



# Hot-box measurements to investigate the internal convection of highly insulated loose-fill insulation roof structures

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## ARTICLE INFO

### Article history:

Received 25 May 2019

Revised 8 February 2020

Accepted 9 March 2020

Available online 17 March 2020

### Keywords:

Internal convection

Roof structures

Calibrated hot-box

Thermal transmittance

Thermal insulation

Laboratory measurements

Heat transfer

## ABSTRACT

The purpose of this study was to investigate how internal convection in loose-fill insulations affects the insulation properties of highly insulated roof structures. This study consists of laboratory measurements of roof structures insulated by two different blown-in insulations. The measurements are repeated with two temperature differences and air velocities for 300 mm and 600 mm thick insulation layers both with and without trusses, making a total of 24 case studies. The measurements were conducted with equipment using the calibrated hot-box method. The results of the tests show that internal convection can reduce insulation capacity significantly, especially with low-density loose-fill insulations, such as blown-in glass wool. A critical evaluation should be performed as to whether international standards and national building regulations take internal convection into account adequately. According to this study, 5 should be used as a critical modified Rayleigh number for horizontal roof structures with an open upper surface when used insulation material is loose-fill glass wool or wood fibre insulation as in this study.

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## 1. Introduction

### 1.1. Research background

From 2019 onwards, all new buildings in Finland should be built as nearly zero-energy buildings (nZEB). One of the outcomes in trying to achieve that goal is the increasing thickness of insulation layers. Designing of nearly zero-energy buildings' structures is demanding even more attention to the structures and their building physical functionality.

Blown-in loose-fill insulation is widely used in roof structures in Nordic countries because the installation procedure is fast and cost-effective. For example, it is relatively easy to blow loose-fill insulation into narrow spaces between structures of trusses, whereas installing insulation boards is a much slower and more challenging task. However, the thickness of the insulation layers can cause problems when using porous loose-fill insulation materials. The drawback with loose-fill insulation is its high air permeability. This can allow air movements and internal convection in the insulation, which in turn increases the heat flow through the insulation and thus reduces its thermal resistance. This not only results in higher energy consumption, but the internal convection can also transfer

water vapor, which may condense on colder surfaces. As the majority of roof structures have wooden parts, condensation can lead to moisture problems, including mould growth.

This paper presents the results of laboratory measurements conducted at the Unit of Structural Engineering in Tampere University previously known as Tampere University of Technology. The study was part of the COMBI-project (Comprehensive development of nearly zero-energy municipal service buildings) which ran from 2015 to 2018. The project focused on defining the impacts and assessing the challenges to improved energy efficiency and, of course, finding solutions to the issues. Tampere University had also carried out studies on internal convection in loose-fill insulations under the earlier FRAME-project (Future envelope assemblies and HVAC solutions). This project, which ran from 2009 to 2012, focused on identifying the effects of climate change and improved thermal insulation on the moisture performance of envelope assemblies, as well as the energy consumption and the indoor climate of buildings [1]. It was because the FRAME-project had raised so many unanswered questions with regard to internal convection that the issue was investigated further under the COMBI-project. Furthermore, there has not been enough experimental research into thick horizontal loose-fill insulation layers.

In the FRAME study, the loose-fill insulations were installed by hand and the area of metering area was rather small (1,44 m<sup>2</sup>). The new research equipment used for the roof structures in the COMBI study had a larger metering area (5 m<sup>2</sup>) and the loose-

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## Nomenclature

$A$	area of metering area ( $\text{m}^2$ )
$c_p$	specific heat capacity ( $\text{J}/(\text{kg K})$ )
$d$	thickness (m)
$g$	gravity ( $\text{m}/\text{s}^2$ )
$k$	air permeability ( $\text{m}^2$ )
$Nu$	Nusselt number (-)
$P_{tot}$	total power input (W)
$q$	density of heat flow rate ( $\text{W}/\text{m}^2$ )
$Ra_m$	modified Rayleigh number (-)
$R$	surface thermal resistance ( $\text{m}^2 \text{K}/\text{W}$ )
$S_f$	uncertainty
$T$	temperature ( $^\circ\text{C}$ or K)
$\Delta T$	temperature difference ( $^\circ\text{C}$ or K)
$U$	thermal transmittance; U-value ( $\text{W}/(\text{m}^2 \text{K})$ )
$U_{0.14}$	measured U-value with standardized surface thermal resistances ( $\text{W}/(\text{m}^2 \text{K})$ )
$\nu$	kinematic viscosity ( $\text{m}^2/\text{s}$ )
$v_a$	airflow (m/s)
$\beta$	heat expansion coefficient ( $1/\text{K}$ )
$\lambda_m$	thermal conductivity ( $\text{W}/(\text{m}^2 \text{K})$ )
$\rho$	density ( $\text{kg}/\text{m}^3$ )
$\Phi$	heat flow rate through the studied structure (W)
$\Phi_{loss}$	heat flow rate through the equipment envelope (W)

### Subscripts

$a$	air
$cd$	conduction
$cr$	critical
$conv$	convection
$e$	exterior, cold side
$i$	interior, hot side
$s$	surface
$srt$	studied structure

fill insulation was installed with a proper insulation blowing machine. Furthermore, the measurements were taken using the calibrated hot-box method. The blown-in insulation is widely used in the building industry so the specific goals of this study were to find out whether internal convection occurs inside a horizontal blown-in insulation layer, and then to determine how much the internal convection affects the thermal behavior of the roof structures, whose insulation layers can be up to 600 mm thick. Therefore, two different insulation materials and thicknesses were tested. The temperature distribution inside the insulation layer was also studied, as were other parameters such as how much the installation method, the size of the metering area and the addition of trusses (common in roof structures insulated with blown-in insulation) affect the results.

### 1.2. Previous research into internal convection in roof structures

Although there have been a number of calculated and experimental studies of internal convection in roofs, the results are somewhat inconsistent. The critical modified Rayleigh number is used to determine the onset of internal convection, but studies [2,3] have shown that some internal convection can occur before this critical value is reached. Furthermore, although internal convection is assumed to start when the Nusselt number is over 1.00, Wahlgren [4] has stated that internal convection has finally started when Nusselt number is over 1.02–1.04.

Shankar and Hagentoft [5] have done internal convection calculations for mineral wool boards, loose-fill insulation and polystyrene ball insulation. However, in their study the insulation

layers were assumed to be homogenous and the outside air velocity was not taken into account. They presented the influence of temperature difference for 300 mm, 400 mm, 500 mm and 600 mm thick insulation layers. For mineral wool boards with air permeability of  $4.36 \cdot 10^{-4} \text{m}^3/(\text{m} \cdot \text{s} \cdot \text{Pa})$  ( $0.75 \cdot 10^{-8} \text{m}^2$ ) they showed that the Nusselt number for a 300 mm insulation layer is 1.00 when the temperature difference is  $20^\circ\text{C}$ , and 1.10 when the temperature difference is  $35^\circ\text{C}$ . Similarly, the Nusselt number for a 600 mm insulation layer is 1.15 for a  $20^\circ\text{C}$  temperature difference and 1.40 for a  $35^\circ\text{C}$  temperature difference. For loose-fill insulation with air permeability of  $5.18 \cdot 10^{-4} \text{m}^3/(\text{m} \cdot \text{s} \cdot \text{Pa})$  ( $1.0 \cdot 10^{-8} \text{m}^2$ ) they showed that the Nusselt number is 1.55 for a 600 mm insulation layer with a  $35^\circ\text{C}$  temperature difference. Their study also shows that the critical modified Rayleigh number should be around 5 for a 600 mm thick insulation with air permeability of  $4.36 \cdot 10^{-4} \text{m}^3/(\text{m} \cdot \text{s} \cdot \text{Pa})$ . However, Hagentoft [6] has also presented the theoretical limit values of modified Rayleigh numbers for a horizontal, homogenous, porous insulation layer with infinite area after which internal convection can begin. He stated that the critical modified Rayleigh number for an open surface is 27.

Ciucasu et al. [7] performed simulated internal convection studies which also took into account the trusses and air movements in the attic. Three different 500 mm insulation layers with air permeabilities of between  $3.9 - 9.0 \cdot 10^{-9} \text{m}^2$  were studied. They showed that the critical modified Rayleigh number was 28. Gullbrekken et al. [8] investigated how natural convection in 500 mm glass wool insulation affects the thermal transmission in wall, roof and floor structures at  $20^\circ\text{C}$  and  $40^\circ\text{C}$  temperature differences. According to their study, significant internal convection in horizontal and pitched roofs occurs with a lower modified Rayleigh number than previous studies had shown, even when the modified Rayleigh number is as low as 4. According to another study of Gullbrekken et al. [9] a smaller effect of natural convection was found in wood fibre insulation compared to mineral wool insulation when they were studying the risk of natural convection of wood-based insulation and mineral wool.

Vinha et al. [1] conducted internal convection measurements under the FRAME-project and observed significant internal convection with both loose-fill glass wool and wood fibre insulations. They tested 300 mm and 600 mm loose-fill glass wool and wood fibre insulation layers at  $20^\circ\text{C}$  and  $35^\circ\text{C}$  temperature difference with and without airflow at the surface of the insulation layer. When the insulation thickness was 600 mm the Nusselt numbers for the loose-fill wood fibre insulation were 1.3–1.5 and for the glass wool insulation they were 1.3–1.4. The modified Rayleigh numbers for these conditions were 8.6 and 13.7. The most significant outcome of the FRAME study was that the critical modified Rayleigh number for horizontal roof structures with an open upper surface should be 5.

Wahlgren studied internal convection for her doctoral thesis [10] using a roughly  $20 \text{m}^2$  test structure, although the measurements were only taken from the middle part of the structure with a measurement area of  $1 \text{m}^2$ . She studied various temperature differences and insulation layers with different thicknesses. For unventilated roof structures insulated with loose-fill glass wool she found that the critical modified Rayleigh number was 22. Furthermore, according to Wahlgren's literature survey [11] small scale measurements made in Sweden and the United States between 1983 and 1991 show that the critical value for the modified Rayleigh number varies widely from 10 to 30.

## 2. Heat transfer

This section presents the basics of the heat transfer modes that are relevant to hot-box tests and to this study. Heat transfer is the process whereby energy is transferred within and between struc-

tural components that have different temperatures. It can also be defined as the transmission of energy from one region to another as a result of the temperature difference between them. Conduction, convection and radiation are the identified modes of heat transfer [12].

The pressure differences arising from driving forces such as temperature difference, wind and fans cause convection. The term 'natural convection' is used to describe the air flow caused by the differences in the density of air due to temperature differences. Natural convection is particularly significant in wintertime when large temperature differences occur between the inside and outside air. Gravity and density differences together lead to swirling air flows in porous structures. This phenomenon is called internal convection. In walls, these air flow swirls are easier to predict as the air moves upwards on the warm side and downwards on the cold side. However, in roof structures, the warm lighter air moves to the top of the insulation layer while the cold, denser air moves to the bottom. This causes swirls of air whose size, direction and effects on each other are hard to predict, especially in a large roof area with various inhomogeneities such as pipes and trusses. The temperature difference over the insulation layer, its air permeability and thermal conductivity, and its geometry (including its thickness) affect the amount of internal convection. Internal convection in roofs can be a mixture of natural convection caused by temperature differences and forced convection, whose driving force can be, for example, the airflow through a ventilation gap.

A non-dimensional quantity, the modified Rayleigh number  $Ra_m$ , describes the potential for internal convection. The higher the modified Rayleigh number, the greater the potential of natural convection. The EN ISO 10456 standard [13] defines the modified Rayleigh number with Eq. (1) (below), where the properties of the insulation material are its thickness  $d$  (m), its air permeability  $k$  ( $\text{m}^2$ ) and its thermal conductivity  $\lambda_m$  ( $\text{W}/(\text{m}^2 \text{K})$ ). The value  $\Delta T_s$  (K) indicates the temperature difference between the insulation layer's surfaces and  $g$  ( $\text{m}/\text{s}^2$ ) is the acceleration of gravity. The properties of the air are given for 10 °C. They are the heat expansion coefficient  $\beta$  ( $1/\text{K}$ ), the density  $\rho$  ( $\text{kg}/\text{m}^3$ ), the specific heat capacity  $c_p$  ( $\text{J}/(\text{kg K})$ ) and the kinematic viscosity  $\nu$  ( $\text{m}^2/\text{s}$ ).

$$Ra_m = \frac{g\beta\rho c_p}{\nu} \frac{d\kappa\Delta T_s}{\lambda_m} \quad (1)$$

The critical modified Rayleigh number  $Ra_{m,cr}$  is used to determine the onset of internal convection. According to SFS standard 10456 [13] the critical modified Rayleigh number is 2.5 when the direction of the heat flow is in a horizontal direction, 15 when the direction of the heat flow is upward and the upper surface has no wind screen, while it is 30 when the upper surface has a wind screen.

In this study a calibrated hot-box method was used to determine thermal transmittance, i.e. the  $U$ -value ( $\text{W}/(\text{m}^2 \text{K})$ ) of the structures. Internal convection can also be evaluated with the Nusselt number, as shown in Eq. (2). The Nusselt number is a non-dimensional quantity and it describes the increase of heat flow due to internal convection.

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

where  $q_{cd} + q_{conv}$  ( $\text{W}/\text{m}^2$ ) is the heat flux measured with the hot-box method and  $q_{cd}$  ( $\text{W}/\text{m}^2$ ) is the heat flux without internal convection, i.e. when heat is transferred only by conduction.

### 3. Test procedure

#### 3.1. Test equipment and procedure

The prototype of the equipment used for the building physical tests on a building's horizontal structures with a metering

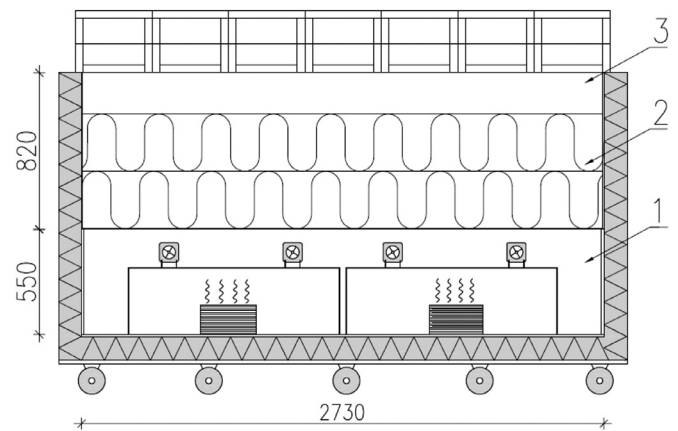


Fig. 1. Building physical equipment for roof structures where (1) is the hot chamber, 2) is the studied structure in the metering area and 3) is the cold chamber.

area of 1.2 m x 1.2 m was built at Tampere University for the FRAME-project [1]. A newer, larger apparatus for building physical tests on a building's horizontal structures came into use in 2016. This equipment was built according to the requirements of the EN ISO 8990 standard [14] and operates with the calibrated hot-box method. The applicable sections of standard EN ISO 12567 [15] were also applied in the building process. The metering area of the new equipment is 1.84 m x 2.73 m, which is large enough to provide a meaningful perspective on the phenomena occurring inside a horizontal insulation layer. The university also has another building physical equipment for vertical structures, which is described in detail in the doctoral thesis of Juha Vinha [16].

The equipment consists of hot and cold chambers which are located in a 2.5 m high freezer room with a floor area of 4.0 m x 2.8 m. The structure to be tested is placed in the metering area between the hot and cold chambers. The schematic diagram is shown in Fig. 1. Both chambers have baffles made of aluminium, which are also used to attach sensors and fans, but their primary purpose is to transfer heat as evenly as possible to the surfaces of the studied structure.

Both the heaters and the temperature measurements in the hot chamber were computer-controlled. The computer program collected data from the temperature, air velocity and air humidity sensors. It also controlled the heaters according to the commands given to the program and gathered information about the power input given to the heaters and the fans. All the data was measured once a minute and the warm chamber conditions were corrected every third minute if needed. The temperature of the freezer room had its own controller which controlled two condensing apparatuses with fans. The reliability of the temperature maintained in the freezer room was  $\pm 0.25$  °C across a temperature range between  $-15$  °C and 0 °C.

The calibrated hot-box needs a specific calibration procedure for the equipment's walls in order to ascertain  $\Phi_{loss}$  (W), which indicates the heat loss through the equipment's envelope. 50 mm and 100 mm thick XPS tongue-and-groove panels were used as calibration elements in this study. The installed panels were overlapping and the seams were sealed with tape to ensure the tightness of the calibration elements. The calibration was performed for the six different conditions used in the measurements, i.e. whenever the structure's thickness, temperature difference or air velocity were changed. Once the exact values of the material properties are known, as well as the dimensions of the calibration panels and the measured temperature difference, the heat loss through the equipment envelope  $\Phi_{loss}$  can be calculated.

The thermal transmittance of the test specimen can be evaluated by assessing the heat flow rate between the chambers. The

heat flow rate through the studied structure  $\Phi_{srt}$  (W) can be calculated with the equation  $\Phi_{srt} = P_{tot} - \Phi_{loss}$ , where  $P_{tot}$  (W) is the total power input measured from all the heaters and fans inside the hot chamber. The U-values are calculated on the basis of the measured heat flow rate through the structure  $\Phi_{srt}$  (W), the metering area  $A$  (m<sup>2</sup>) and the temperature difference across the test section  $\Delta T$  (K or °C) according to the equation  $U = \Phi_{srt} / (A \cdot \Delta T)$ .

The surface thermal resistance coefficients for the tests were not exactly the same as those recommended by the standards. The air velocities in the hot chamber were actually higher than stated in the standard [14] in order to ensure good air circulation and to make sure the temperature throughout the chamber was as consistent as possible. With eight small fans and two fans with the heaters, it was possible to control the air velocity in order to maintain a constant temperature of 20.00 °C in the hot chamber. The power input to all the fans was measured and included in the total power input. The freezer room's temperature was not computer controlled. This meant that the temperature in the cold chamber fluctuated slightly between the tests, so the  $\Phi_{loss} / \Delta T$  value was used to ensure the calibration and test results were exactly comparable.

Two air velocities (0.0–0.1 m/s and 0.5–0.7 m/s) were used in the cold chamber for the tests. Therefore, the temperature difference between the structure's interior and exterior surfaces was used as U-value calculation instead of environmental temperature difference. Once the U-value from surface to surface had been calculated, the effect of the standardized surface thermal resistances was added to the U-value to make sure that all the situations were comparable with each other. When the heat flow is going upwards the interior surface thermal resistance  $R_{si}$  is 0.10 W/(m<sup>2</sup> K) and the exterior surface thermal resistance  $R_{se}$  is 0.04 W/(m<sup>2</sup> K) according to EN ISO 6946 [17].

All the tests ran for at least 72 h. During this period, all the measurements reached the steady-state when the temperature and power inputs agreed to within 1 % of each other. The values used in the calculations were measured for 6 h once the steady-state condition had been reached.

In this study, the U-value without internal convection was calculated according to EN ISO 6946 [17]. This standard includes a procedure for choosing a correction factor for any air voids. However, these correction factors were not taken into account because according to the standard the structures used in our tests belonged to the level 0 category, in which there are only minor air voids that have no significant effect on the thermal transmittance. The calculations were conducted with the measured thermal conductivities of the materials.

### 3.2. The studied structures and boundary conditions

First, four different structures were tested. Each structure had a 20 mm plywood and plastic vapor barrier at the bottom. In the first set of measurements, the trusses in the structures were 900 mm apart. Both blown-in glass wool and blown-in wood fibre were used as insulation materials. The insulations were installed in the metering area with a typical commercially available blowing machine used for loose-fill insulations in order to make the texture of the insulation as realistic as possible. Two insulation thicknesses of 300 mm and 600 mm were studied. Then, a second set of measurements were conducted for the same structures without trusses in order to ensure a fair comparison. These additional tests were done to get an evidence-based idea of how much influence the trusses had on the U-value. Fig. 2 shows the structure with trusses after blowing in 300 mm and 600 mm of wood fibre insulation layers.

During the tests, the temperature, relative humidity and air velocity were measured in both the hot and cold chambers. Twelve

**Table 1**  
Abbreviations used to denote the structures and conditions in the tests.

Abbreviation	Description
W300	300 mm layer of blown-in wood fibre insulation
W600	600 mm layer of blown-in wood fibre insulation
GL300	300 mm layer of blown-in glass wool insulation
GL600	600 mm layer of blown-in glass wool insulation
TR	with trusses
INS	without trusses
20	20 °C temperature difference
35	35 °C temperature difference
AF0.0	with airflow 0.0–0.1 m/s on the insulation's surface
AF0.6	with airflow 0.5–0.7 m/s on the insulation's surface

(12) semiconductor temperature sensors were used to measure the air temperature, the baffles' surface temperature and the structure's surface temperature in both the hot and cold chambers, so a total of 72 temperature sensor values were used to calculate the results. In addition, another 22 temperature sensors were added inside the insulation layer at heights of 235 mm and 420 mm from the bottom of the layer. Each truss had 6 temperature sensors attached to its side face at heights of 50 mm, 235 mm and 420 mm from the bottom of the insulation layer as shown in Fig. 3. When studying the insulation layer without trusses there were 21 temperature sensors inside the insulation layer placed at the same heights as in the tests with the trusses. The hot and cold chambers each had one sensor for air velocity measurement. All the sensors were installed in the middle of the metering area and around the middle of the baffles and the surfaces of the structures under study.

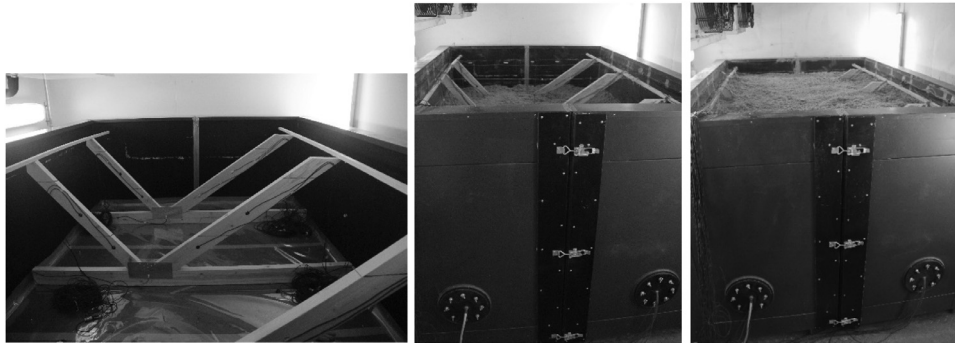
The measurements were performed with temperature differences of 20 °C (0 °C to +20 °C) and 35 °C (–15 °C to +20 °C) across the test section. The constant mean temperatures of the structures were +10 °C and +2.5 °C. During the measurements, the relative humidity varied between 8 and 25% RH at 20 °C in the hot chamber and between 74 and 84% RH at 0 °C and 60–66% RH at –15 °C in the cold chamber. When the cold chamber had almost no air movement the air velocity was around 0.0–0.1 m/s and with high ventilation the air velocity was 0.5–0.7 m/s. The abbreviations used to denote each of the tested structures and conditions are presented in Table 1.

### 3.3. Material properties

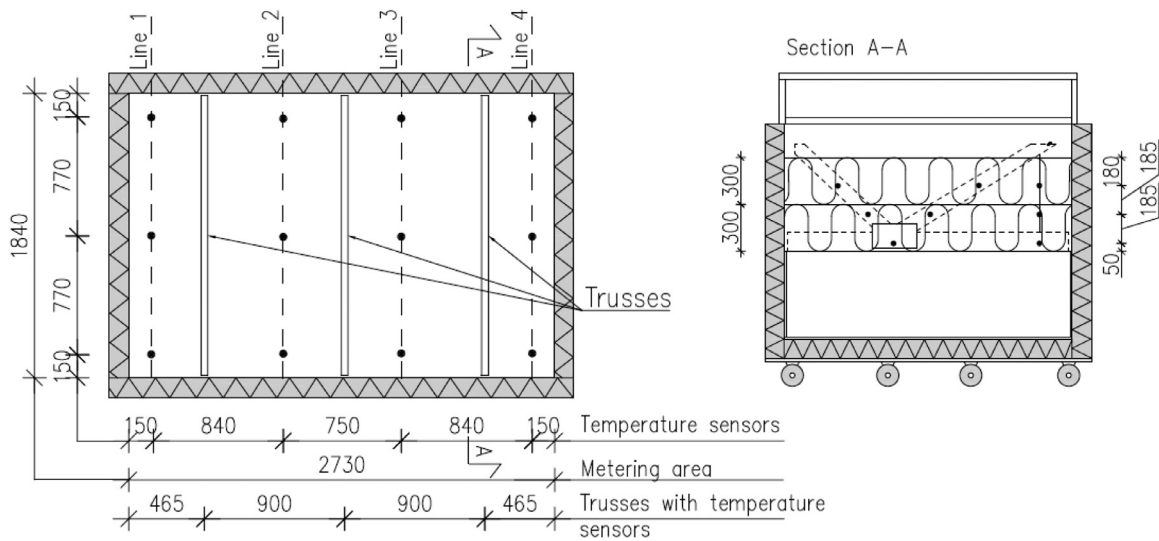
A FOX304 heat flow metre was used to study the thermal conductivity of the materials. The European standards SFS-EN 12,664 [18] and SFS-EN 12,667 [19] describe the procedures for determining thermal conductivity. The absolute thermal conductivity test accuracy was ±3% at the range from 0.005 to 0.35 W/(m K) [20].

The hot chamber cannot be calibrated accurately unless the exact thermal conductivity values for the calibration panels are known. The thermal conductivity value for both the 50 mm thick and 100 mm thick XPS panels used in the calibration was the average of five measurements. To get as realistic values as possible for the calculations, the thermal conductivities of the plywood, the blown-in wood fibre and glass wool insulations, and the spruce used in the trusses were also measured when the direction of the heat flow was parallel to the grain of the wood. Both 50 mm and 100 mm sample thicknesses were used when measuring the spruce trusses. The thermal conductivity of the horizontal spruce trusses had been measured earlier and was 0.13 W/(m K) in the test conditions. The thermal conductivities of the calibration panels and both the insulation materials were measured at both of the mean temperatures used, i.e. 10 °C and 2.5 °C.

The density of a material can affect the material properties. The density of the blown-in wood fibre insulation increases as the insulation layer gets thicker. The density of the 300 mm wood fi-



**Fig. 2.** The trusses before installing the cold chamber baffles and protective chamber. Before installing the insulation (left), after the installation of a 300 mm layer of blown-in wood fibre insulation to the metering area (middle) and after the installation of a 600 mm layer of blown-in wood fibre insulation to the metering area (right). The equipment is inside the freezer room.



**Fig. 3.** Dimensions of the metering area and the positions of the temperature sensors and trusses.

bre insulation layer was  $36 \text{ kg/m}^3$  and this increased to  $40 \text{ kg/m}^3$  when the layer was 600 mm thick. Hence, the thermal conductivity was measured for both insulation densities so that the blown-in wood fibre insulation was measured under four different conditions altogether. The density of the blown-in glass wool insulation wasn't affected by the thickness of the insulation in the metering area, so the material density was  $25 \text{ kg/m}^3$  for all the glass wool measurements. The plywood specimens were measured at a mean temperature of  $20 \text{ }^\circ\text{C}$ , which is close to the real mean temperature of the plywood used in the tests. The details of the thermal conductivity measurements and the measured samples are shown in Table 2.

When determining the Modified Rayleigh numbers, the air permeabilities used were  $4.0 \cdot 10^{-4} \text{ m}^3/(\text{m s Pa})$  for the wood fibre insulation (density  $36 \text{ kg/m}^3$ ),  $2.4 \cdot 10^{-4} \text{ m}^3/(\text{m s Pa})$  for the wood fibre insulation (density  $40 \text{ kg/m}^3$ ) and  $3.4 \cdot 10^{-4} \text{ m}^3/(\text{m s Pa})$  for the glass wool insulation (density  $25 \text{ kg/m}^3$ ). Insulations were installed with an appropriate blowing machine for loose-fill insulations in this study. However, installing the insulations with blowing machine to an apparatus measuring air permeability of materials available in Tampere University is challenging and it would lead to too inaccurate results. The air permeability values were measured in FRAME study [1] from the same insulations which were installed by hand. These values and literature values (e.g. [21]) were used to determine the air permeabilities to insulations of this project. As glass wool were studied to have the same kind of tex-

ture, density and internal convection when installed by hand or with blowing machine, the same air permeability value was used as measured in FRAME study. Also, literature values presented air permeabilities same magnitude. The texture of wood fibre insulation differed between hand installed and machine blown insulation. That made the determination of air permeability of wood fibre insulation more challenging. After doing a literature review and comparing the literature values to the measured values in FRAME study, we ended up using the same value as measured in FRAME study for 300 mm wood fibre insulation layer. For 600 mm insulation layer internal convection were bigger with hand installed than installed by blowing machine which indicates that air permeability can be a slightly smaller when installing is done with blowing machine. Used air permeability was  $0.2 \cdot 10^{-4} \text{ m}^3/(\text{m s Pa})$  smaller than measured in FRAME in this study.

## 4. Results

### 4.1. Internal convection in insulation layers

Table 3 and Fig. 4 show the main results of this study. The bases for the uncertainty calculations are presented in Section 4.5.

The Nusselt numbers indicate the extent to which the internal convection increases the heat flux. Fig. 4 shows that with the blown-in wood fibre insulation layer these values ranged between 0 and 16%, through the blown-in glass wool insulation layer with trusses it was 10–53%, and without trusses it was 38–63%. With

**Table 2**  
Mean thermal conductivities of the materials used for the measurements. The thicknesses, mean temperatures and thermal conductivities are the mean values of the measured samples.

Material	Samples (pcs.)	Thickness of sample (mm)	Edges (mm)	Density (kg/m <sup>3</sup> )	Mean temperature (°C)	Thermal conductivity (W/(m · K))
XPS 50	5	51.3	300 ± 1	41.3	10.02	0.0361 ± 0.0011
XPS 50	5	51.3	300 ± 1	41.3	2.52	0.0344 ± 0.0010
XPS 100	5	100.3	300 ± 1	33.1	10.01	0.0372 ± 0.0011
XPS 100	5	100.3	300 ± 1	33.1	2.51	0.0358 ± 0.0011
Plywood 20	4	20.2	300 ± 1	681.6	20.02	0.1274 ± 0.0038
Wood fibre wool D36	3	100	238 ± 2	36.0	10.01	0.0434 ± 0.0013
Wood fibre wool D36	3	100	238 ± 2	36.0	2.51	0.0398 ± 0.0012
Wood fibre wool D40	3	100	238 ± 2	40.0	10.01	0.0434 ± 0.0013
Wood fibre wool D40	3	100	238 ± 2	40.0	2.51	0.0398 ± 0.0012
Glass wool D25	3	100	238 ± 2	25.0	10.01	0.0399 ± 0.0012
Glass wool D25	3	100	238 ± 2	25.0	2.52	0.0379 ± 0.0011
Spruce (trusses)	3 + 3	50/100	289 ± 9	458.3	10.01	0.298 ± 0.0089
Spruce (trusses)	3 + 3	50/100	289 ± 9	458.3	2.52	0.290 ± 0.0087

**Table 3**  
Measured conditions and calculated U-values and Modified Rayleigh numbers of the studied situations.

Test	T <sub>a,i</sub> (°C)	T <sub>a,e</sub> (°C)	ΔT <sub>a</sub> (°C)	v <sub>a,e</sub> (m/s)	q <sub>srt</sub> (W/m <sup>2</sup> )	U <sub>0,14</sub> (W/m <sup>2</sup> K)	Ra <sub>m</sub> (-)
W300-TR-20-AF0	20.00	0.03	19.97	0.02	2.70	0.1457 ± 0.0071	2.6
W300-TR-35-AF0	20.00	-14.58	34.58	0.02	4.76	0.1476 ± 0.0067	5.0
W600-TR-20-AF0	20.00	-0.06	20.06	0.03	1.52	0.0778 ± 0.0038	3.4
W600-TR-20-AF0.6	20.00	-0.01	20.01	0.71	1.39	0.0708 ± 0.0038	3.4
W600-TR-35-AF0	20.00	-14.84	34.84	0.00	2.79	0.0812 ± 0.0035	6.5
W600-TR-35-AF0.6	20.00	-14.89	34.89	0.72	2.64	0.0762 ± 0.0034	6.5
W300-INS- 20-AF0	20.00	0.13	19.87	0.05	2.70	0.1461 ± 0.0071	2.6
W300-INS- 35-AF0	20.00	-14.30	34.30	0.05	4.70	0.1473 ± 0.0067	5.0
W600-INS-20-AF0	20.00	-0.17	20.17	0.02	1.26	0.0632 ± 0.0037	3.4
W600-INS-20-AF0.6	20.00	0.00	20.00	0.61	1.29	0.0647 ± 0.0037	3.4
W600-INS-35-AF0	20.00	-14.67	34.67	0.01	2.40	0.0701 ± 0.0034	6.4
W600-INS-35-AF0.6	20.00	-14.66	34.66	0.69	2.30	0.0664 ± 0.0034	6.5
GL300-TR-20-AF0	20.00	-0.16	20.16	0.02	2.98	0.1555 ± 0.0072	2.5
GL300-TR-35-AF0	20.00	-14.79	34.79	0.02	5.09	0.1541 ± 0.0068	4.8
GL600-TR-20-AF0	20.00	-0.29	20.29	0.02	1.58	0.0804 ± 0.0038	5.2
GL600-TR-20-AF0.6	20.00	0.00	19.99	0.59	1.93	0.0989 ± 0.0040	5.2
GL600-TR-35-AF0	20.00	-15.32	35.32	0.12	2.62	0.0769 ± 0.0034	9.5
GL600-TR-35-AF0.6	20.00	-14.65	34.65	0.52	3.67	0.1074 ± 0.0036	9.5
GL300-INS-20-AF0	20.00	0.10	19.90	0.06	3.39	0.1827 ± 0.0075	2.4
GL300-INS-35-AF0	20.00	-14.33	34.32	0.06	5.68	0.1780 ± 0.0069	4.4
GL600-INS-20-AF0	20.00	-0.14	20.14	0.05	1.79	0.0899 ± 0.0039	5.3
GL600-INS-20-AF0.6	20.00	0.06	19.94	0.53	1.89	0.0950 ± 0.0039	5.3
GL600-INS-35-AF0	20.00	-14.48	34.48	0.05	3.09	0.0906 ± 0.0035	9.5
GL600-INS-35-AF0.6	20.00	-14.35	34.35	0.49	3.47	0.1012 ± 0.0035	9.5

the blown-in wood fibre insulation and a temperature difference of 20 °C, the Nusselt numbers were 1.00–1.05, which indicates that there is hardly any internal convection. However, internal convection can already occur in the blown-in glass wool insulation with a 20 °C temperature difference. These results show that internal convection does occur inside the insulation layer in cold climates and it should be taken into account when designing roof structures. The Modified Rayleigh numbers for the studied situations were between 2.4 and 9.5.

#### 4.2. Temperature distribution

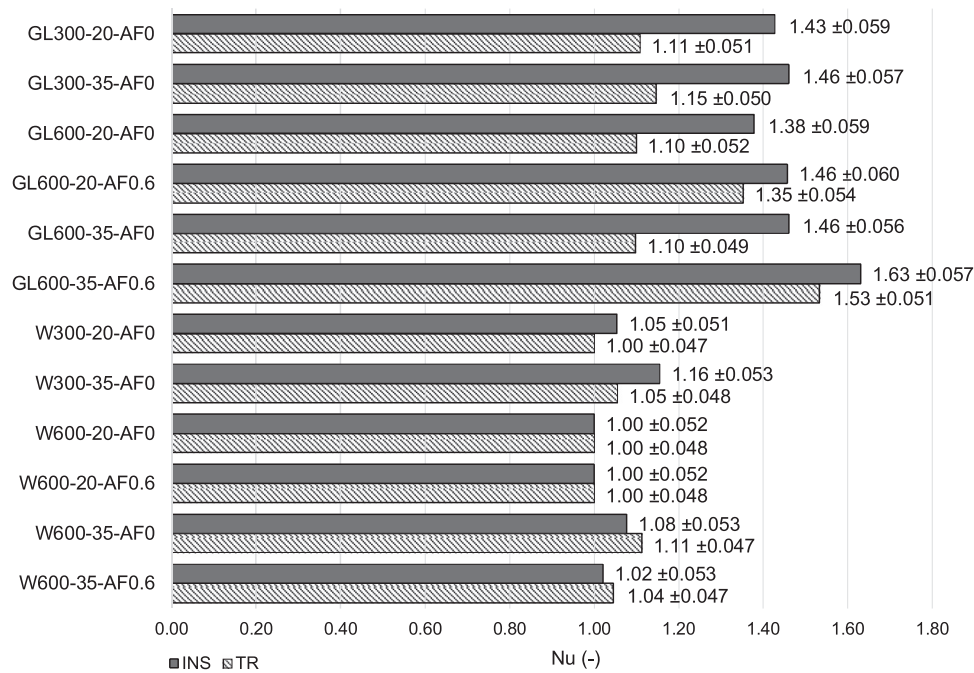
The temperature distribution throughout the insulation layers was also measured. According to our results, the trusses did not increase internal convection. However, the temperature measurements do show that the normal thermal bridge effect is present. The convective air movements inside the insulation layer can be seen when comparing the temperature distributions inside the insulation. The temperatures were mainly higher in the middle parts of the insulation when comparing them in both the transverse and longitudinal directions. In the measurements with the blown-in wood fibre insulation, the temperatures were on average 1–5 °C higher in the middle than they were near the edges. In the mea-

surements with the blown-in glass wool insulation, the difference between the middle and edge temperatures could be as high as 10 °C in certain cases. Generally, the temperature distribution was wider in the blown-in glass wool insulation than it was in the blown-in wood fibre insulation. This can also be seen from the Nusselt numbers and indicates that there is more internal convection inside the insulation layer.

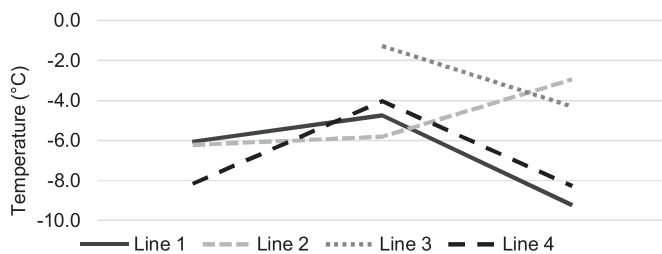
The results show that internal convection caused the air to move upwards in the middle parts of the insulation and downwards near the edges. Internal convection occurred throughout the whole insulation section. Fig. 5 shows the temperature distribution in the blown-in glass wool insulation at a height of 420 mm from the bottom of the insulation layer when the temperature difference was 35 °C and there was almost no air movement at the surface of the insulation layer. In the transverse direction, the temperatures were higher in the middle than they were near the edges apart from one measurement point. The temperatures in the middle also increased somewhat in the longitudinal direction.

#### 4.3. Different individual variables affecting to internal convection

This study compared five different variables affecting internal convection. These were the temperature differences, the trusses,



**Fig. 4.** The Nusselt numbers of the studied situations. Internal convection is happening when the Nusselt number is  $\geq 1.0$ . More information about the margins of error is presented in Section 4.5.



**Fig. 5.** The temperature distribution in the blown-in glass wool insulation at a height of 420 mm from the bottom of insulation layer when the temperature difference was 35 °C and there were almost no air movement at the insulation layer's surface. Line 3 was missing one sensor; in total 11 sensors took measurements at this height. The locations of lines 1–4 in the test structure can be seen in Fig. 3.

the air velocity at the surface of the insulation, the thickness of the insulation and the insulation material. The effect of any one variable on the internal convection can be evaluated by comparing two equivalent cases in which only one variable is changed. Fig. 6 shows the results when the trusses were compared in this way. The figure shows that the trusses have almost no effect on internal convection for blown-in wood fibre insulation due to the uncertainty of the measurements. However, with blown-in glass wool insulation, the addition of the trusses decreased the internal convection by 11–36%-units.

It is clear that the insulation material itself has the greatest effect on the amount of internal convection as in every case except one there was more internal convection with the blown-in glass wool insulation than with the wood fibre insulation. The greatest effects were in the cases with no trusses, where the blown-in glass wool insulation had 61%-units more internal convection than the blown-in wood fibre insulation.

When comparing the variables affecting internal convection with blown-in wood fibre insulation, the increase in the temperature difference had the greatest influence. In two cases there were around 10%-units increase. The airflow did not have much effect on internal convection with the blown-in wood fibre insulation.

The thickness of the insulation layer alone did not seem to have as much effect as the other variables in any of the cases, either for blown-in wood fibre or glass wool insulation.

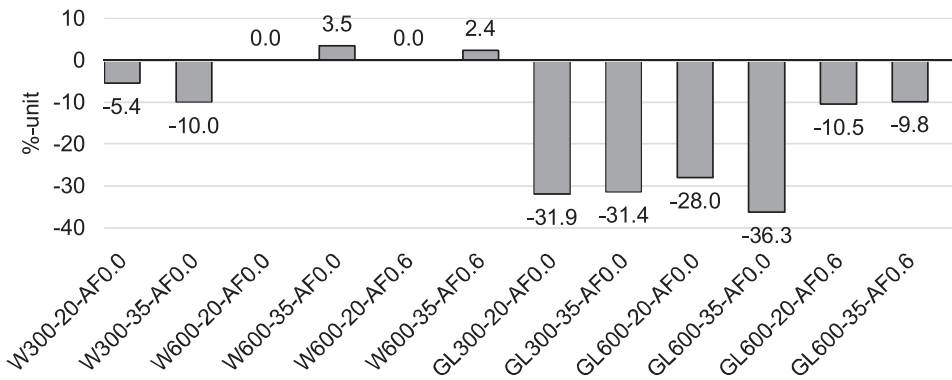
With the blown-in glass wool insulation, increasing the air flow at the surface of the insulation layer increased the internal convection. However, the effect of the airflow was greatest when there were trusses in the structure. The effect of the trusses could be as much as 36%-units when the air flow was only 0.0–0.1 m/s. For the blown-in glass wool insulation, although the higher temperature difference has almost no influence with the low air flow, the higher temperature difference and air flow together increased the internal convection by 17–18%-units.

#### 4.4. The installation method and the size of the metering area

The same kind of internal convection measurements were conducted in the FRAME study [1], and these showed significant internal convection with both loose-fill glass wool and wood fibre insulation. The hot-box used in the in FRAME study only had a metering area of 1.44 m<sup>2</sup>. However, the effect of the edges of the equipment did not seem to be too strong even with the smaller equipment as the loose-fill glass wool insulation results were similar to the results of this study. In the FRAME study, the insulation was installed by hand rather than with the appropriate blowing machine for loose-fill insulations. Installing the wood fibre insulation by hand had a significant effect on the internal convection, although there was hardly any effect with the glass wool. Similarly, the installation method had an effect on the texture of the insulation layer with the loose-fill wood fibre insulation, but not with the glass wool. This indicates that loose-fill wood fibre insulation should be installed with an appropriate blowing machine for loose-fill insulations.

#### 4.5. Uncertainty

When taking the measurements, every effort was made to ensure accurate and comparable results. The test apparatus was kept



**Fig. 6.** The effect on the amount of internal convection when adding trusses to the structure. The abbreviations indicate which variables were the same with any two studied situations. The negative values mean that adding trusses has decreased the internal convection.

**Table 4**

The measurement tolerances of the sensors used in tests.

Quantity and sensor	Tolerance	Terms
Temperature (semiconductor)	$\pm 0.4$ °C	-20...+20 °C
Relative humidity (Vaisala T/RH) [22]	$\pm 2\%$ RH	0-90% RH
	$\pm 3\%$ RH	90-100% RH
Air velocity (anemometer) [23]	$\pm 3\%$ of reading	0.05-
	$\pm 1\%$ of chosen region	2.50 m/s

in exactly the same place inside the freezer room for all the measurements and the studied structures and sensors were installed in the same way for all the different cases.

To ensure as accurate results as possible, it is also vital to make sure all the equipment and sensors are calibrated properly. Therefore, the temperature sensors were calibrated at three different temperatures in the calibration chamber: -20 °C, 0 °C and +20 °C. The relative humidity sensors were also calibrated with three different salt brines at 20 °C: MgCl 33.1%, NaBr 58.2% and KCl 85.1%. The transducers used to measure the air velocity were calibrated at the factory. While the uncertainty of the semiconductor sensors was calculated by Tampere University, the values for all the other sensors were as specified by the manufacturers. Table 4 presents the measurement tolerances for the sensors used in the experiments.

The most reliable measure of uncertainty result could be achieved by doing a comprehensive set of measurements to confirm the uncertainty calculations. However, only the calculated uncertainty has been defined in this study. The uncertainty of the measured heat flow through the structure and the U-values were calculated with Eq. (3).

$$s_f = \left( s_1 \frac{\partial f}{\partial u_1} + s_2 \frac{\partial f}{\partial u_2} + \dots + s_n \frac{\partial f}{\partial u_n} \right) \quad (3)$$

where  $s_1 \dots s_n$  are the uncertainties of individual quantities and  $\partial f / \partial u_1 \dots \partial f / \partial u_n$  are partial derivatives calculated for every quantity of the equation. The uncertainties are presented with a coverage factor of two standard deviations and the correspondence of the results is 95%. The EN ISO 8990 standard [14] states that it is studied experimentally that when measuring homogenous materials, the accuracy of the measurements should be  $\pm 5\%$ . The calculated uncertainties for the U-values in this study were all between  $\pm 3.3$  to  $\pm 5.9\%$ .

## 5. Discussion

The results of this study show that the U-value can increase significantly due to internal convection. This should be taken into account when choosing the insulation materials and installation

methods. The research has also shown that in studied structures insulated with low-density blown-in glass wool insulation, the internal convection can increase the heat flow rate through the structure by as much as 60%. However, the average increase for studied wood fibre insulation was only 0–10%, while for glass wool it was 30–40%.

The results of both the COMBI and FRAME projects indicate that a critical evaluation of the EN ISO 6946 [17] and the EN ISO 10,456 standards [13] should be made to ascertain whether they adequately account for the effects of internal convection. At the moment the EN ISO 10,456 standard [13] sets 15 as a boundary value for the critical modified Rayleigh number for horizontal roofs when the upper surface of the insulation has no wind screen. However, when considering the situations as studied this usually leads to the situation where the effect of internal convection is not taken enough into account even if internal convection has a significant influence on a roof's U-value and its thermal resistance. The modified Rayleigh numbers for our measurements were between 2.4–9.5, all well below 15, yet internal convection was present in 80% of the studied cases. In the cases where there was no internal convection, the modified Rayleigh numbers were 2.6–3.4. Our results also show that with wood fibre insulation, the Nusselt number went above 1.00 when the modified Rayleigh number exceeded 5. The results of both the COMBI and FRAME studies show that the critical modified Rayleigh number should be 5 with loose-fill glass wool and food fibre insulation when the insulation's upper surface is open in order to prevent the internal convection from decreasing the thermal resistance of these insulations. This value also corresponds to the results of calculations by Shankar and Hagetoft [5] and measurements by Gullbrekken et al. [8]. In some cases, the modified Rayleigh number was only 2.4, even though there was still significant internal convection. This indicates that the critical modified Rayleigh number should be even smaller. On the other hand, in the measurements with the blown-in glass wool, the Nusselt number did not increase even when the modified Rayleigh number was doubled. This indicates that the measured results can vary a lot so a critical modified Rayleigh number of 5 would seem to be a justifiable value also for glass wool insulation.

The results of this study are coherent with studied materials which stand for that these results can be used when investigating the similar structures as studied in this study. However, the results cannot be directly generalized to all blown-in loose-fill insulations because the microscopic texture can be different even if the density would be the same. This can be seen when taking a look to the results of installation methods. Installing loose-fill wood fibre insulation by hand and with proper blowing machine gave unlike internal convection results even if the density and material were the same. Therefore, the exact results for internal convection should



be restricted only to these materials and installing method used in COMBI and FRAME studies. To get more detailed view it would be necessary to do supplemental measurements with different insulation materials and installing methods. Also, one further investigation need is to analyze the microscopic texture of thermal insulation materials. Nevertheless, 5 is recommended to use as critical modified Rayleigh number if there is not more information known about porous structure of the material or behavior of internal convection. In some situations, this value can include additional reliability but this is justifiable when we are trying to design structures without any internal convection.

When comparing these results to Wahlgren's measurements, which determined 22 as a critical modified Rayleigh number, attention has to be paid to the fact that in Wahlgren's measurements the measurement area was relatively small and the measurements were taken from the middle area of the insulation. Usually, the densities of the heat flow rates are greater at the edges of the insulation than they are in the warmer middle area. Our study also shows that there is a difference in temperatures between the edges and the middle areas of the insulation, which indicates that internal convection occurs widely over the whole insulation area. Thus, the total internal convection cannot be evaluated just by measuring the middle parts of the structure. A comprehensive investigation of the thermal behavior of internal convection requires the whole insulation area to be measured.

12 temperature sensors were used to measure the air temperature in the cold chamber. In addition, four temperature sensors were used to measure the temperatures in the freezer room outside the warm chamber. Nevertheless, one thing that might have affected the results could be that there were different kinds of temperature fields surrounding the warm chamber in the calibration tests as opposed to the actual experiments. However, none of the four temperature sensors that were used indicated any significant changes in the temperature fields, so this is assumed not to have had any notable impact on our results.

In the structures with blown-in wood fibre insulation, the effect of the trusses was negligible. Surprisingly, in the structures with the blown-in glass wool insulation, the addition of the trusses decreased the internal convection by around 10 to 30%-units. Delmas and Arquis [24] state that the horizontal bottom joists of trusses can decrease the critical modified Rayleigh number, but they can also reduce the speed of the airflow inside the insulation when the modified Rayleigh numbers are higher. The modified Rayleigh numbers in our case studies were not as high as those stated in [24], but the internal convection inside the insulation was significant with low-density insulation. Hence, the horizontal bottom joists of trusses may hinder the internal convection in the longitudinal direction with our experimental set-up. On the other hand, the temperature distribution of our study indicates that the airflow due to internal convection also occurs in the other direction.

There were also other discrepancies perceived. The presumption is that internal convection should be growing when temperature difference and thickness of insulation layer is growing. However, when temperature difference increased from 20 °C to 35 °C with 600 mm class wool insulation the Nusselt numbers were essentially equal for the situations where airflow was 0.0–0.1 m/s. Also, increasing thicknesses of insulations were increasing the internal convection only in one case 5.7%-units when studying wood fibre insulation with trusses and airflow 0.0–0.1 m/s. In other cases, increasing thicknesses of insulations were decreasing Nusselt number from 0.0 to 7.8%-units. When performing a laboratory measurement there is always a change that the measurement settings differ a bit from each other even if the situations are tried to do as evenly as possible. Test results are always including a set of uncertainty factors which human are causing. For example, the place of hot box in freezer room can vary a little, the thickness of insula-

tion can vary within an insulation layer etc. When considering the results, it has to be kept in mind that the calculated uncertainties for the Nusselt numbers in this study were on average  $\pm 5\%$ .

To build well-functioning roof structures, the functionality of the whole structure has to be evaluated. In real roof spaces, any discontinuities such as pipes, trusses and illuminators (which can cause spot-like heat sources) can increase the internal convection within the insulation layer. Indeed, the FRAME study showed that light bulbs can have a significant effect on the development of internal convection in roofs. To prevent internal convection, it is important to install the insulation properly and to make sure that it fills the whole area with no air gaps or cavities. It is also essential to install proper wind protection boards correctly when using porous loose-fill insulation in ventilated roof structures as these prevent air from entering directly into the insulation. Other ways to decrease the internal convection inside the insulation are to decrease the air permeability of the insulation layer, for example by increasing its density or adding adhesives to the insulation material when installing it with a blowing machine. Furthermore, inserting a layer of insulation board under loose-fill insulation is beneficial as long as the insulation boards are carefully installed with no air gaps between them. The FRAME study showed that using 100 mm insulation boards decreased the effects of internal convection by 30–50% with loose-fill wood fibre and glass wool insulations installed by hand.

## 6. Conclusion

A total of 24 different roof structures were studied to find out how internal convection in loose-fill insulations affects the insulation properties of highly insulated roof structures. Internal convection occurs widely throughout the whole insulation area, which can have a significant effect on the U-value of the structure. This should be taken into account when choosing the insulation materials and the installation methods. The results of this study emphasize the importance of designing roof structures carefully. In studied situations, more internal convection was observed with blown-in glass wool insulation than with the thicker wood fibre insulation. Of all the individual variables studied, temperature difference had the greatest impact on the amount of internal convection with higher density insulations while airflow over the surface of the insulation layer had the greatest impact with low-density insulations. The results of this study cannot be directly generalized to all blown-in loose-fill insulations because the microscopic texture can be different even if the density would be the same. Therefore, the results of internal convection should be restricted only to these materials and installing method used in this study. The results of this study indicate that, if internal convection is to be adequately taken into account, 5 should be used as the critical modified Rayleigh number for horizontal roof structures with an open upper surface when investigating loose-fill glass wool or wood fibre insulations. 5 is also recommended to use as the critical modified Rayleigh number if there is not more information known about porous structure of the material or behavior of internal convection. In some situations, this value can include additional reliability but this is justifiable when we are trying to design structures without any internal convection.

## Declaration of Competing Interest

None.

## CRedit authorship contribution statement

**Henna Kivioja:** Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Juha Vinha:** Con-

ceptualization, Methodology, Validation, Supervision, Funding acquisition.

## Acknowledgments

This research was part of the COMBI-project (Comprehensive development of nearly zero-energy municipal service buildings). The project has received funding from the [European Regional Development Fund](#), which is part of the Innovative Cities project of the [Finnish Funding Agency](#) for innovation, [TEKES](#). The project also benefited from significant funding contributions from 37 companies and 9 cities. Our great thanks go to Mikko Viitala and Eero Tuominen for their invaluable assistance in carrying out the tests. The authors have no conflict of interest.

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