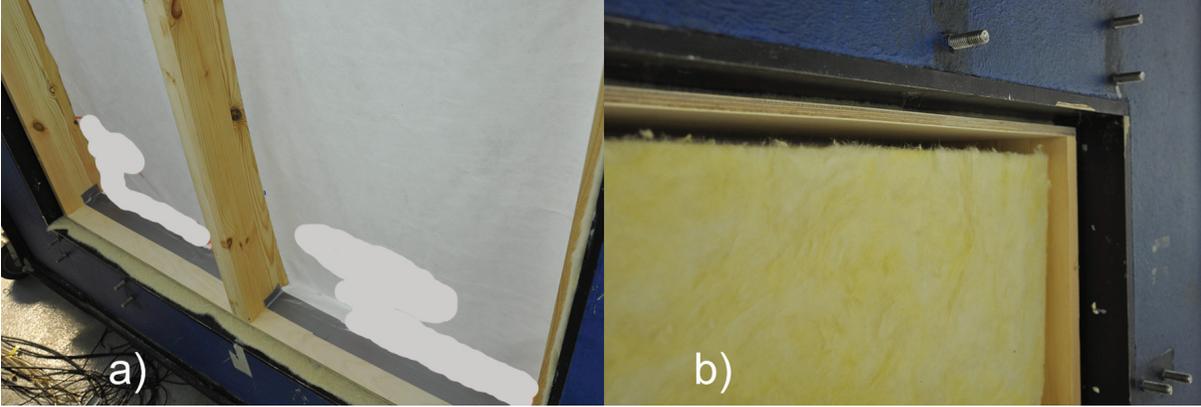
Unexpectedly extensive creep turned up in the cellulose insulated test walls during the test series and its effect on test results is discussed later in this paper.

In total, 14 U-factor measurements were carried out and the attributes of test walls are listed in Table 1.

In Table 1 the insulation material is denoted in the first column (MW = mineral wool, CI = cellulose insulation) and the values of  $R_{a_m}$  according to the testing conditions in the third column.

### Computational Studies

U-factors of part of the test walls were also determined with a commercial FEM-software COMSOL Multiphysics version 4.2a. The module used in the software uses Brinkman's equation, which can be used to model the fluid flow in porous media (Nield and Bejan 2006). With very low airflow velocities, the Forcheimer's drag can be neglected and in



**Figure 4** (a) Convection barrier showing in a test wall from which the wind shield and half of the insulation is removed and (b) horizontal air-gap in a test wall from which the wind shield is removed.

**Table 1. Test Series of U-Factor Measurements**

Test Wall	Insulation Thickness, in. (mm)	$R_{a_m}$	Installation	CB	Horizontal Air Gap
MW01	7.87 (200)	1.80	ideal	no	no
MW02	7.87 (200)	—	ideal	yes	no
MW03	7.87 (200)	1.80	sloppy	no	no
MW04	7.87 (200)	1.80	sloppy	no	yes
MW05	7.87 (200)	—	sloppy	yes	yes
MW06	12.60 (320)	3.08	ideal	no	no
MW07	12.60 (320)	—	ideal	yes	no
MW08	12.60 (320)	3.08	sloppy	no	no
MW09	12.60 (320)	3.08	sloppy	no	yes
MW10	12.60 (320)	—	sloppy	yes	yes
CI01	7.87 (200)	1.83	—	—	no
CI02	7.87 (200)	1.83	—	—	yes
CI03	12.60 (320)	3.13	—	—	no
CI04	12.60 (320)	3.13	—	—	yes

**Table 2. Measured Material Properties**

Material	Thermal Conductivity ( $\lambda$ ), Btu/(h·ft·°F) (W/[m·K])	Permeability ( $k$ ), $10^{-9}$ ft <sup>2</sup> ( $10^{-9}$ m <sup>2</sup> )
Mineral wool	0.020 (0.035)	39 (3.6)
Cellulose insulation	0.024 (0.042)	46 (4.3)
Glued-timber board	0.058 (0.10)	—
Plywood	0.14 (0.25)	—
Mineral-wool wind shield	0.029 (0.050)	—
Wood-fiber wind shield	0.017 (0.029)	—

Heat transfer by conduction and convection:

$$\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (\lambda \nabla T) \quad (6)$$

The density of air was expressed in the governing equations as a function of pressure and temperature. From the ideal gas law can be derived:

$$\rho = \frac{p}{R_{air} T} \quad (7)$$

stationary state the governing equations of incompressible flow in porous media and heat transfer are reduced to:

Brinkman's equation:

$$\frac{\rho}{\varepsilon_p} \left[ (\mathbf{u} \cdot \nabla) \frac{\mathbf{u}}{\varepsilon_p} \right] = \nabla \cdot \left[ -p \mathbf{I} + \frac{\eta}{\varepsilon_p} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2\eta}{3\varepsilon_p} (\nabla \cdot \mathbf{u}) \mathbf{I} \right] - \frac{\eta}{k} \mathbf{u} + \mathbf{F} \quad (4)$$

Continuity:

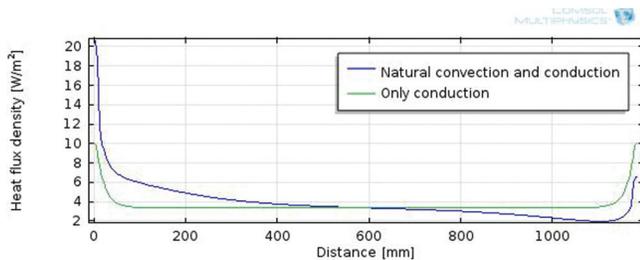
$$\nabla \cdot \mathbf{u} = 0 \quad (5)$$

Coupled simulations were carried out in 2D and the effect of linear thermal transmittances due to vertical wood frame parts in the test walls were first determined with the same software and added afterwards to the U-factors based on 2D simulations where the airflows were taken into account. Material properties used in the calculations were measured in accordance with the standards ISO 8301 (1991) (thermal conductivity) and ISO 9053 (1991) (air permeability). Measured values are shown in Table 2.

Thermal conductivity of polycarbonate used in the calculations was not measured. In calculations, a tabulated design

**Table 3. U-Factor Results, Btu/(h·ft<sup>2</sup>·°F) [W/(m<sup>2</sup>·K)]**

Test Wall	Measured	COMSOL	EN ISO 6946
MW01	0.0294 (0.167)	0.0294 (0.167)	0.0285 (0.162)
MW02	0.0291 (0.165)	0.0291 (0.165)	0.0285 (0.162)
MW03	0.0305 (0.173)	—	—
MW04	0.0308 (0.175)	—	—
MW05	0.0313 (0.178)	—	—
MW06	0.0229 (0.130)	0.0211 (0.120)	0.0195 (0.111)
MW07	0.0220 (0.125)	0.0199 (0.113)	0.0195 (0.111)
MW08	0.0224 (0.127)	—	—
MW09	0.0247 (0.140)	—	—
MW10	0.0247 (0.140)	—	—
CI01	0.0410 (0.233)	0.0370 (0.210)	0.0361 (0.205)
CI02	0.0454 (0.258)	—	—
CI03	0.0321 (0.182)	0.0259 (0.147)	0.0240 (0.136)
CI04	0.0326 (0.185)	—	—



**Figure 6** Heat flux density as a function of distance from lower edge in test wall MW06 (interior surface).

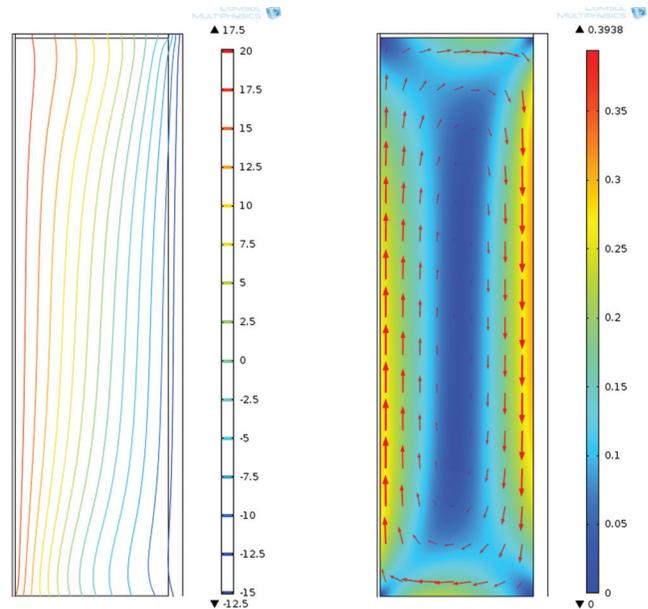
value (0.12 [Btu/(h·ft<sup>2</sup>·°F)] 0.2 W/[m<sup>2</sup>·K]) from the standard EN ISO 10456 (2007) was used. Permeability of mineral wool was measured in the direction parallel to the batts.

## RESULTS

Measured, simulated, and standard calculated U-factors of the test walls are shown in Table 3.

Examples of visualized result data of simulations are shown in Figures 5 and 6.

Based on measured U-factors and software simulations Nusselt numbers were calculated for test walls with mineral wool (ideal installation, no air gaps). Because convection barrier was used only in mineral wool insulated test walls, only simulation based Nusselt numbers were calculated for cellulose insulated test walls. Results are shown in Table 4.



**Figure 5** Isotherms and airflow velocity field in test wall MW06.

**Table 4. Nusselt Numbers Based on Measurements and Simulations**

Insulation Material and Thickness, in. (mm)	Measured	COMSOL
MW 7.87 (200)	1.01	1.01
MW 12.60 (320)	1.04	1.06
CI 7.87 (200)	—	1.02
CI 12.60 (320)	—	1.07

## DISCUSSION

Based on U-factor measurements, it can be concluded that natural convection had relatively easily measurable effect on heat transfer in exterior walls when the temperature difference was only 63°F (35°C), yet the differences between all measured U-factors were fairly small. The total uncertainty of any U-factor measured with the equipment which was used in this research is ±4% with a safety factor of 2 (Vinha 1998). The majority of this uncertainty is caused by the inaccuracies involved in the calibration procedure of the equipment. Because the absolute value of error due to calibration inaccuracy is exactly the same in two sequentially determined U-factors, the differences between the U-factors of test walls with same thickness can be determined very accurately. In practice, the total uncertainty is almost impossible to determine accurately because of the problem of border effect involved in CHB-method. However, when studying the effect of natural convection by laboratory measurements, the border effect is hard to eliminate by using separate guarding box and measuring box because the natural convection alters



**Figure 7** The effect of creep in cellulose insulated test wall. Air gap is refilled in the left side.

heat flux densities for the most part at the border regions of the test wall as shown in Figure 6.

Measurements and simulations of test walls with mineral wool insulation were in relatively good agreement. Differences between measured and numerically determined U-factors of the test walls with 12.60 in. (320 mm) thick insulation was assumed to be mainly caused by the border effect. From Table 3 can be seen that poor workmanship may in different cases increase U-factor 5% to 10% and use of convection barrier did not positively affect the test walls with horizontal air gaps.

Unexpectedly large U-factors were measured from all the cellulose insulated test walls. Although the cellulose insulation has somewhat greater permeability, the simulated effect of natural convection was of the same order as in the mineral wool test walls. Eventually, the large values could not be entirely explained, but it was clear that the unexpected creep of the insulation material had great effect. The test walls were stored in vertical position during the test series and in Figure 7 it is shown how air gaps were formed due to creep also in the test walls which were originally sprayed full. These air gaps were refilled with the insulation material but without the adhesive that was used in wet-spraying. Wet-spraying of the insulation material was carried out in other facilities and during the transports minor damages were caused to the test walls which may have also affected the results.

Computational studies were at first attempted in 3D, but the numerical solvers programmed in the software failed to reach sufficient level of convergence. Also, the orthotropy of mineral wool's permeability was neglected in the computational studies. These issues should be taken into account when planning future studies of modeling convection in porous insulation.

Repetitions of the U-factor measurements and more thorough statistical analysis were not made partly due to scheduling and financial reasons and because the test results did not show clear need for that.

## CONCLUSION

A series of U-factor measurements and numerical determinations were carried out for typical Finnish wood frame exterior wall structures. Results showed that the effect of natu-

ral convection on the thermal transmittance is fairly small in exterior walls and can be eliminated by careful installation and convection barrier. Thus, convection barrier can be effectively used to restrict natural convection's effects as demanded by the building code. Air gaps formed due to poor workmanship do not dramatically increase the U-factor if they do not enable air circulation from hot side to cold side. When evaluating the results shown in this paper, it should be kept in mind that the height of the test walls was approximately only half of actual whole walls. On the other hand, in the Finnish climate the temperature difference can occasionally be much larger than in the measurements of this research.

The only certain conclusion that could be made from the cellulose insulated test walls was that the elastic behavior of wet-sprayed cellulose insulation materials should be investigated more.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

$\rho$	=	density of air, kg/m <sup>3</sup>
$\Delta$	=	difference, dimensionless
$\epsilon_p$	=	porosity, dimensionless
$d$	=	thickness, m
$\lambda$	=	thermal conductivity, W/(m·K)
$\eta$	=	dynamic viscosity of air, Pa·s
$k$	=	permeability, m <sup>2</sup>
$\mathbf{u}$	=	velocity field, m/s
$\mathbf{I}$	=	identity matrix, dimensionless
$\mathbf{F}$	=	volume force, N/m <sup>3</sup>
$C_p$	=	specific heat capacity, J/(kg·K)
$T$	=	temperature, K
$p$	=	pressure, Pa
$R_{\text{air}}$	=	specific gas constant of air, J/(kg·K)
$\phi$	=	heat flux, W

## Subscripts

cd	=	conduction
conv	=	convection
CB	=	convection barrier

## REFERENCES

- ISO. 2007. EN ISO 6946, *Building Components and Building Elements – Thermal Resistance and Thermal Transmittance – Calculation Method*. European Committee for Standardization.

- ISO. 1996. EN ISO 8990, *Thermal Insulation: Determination of Steady-State Thermal Transmission Properties, Calibrated and Guarded Hot Box*. European Committee for Standardization.
- ISO. 2007. EN 10456, *Building Materials and Products, Hygrothermal Properties—Tabulated Design Values and Procedures for Determining Declared and Design Values*. European Committee for Standardization.
- ISO. 1991. ISO 8301, *Thermal Insulation—Determination of Steady-state Thermal Resistance and Related Properties —Heat Flow Meter Apparatus*. International Organization for Standardization.
- ISO. 1991. ISO 9053, *Acoustics – Materials for Acoustical Applications—Determination of Airflow Resistance*. International Organization for Standardization.
- Nield D.A. and A. Bejan. 2006. *Natural Convection in Porous Media*, 3<sup>rd</sup> edition. Springer.
- Vinha, J. 1998. *Rakenteiden lämmöneristysominaisuuksien mittauslaitteisto* (in Finnish). Licentiate thesis. Tampere University of Technology.