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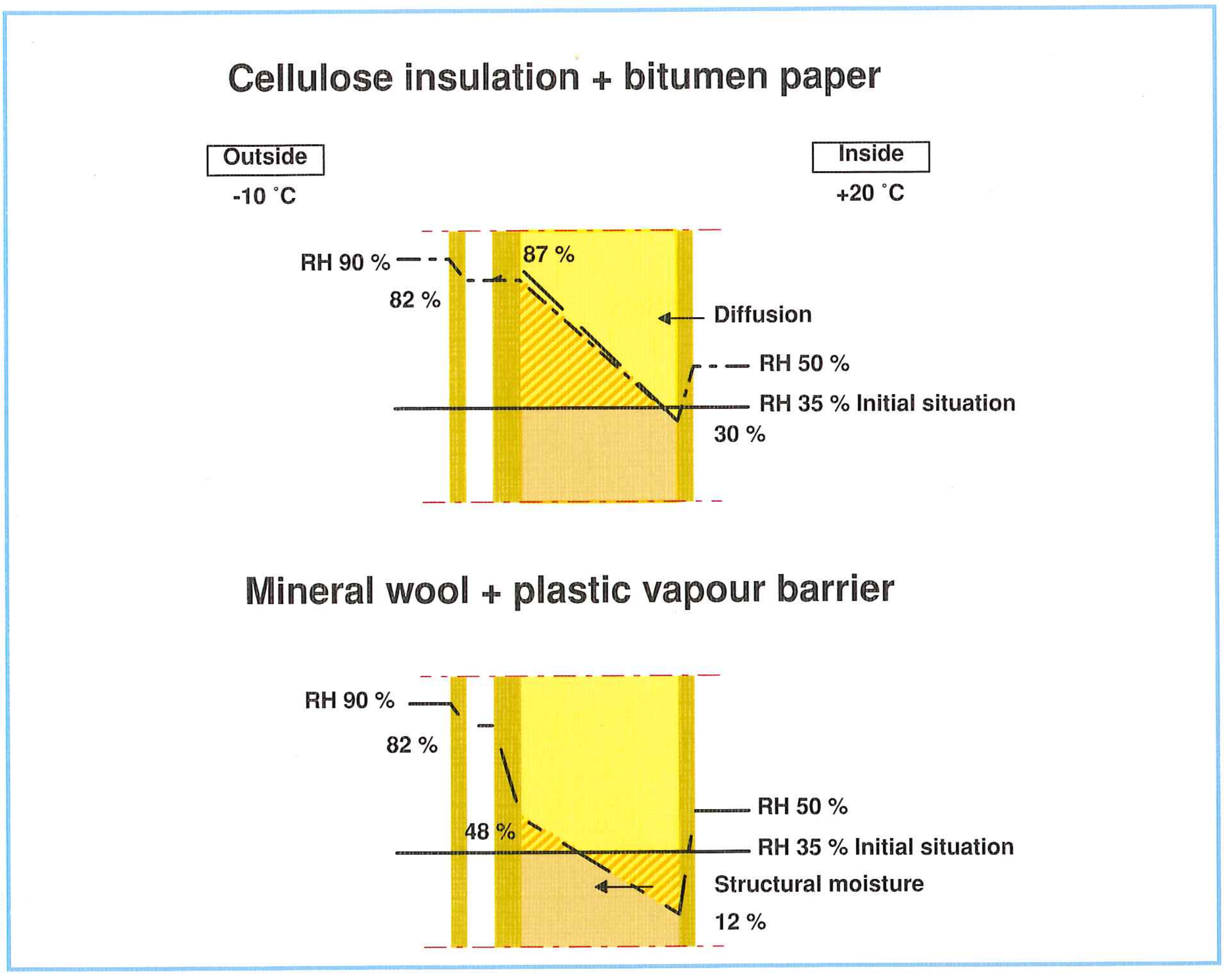

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Keywords: building physics, test equipment, laboratory tests, measurement and control system, diffusion, convection, pressure difference, condensation, timber-framed walls, vapour barrier, air barrier, mineral wool, cellulose insulation

Abstract

New equipment for building physics tests has been built by the Laboratory of Structural Engineering at Tampere University of Technology (TUT) which allows studying the moisture behaviour of shell structures under different conditions. The equipment has been developed on the basis of earlier thermal transmittance testing equipment and has taken altogether some 4 years.

The new equipment consists of a warm and a cold chamber - the examined structure is placed between them. The warm chamber is used to model indoor air conditions while the cold chamber models outdoor air conditions. The equipment incorporates numerous measurement and control instruments that are computer-controlled. Accurate and fast regulation of conditions requires an effective control program that continually maintains an equilibrium between various factors.

In tests, the controllable variables are indoor and outdoor air temperature and relative humidity (RH) as well as the pressure difference across the examined structure. Tests can be conducted either under constant or varying conditions.

The building physical test equipment has many features that together make it a novel and versatile apparatus such as:

- all indoor and outdoor air conditions can be controlled simultaneously during tests
- structures can be tested in indoor and outdoor air conditions that correspond to real-life situations (e.g. RH of outdoor air can be made to correspond to the actual value also under freezing conditions)
- all controllable condition variables can be set freely within the control range
- all measurements and adjustments are automatic, accurate and quick as they are computer-controlled
- in the test, the moisture flow rates into the structure by diffusion and convection can be measured separately.
- structures can be tested under constant conditions or conditions may be changed cyclically
- as a result of the air tightness of the equipment and the installation technique of the element, the air flow rate through the tested structure is controlled
- the test opening is large (area: 1200 x 1200 mm^2, depth: 400 mm) which means that the same phenomena occur in the tested structure as in actual structures (e.g. convection inside structure)
- the control and measurement systems of the equipment can be augmented or changed as needed
- the equipment may be rotated as needed so that wall, roofing deck and base floor structures can be tested in the proper position
- the control and measurement systems developed in connection with the building of the equipment can also be used in other laboratory tests

The new test equipment was used to study the transmission of water vapour in timber-framed external wall structures due to diffusion and convection. Conducted tests gave the following results:

Effect of diffusion

1. All wall structures perform well from the viewpoint of diffusion, if
   - the moisture increase of indoor air is small **and**
   - water cannot enter the structure as a result of moisture leaks
2. A structure permeable to moisture is clearly more at risk for condensation than one with a vapour barrier.
   → The internal wall surface must have sufficient water vapour resistance (5:1 rule).
3. If the internal wall surface has proper air and vapour barriers, both cellulose and mineral wool insulation can be used.
4. The moisture-retention capacity of wood-based materials delays the onset of condensation but is not always enough to prevent condensate from forming.
5. Surplus moisture retained by materials increases the risk of condensation. In the case of wood-based materials the risk is high since they can retain a lot of moisture.
6. A windshield sufficiently permeable to water vapour must be attached to the external wall surface in order to allow surplus moisture to exit. There must also be a functioning ventilation gap outside the windshield.

Effect of convection

1. All wall structures perform safely with regard to convection if
   - underpressure prevails in the building **or**
   - the structure has a solid air barrier
2. Internal underpressure does not reduce moisture contents of a perforated wall structures significantly compared to a situation where there is no pressure difference. However, underpressure prevents the build-up of overpressure in a building.
3. Internal overpressure increases the equilibrium moisture contents of a perforated wall structure and increases its risks for condensation and moulding.
4. Condensation is possible in a moisture-permeable wall structure despite pressure difference (diffusion).
5. The risk of condensation exists for a wall structure with a vapour barrier only if the structure has holes clear through the internal surfaces and there is overpressure.
6. The use of cellulose insulation slows down increases in RH values in overpressure situations at holes, but in the final end the moisture rates of the structure correspond to those of a mineral wool wall.
7. When holes penetrate only the air/vapour barrier, RH values are not affected by pressure difference. This applies also to the attachment of the inner sheet to the bracing through an air/vapour barrier.
8. Joints of the inner sheet and air/vapour barrier at the bracing have no effect on the RH values of the wall structure in over- or underpressure situations. A 200-mm overlap is sufficient at the joint of an air/vapour barrier. Taping of joints is always recommended but is not necessary at the bracing.

Other test results

1. The more permeable the wall structure is, the more calculated diffusion values differ from the real-life situation.
   → It is difficult to determine the moisture specifications of a wall structure permeable to moisture.
2. A permeable wall structure is incapable of increasing indoor air humidity in winter.
3. Overpressure raises significantly temperatures on the internal surface of the windshield in structures with holes clear through the internal surface.
4. Exterior cladding increases the temperature in the ventilation gap compared to outdoors whereby the RH values on the internal surface of the windshield drop in the case of airtight and vapourtight structures.
5. Under winter conditions the wall structures do not generally provide temperature or RH conditions conducive to mould growth.

Foreword

This research project has faced stiff challenges as its goal has been to build new kind of test equipment for studying the moisture behaviour of shell structures. The integration of the various components has required a lot of innovativeness, effort and long-term development work.

The study was launched on 1 January 1996 and it ended on 31 December 1998. The design, construction and testing of the new test equipment took about 2 years of that time; the last year was spent examining different wall structures. The equipment is based on earlier equipment used to study thermal transmittance (CHB). Thus, it can be said that the building physical test equipment is the result of a total of about 4 years of development.

The research was conducted at TUT under Prof. Ralf Lindberg and Juha Vinha, Lic.Sc.(Tech.). Mr. Juha Vinha has led and supervised the research team. He has also mainly designed the new test equipment and the building physical tests run with it. The research team consisted of Timo Niemelä, M.Sc.(Tech.), who built the warm chamber and protective chamber of the equipment, Pasi Käkelä, M.Sc.(Tech.), who conducted the building physical tests with the equipment as well as their documentation, and Pekka Viitala, M.Sc.(Tech.), who wrote the control program for the equipment. Timo Niemelä and Pasi Käkelä were also involved the planning and building of the measurement and control systems of the equipment. Laboratory engineer Kauko Sahi and laboratory technician Kari Häyrinen, among others, were also involved in the design and building of the electrical systems of the equipment. Many others also assisted in the development of the equipment.

The project management group consisted of:

Vaito Rossi	Schauman Wood Ltd., chairman
Juha Ryyppö	Isover Ltd.
Jouko Kujala	Turun Rakennustuote Ltd.
Pekka Peura	TEKES, Finnish Wood Research Ltd.
Lasse Pöyhönen	TEKES
Outi Palttala-Heiskala	TUT, Architecture
Ralf Lindberg	TUT, Structural Engineering

The research was part of TEKES (National Technology Agency of Finland) building physics studies conducted as part of the Wood in Construction technology programme. In addition to TEKES, financing was provided by Isover Ltd., Turun Rakennustuote Ltd. and Finnish Wood Research Ltd.. We extend our thanks to the members of the management group and the financiers of the research for their cooperation during the study.

Tampere, 30 March 1999

Juha Vinha Pasi Käkelä

Foreword to English version

This is an English translation of the original Finnish publication no. 96 by the Laboratory of Structural Engineering (1999). In connection with the translation, the text has been revised slightly. Some incorrect test results caused by measurement and calculation errors have also been corrected. . Thanks are due to Mr. Jorma Tiainen and Mr. Seppo Siuro for translating our publication into English.

Tampere, 28 December 1999

Juha Vinha Pasi Käkelä

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List of symbols

A	area	m^2
G	moisture flow rate	kg/s, g/day
K	air permeance	$m^3/(m^2\cdot s\cdot Pa)$, $m/s\cdot Pa$
P	heating power	W
R	air flow rate	m^3/s, l/min
T	temperature	°C
U	voltage	V
U	thermal transmittance	$W/m^2\cdot K$
W_p	water vapour (moisture) permeance (calculated using partial water-vapour-pressure difference)	$kg/m^2\cdot s\cdot Pa$
W_v	water vapour (moisture) permeance (calculated using water-vapour-content difference)	m/s
Z_p	water vapour (moisture) resistance (calculated using partial water-vapour-pressure difference)	$m^2\cdot s\cdot Pa/kg$
Z_v	water vapour (moisture) resistance (calculated using water-vapour-content difference)	s/m
a	auxiliary variable	
b	constant	
d	thickness	m
g	density of moisture flow rate	$kg/m^2\cdot s$, $g/m^2\cdot day$
k	coefficient	
m	mass	kg, g
Δp	pressure difference	Pa
q	density of heat flow rate	W/m^2
r	density of air flow rate	$m^3/(m^2\cdot s)$, $l/m^2\cdot min$
r	velocity of air flow	m/s
t	time	s
u	variable	
u	moisture content percent by mass	mass %
x	distance	m
δ_p	water vapour (moisture) permeability (calculated using partial water-vapour-pressure difference)	$kg/m\cdot s\cdot Pa$
δ_v	water vapour (moisture) permeability (calculated using water-vapour-content difference)	m^2/s
Φ	heat flow rate	W
ϕ	relative humidity (RH)	%
ν	humidity by volume	kg/m^3, g/m^3
λ	thermal conductivity	$W/m\cdot K$
ℓ	air permeability	$m^3/(m\cdot s\cdot Pa)$, $m^2/s\cdot Pa$

Most common subscripts

dif	diffusion
l	loss (warm chamber)
tot	total
conv	convection
calc	calculated
meas	measured
vel	velocity
str	structure
p	partial vapour pressure
i	inner
is	inner/internal surface
o	outer
os	outer/external surface
v	humidity by volume

Concepts and definitions

Air barrier

An air barrier is a layer of material whose main function is to prevent harmful air flow through a structure. The air permeability of an air barrier is low.

Air permeability

Air permeability (ℓ) refers to the air volume that under a steady state passes through a homogeneous layer of material of one surface unit in area, and one unit of length thick, in one unit of time as a laminar flow, when the pressure difference between the atmospheres on opposite sides of the material layer is one unit.

Air permeance

The air permeance (K) indicates the air flow that under a steady state passes in one unit of time, in the form of a laminar flow, through a structural element one surface unit in size when the pressure difference between the atmospheres on opposite sided of the structural element is one unit.

Condensation

Condensation refers to the conversion of water vapour into water or ice in structures as the humidity by volume of air reaches saturated humidity (RH = 100 %) at the area in question. Condensation generally occurs at the interfaces of material layers.

Convection

Convection occurs when a gas or a liquid flows due to an external force (forced convection) or as a result of differences in density due to temperature differences (natural convection). Water vapour is carried along by the air flowing due to convection.

Diffusion

Diffusion is movement of gas molecules that seeks to equalize the differences in concentrations (or partial pressures) of a certain gas in a gas mixture. Diffusion moves a gas from a region of higher to one of lower concentration.

Humidity by content

Humidity by content (v) expresses the amount of water vapour in the air. Differences in humidity contents tend to become equalized through diffusion.

Hygroscopic equilibrium moisture content

Hygroscopic equilibrium moisture content refers to the moisture content taken up and retained by a porous material in the steady state at certain environmental relative humidity and temperature.

Hygroscopicity	Hygroscopicity refers to the capacity of a porous material to take up and retain moisture from the air and to release it back into air.
Impermeable structure	An impermeable structure has a solid air barrier and a sufficiently tight vapour barrier.
Overpressure	When the absolute pressure of a certain atmosphere is higher than ambient air pressure, overpressure is said to prevail in the atmosphere. In the case of TUT test equipment, overpressure means that air pressure within the warm chamber is higher than in the protective chamber. Overpressure is created by pumping air into the warm chamber. The sign of overpressure is +.
Permeable structure	A permeable structure has a solid air barrier but no vapour barrier.
Relative humidity	Relative humidity (ϕ, RH) indicates the amount of water vapour in the air as a proportion of saturated humidity at a certain temperature.
Saturated humidity	Saturated humidity indicates the maximum humidity by volume of air at a certain temperature.
Steady state	A system that is in a steady state takes in and discharges a constant amount of a substance and thermal energy in a unit of time. In steady state temperatures and the contents of various substances have reached an equilibrium and do not change over time.
Thermal conductivity	Thermal conductivity (λ) indicates the heat volume that under a steady state passes through a homogeneous material layer of one surface unit in size, and one unit of length thick, in a time unit, when the temperature difference between the atmospheres on the opposite sides of the material layer is one unit.
Thermal transmittance	Thermal transmittance (U) indicates the heat volume that under a steady state passes through a structural element of one surface unit in size in a time unit, when the temperature difference between the atmospheres on opposite sides of the structural element is one unit.

Underpressure

When the absolute pressure of a certain atmosphere is lower than the ambient air pressure, underpressure is said to prevail in the atmosphere. In the case of TUT test equipment, underpressure means that air pressure within the warm chamber is lower than in the protective chamber. Underpressure is created by sucking air out of the warm chamber. The sign of underpressure is -.

Vapour barrier

A vapour barrier is a layer of material whose main function is to prevent harmful diffusion of water vapour to or within a structure. The water permeability of a vapour barrier is low.

Water vapour permeability

Water vapour permeability (δ_v or δ_p) indicates the amount of water that under a steady state passes through a homogeneous material layer of one surface unit in size, and one unit of length thick, in a time unit, when the difference in the humidity by volumes (or partial water-vapour-pressure difference) of the atmospheres on opposite sides of the material layer is one unit. Moisture may migrate through a material also in forms other than water vapour. Then, we may also speak of a material's moisture permeability.

Water vapour resistance

Water vapour resistance (Z_v or Z_p) refers to the reciprocal of water vapour transmission. To be precise, only water vapour transmission reflects the impact of the mass transfer coefficients of interfaces, but their share is practically insignificant. The water vapour resistance of a specific material layer can be derived from the formula $Z = d/\delta$.

Water vapour permeance

Water vapour transmission (W_v and W_p) indicates the amount of water that under a steady state passes through a structural element of one surface unit in size in a time unit, when the difference in the humidity by volume (or partial water-vapour-pressure difference) of the atmospheres on opposite sides of the structural element is one unit.

Windshield

A windshield is a layer of material whose primary function is to prevent harmful air flow in the thermal insulation layer of a structure due to wind. The windshield material must be highly permeable to water vapour.

1 Introduction

1.1 Background

The moisture behaviour of shell structures has been of interest to researchers since the earlier massive structures were replaced by heat-insulated layered structures and, at the same time, the use of water inside buildings increased considerably. Ideas of ideal structures have varied thereafter, and researchers still have contradicting opinions of the performance of alternative structures. One reason for the confusion has been the lack of reliable research data on the building physical behaviour of structures.

Most moisture damage in structures is caused by running water or moisture in the soil (rain, run-off, moisture transmitted by capillary action, pipe leaks, wash water). There are only two ways to remove running water from structures: installing a tight moisture barrier on the surface or removing the source of moisture from the structure or its vicinity. These are quite obvious solutions, but for some reason errors have still constantly been made in the implementation. It is evidently very difficult to protect structures from moisture throughout the life cycle of the building. Therefore, fast drying is also a characteristic of a good structure, which can be achieved by proper design and selection of materials. More research data on drying are also needed.

The behaviour of water vapour in structures is much less well known. Many solutions have worked well in some cases but in some others the opposite has been true. Some environmental condition has been different and caused moisture damage in the structures. Many efforts have been made to improve shell structures, but experience has shown them to have been mostly defective or inadequate. In recent years these failures have also been increasingly publicized.

It is obvious that under some conditions – with low moisture increase of indoor air or outdoor conditions favourable to drying (wind, temperature, solar radiation) – all structures perform ideally with respect to the transmission of water vapour. But the same structures may not behave ideally when the moisture load increases. Different structures do behave differently, and the differences should be determined before new structures can be introduced. New research methods are therefore urgently needed for reliable analysis of structures.

Analyzing the moisture behaviour of shell structures has been problematic, because different research methods have failed to provide a reliable overall picture of the behaviour of structures in different situations. Field tests can only be used to analyze the behaviour of individual buildings, and the mutual significance of the factors affecting the results often remains ambiguous. In computational analysis the problem often lies with selecting correct material properties and environmental factors and modeling the structures to correspond to reality. Theory may not necessarily coincide with reality because of the great number of factors to be considered. Laboratory experiments, on the other hand, have failed to control all environmental conditions simultaneously and independently of each other. Test have been made mostly at temperatures exceeding 0°C. However, the behaviour of structures and materials changes radically at subzero outdoor temperatures.

1.2 Objectives of this research project

The main objective of this research project was to design and build new laboratory test equipment for studying shell structures under desired indoor and outdoor conditions and controlling the conditions freely. It was also our intention to test various timber-framed wall structures with the new apparatus.

One important starting point in the development of the new equipment was to offer companies the possibility to test the structures and materials they manufacture and ensure their moisture behaviour under different conditions.

Tampere University of Technology was well suited for building the test equipment, because the research team members had extensive experience of building laboratory test apparatus. The earlier built calibrated hot box equipment (CHB) provided a good basis for the development. The equipment is used to determine the thermal transmittance of structures (U value) or the thermal conductivities of different materials (λ value). This equipment already had an accurate temperature measurement and control system. Precise temperature control was also of primary importance to ensure proper control of other conditions, since both relative humidity and pressure depend on temperature.

2 Building physical test equipment of TUT

2.1 Operating principle

To test the impact of environmental conditions on structures, the desired indoor and outdoor conditions are created on opposite sides of the structure. The controlled variables are temperature, relative humidity (RH) and pressure difference across the structure. Tests can be made either under constant or varying conditions. A test under constant conditions examines the behaviour of the structure in a steady situation. In a test under varying conditions, one or more environmental factors are varied at certain intervals. Cyclical variation is useful for modeling, for example, variation in ventilation, time of day, or season. The most typical variables to be controlled in this test are pressure difference and outdoor temperature.

Before starting the experiment, the control program's input files are prepared by entering data on the measurement arrangements, channels, measured variables, calibration factors of measurement sensors, test conditions, properties of the element to be tested, and measurement values to be observed during the test.

During the test the computer runs the same measurement and control procedure at regular intervals. During the measurement and control procedure, the output voltages of a total of about one hundred measurement channels are read at intervals of one minute. The voltage readings are then converted to corresponding calculation variables (temperature, relative humidity, pressure difference, velocity of air flow, heating power, etc.) by conversion formulas, and averages of different variables are calculated.

The computer then computes various calculated values for the structure under study based on the averages (moisture transmitted by diffusion and convection, air permeability and water vapour permeability, etc.). The values measured and calculated during the test are stored in output files. The progress of the test can be monitored during the test by numerical and graphic pages on the computer display.

Based on the measurement results, the computer controls the indoor and outdoor conditions to match the set values as closely as possible. The control values are calculated by the computer using control formulas.

Constant indoor and outdoor conditions were reached in the tests rather quickly: typically within one day from the start of the test (Figure 2.1). The rapid condition control proves that the control system is effective. On the other hand, reaching constant moisture contents in structures may take considerably longer (even more than one month). This depends on the initial moisture contents and water vapour permeabilities of the materials used in the structure and the controlled environmental conditions.

In tests under constant conditions, individual environmental conditions remain constant for at least one week, and the total test duration is about one month. In cyclical tests, the test duration varies depending on the environmental conditions to be varied. During a month-long test, the equipment typically makes about 4.5 million measurements, produces 2 million calculated values, and controls the process about 250,000 times.

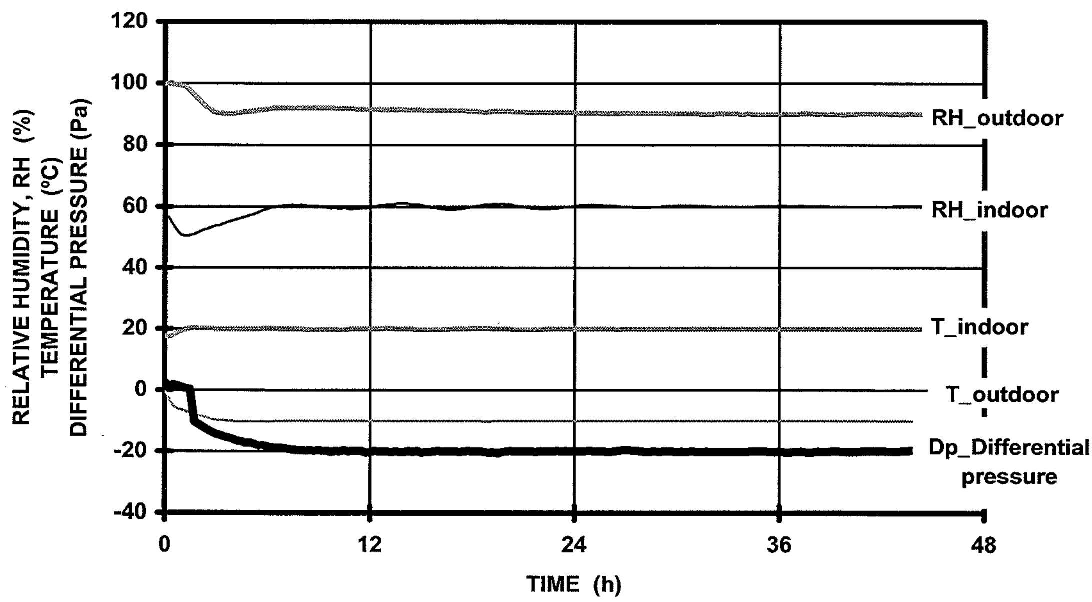


Figure 2.1. Example of reaching constant conditions in a building physical test as a function of time.

2.2 Parts of the equipment

The research equipment consists of a warm chamber and a protective chamber that are located in a big cold room. The wall of the warm chamber has a test opening where the structure to be studied is inserted. The protective chamber is opposite to the warm chamber facing the outer surface of the structure to be studied. The warm chamber is controlled to match the conditions of indoor air and the protective chamber to match those of outdoor air (Figure 2.2).

Baffles are placed on both sides of the structure to be studied to produce more even temperature and air flow conditions near the surfaces of the structure. The baffles also serve as mounting racks for the measurement sensors.

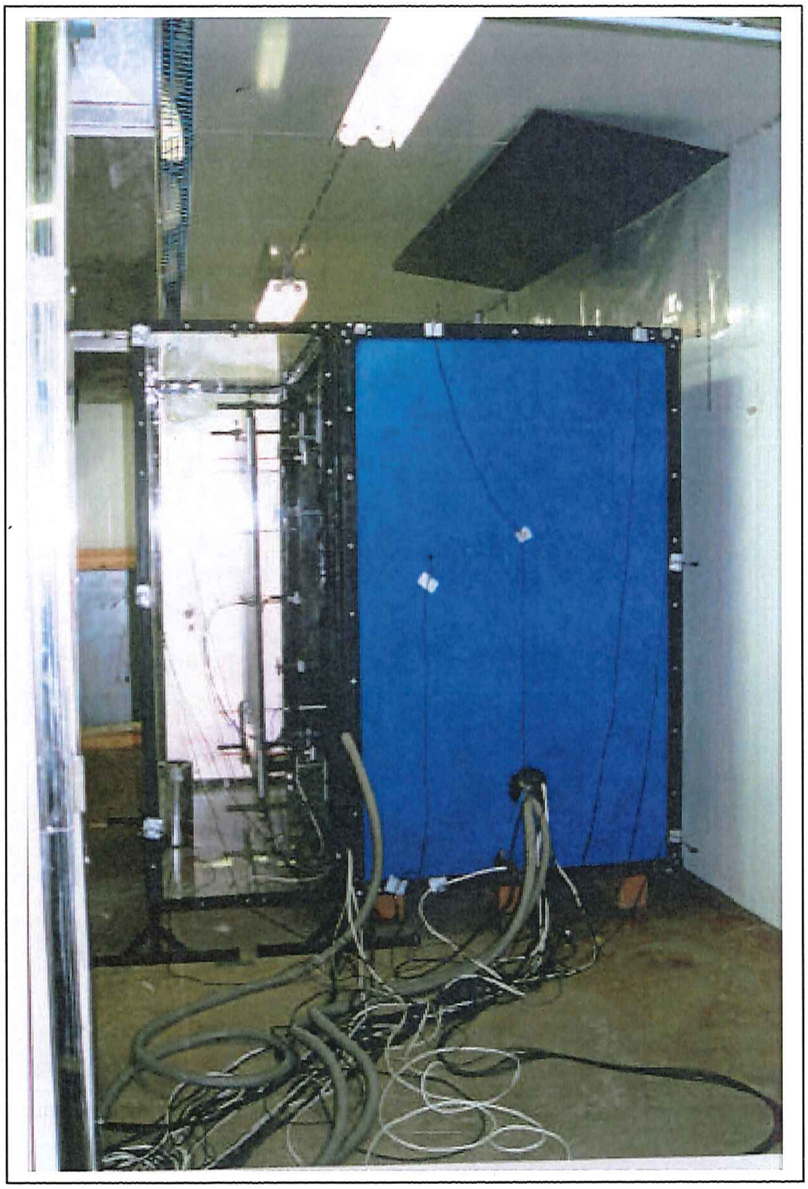


Figure 2.2. The warm chamber and protective chamber of the TUT building physical test equipment in a cold room.

The test is controlled by various measurement and control instruments, some of which are inside the chambers and some in a measurement room outside the cold room (Figure 2.3). The measurement, control and calculation procedures under the test are made by computer that runs a control program designed for the test.

The new test equipment was built on the basis of earlier thermal transmittance equipment. The cooling of the cold room and heating of the warm chamber as well as the measurement system were transferred from the thermal transmittance equipment almost as such. The operating principle of the thermal transmittance equipment is presented in references /16/ and /17/.

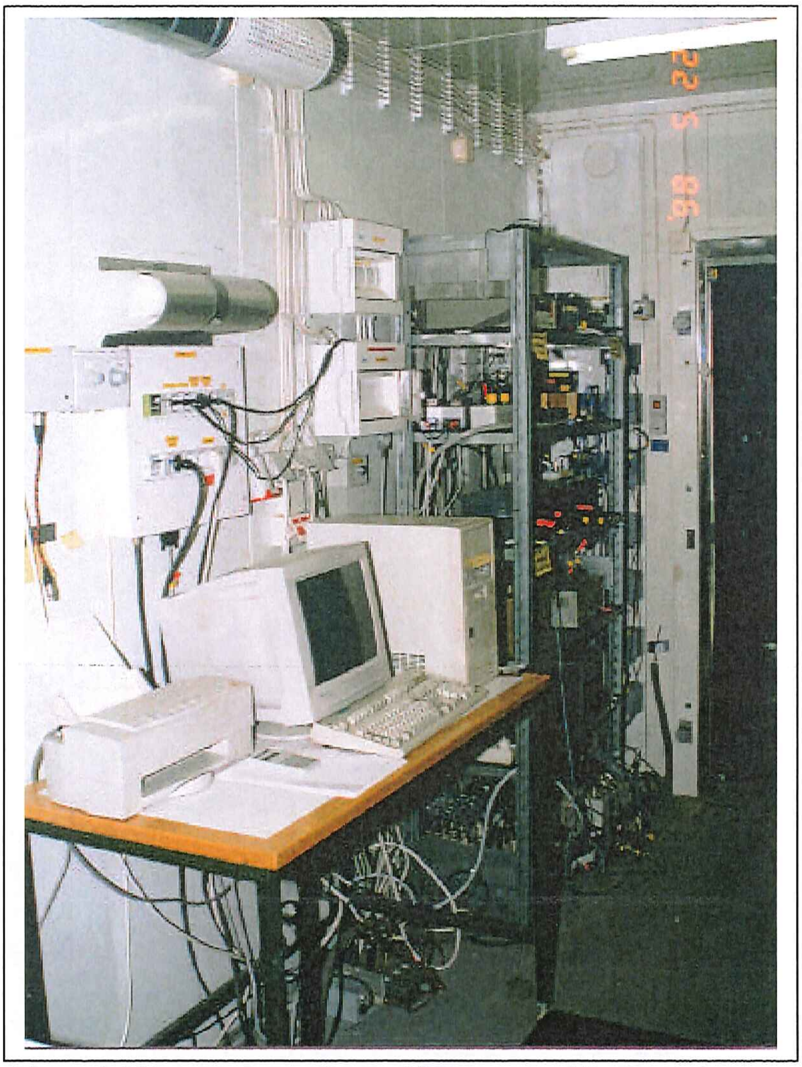


Figure 2.3 Measurement and control instruments of the test equipment.

Cold chamber

The cold room used as the cold chamber is insulated from other premises by polyurethane insulation, and its inside dimensions are: width 2.7 m, length 6.4 m, and height 2.6 m. The inner surfaces of the walls and roof are painted steel sheet. The floor is a surfaced concrete slab, which is equipped with heating cables to prevent freezing. The door of the cold room is an insulated 1300 x 2000 mm^2 door, and the door frames are also equipped with heating elements to prevent freezing. The temperature of the cold room is adjustable within the range +20...-40 °C.

Warm chamber

The outer diameters of the warm chamber are about 1800x1800x1100 mm. The chamber is sized so that it can be turned in the cold room to study roofing deck and base floor structures.

The warm chamber is designed to be as air-tight as possible to allow controlling the pressure difference. For this reason, the interior of the chamber is a cabinet made of 6-mm PVC plastic sheets by welding (front wall thickness is 10 mm). A 150-mm polyurethane insulation surrounds the cabinet (front wall insulation thickness is 400 mm) and the outer surface is made of film coated plywood surfaced with a waterproofing compound. Outside the chamber is a support frame made of aluminium section. To improve tightness, all joints are also sealed with silicone.

The test opening of the warm chamber has an area of 1200 x 1200 mm^2 and a depth of 400 mm. The sides of the test opening are made of plywood laminated on both sides, which has good moisture resistance but relatively low thermal conductivity and thermal expansion factor. The side plywood boards are supported and attached to the plastic cabinet by a wooden frame. The plastic sheets extend over the inner edge of the test opening, providing 25 mm wide flanges for installing the structures to be studied. Sealings made of EPDM cellular rubber are glued to the flanges.

There are eight support points outside the test opening where the tested element is tightened against the inner flanges by eight threaded bars. A steel band with EPDM rubber seals is used in the tightening.

Appendix I shows photographs of the building of the warm chamber.

Protective chamber

In the early stage of the test equipment design, the target value of the relative humidity of outdoor air was set to RH 90 % even at subzero temperatures. However, the relative humidity of refrigerated rooms (such as cold rooms and freezers) is typically about 60...80 %. The low relative humidity is due to the fact that airborne water vapour tends to condense on the cold surfaces of the evaporators. In the test equipment, this problem was solved by using a protective chamber to separate the outdoor air to be controlled from the cold-room air. The walls of the protective chamber are made of thin polycarbonate sheets, which make it possible to control the temperature by changing the temperature of the cold room.

A high outdoor RH is maintained in the protective chamber by forced air circulation. The air circulation is achieved by two fans. There are also heating sheets on the surfaces of the chamber to allow defrosting the surfaces if necessary.

The outer dimensions of the protective chamber are 1800x1800x600 mm. The load-bearing frame of the chamber is made of aluminium angle sections, as in the warm chamber. The protective chamber is sealed against the warm chamber with the same kind of rubber seals as the element to be studied.

Baffles

The baffles on both sides of the tested element are made of aluminium. Their purpose is to protect the element from direct heat radiation, guide air flows and serve as mounting racks for measurement sensors. The reverse sides of the sheets are of reflective aluminium while the surfaces facing the tested element are painted matt black. Both the inner and outer sheet are attached to the warm chamber. The area of the inner sheet is 1000x1000 mm^2 and that of the outer sheet is 1200x1200 mm^2.

Measuring equipment

The building physical test equipment uses the following kinds of measuring equipment.

- temperature sensors
- moisture transmitters
- air flow transmitters
- differential pressure transmitters
- laminar pipes
- load cell
- voltage measuring equipment

In addition, the equipment may be outfitted with wood moisture sensors, heat flow meters and radiation sensors as necessary.

Control equipment

The control equipment can be divided into the following groups:

- heating control equipment
- refrigeration control equipment
- moisture control equipment
- differential pressure control equipment
- air flow control equipment

The control equipment regulate the heating of the interior of the warm chamber, the refrigeration of the cold room, the humidifying of the indoor and outdoor air, the differential pressure across the structure, and the velocity of air flow near the structure to be studied.

Other equipment and accessories

The calibration equipment include calibrating vessels for temperature and moisture sensors, calibration salts for determining relative humidity, and calibration weights for the load cell. In addition, there is also a calibration sheet for calibrating the leakage air quantity, and 7 calibration elements for calibrating the heating power consumption.

The alarm system includes a blinking pilot lamp in the laboratory that lights in case of disturbance in the test. There is also a separate fire alarm in the measurement room. The accessories include a lifting fork to be attached to an overhead travelling crane for installing heavy elements as well as various tools and accessories for installing the element.

2.3 Measurement of conditions

The electronic sensors used for measuring different variables have a constant voltage supply. The sensor uses the supply voltage to generate a voltage corresponding to the measured variable. This sensor output voltage (U_i) can be converted to the measured variable by the following conversion formula:

$$u_\mathrm{i} = kU_\mathrm{i} + b \tag{2.1}$$

where u_i is the value of the variable to be measured. Factors k and b depend on the measurement range of the sensor or transmitter and used output voltage range. The factors for temperature sensors, moisture sensors and load cell are determined by calibration tests made at TUT. The factors for other measurement sensors are given as constants based on the manufacturer's calibration.

Most of the measuring equipment are located in the measurement room in front of the cold room, and only the sensors and sensor cables are led through penetrations to the warm chamber and protective chamber. In the measurement room, the sensors and transmitters are connected to a special measurement channel selection unit and further to a data logger or AD/DA converter.

Temperature measurement

The test equipment measures temperatures using semiconductor sensors whose output voltage varies with temperature. The selected semiconductor sensor was the LM 335 type sensor manufactured by National Semiconductor Corporation. A temperature sensor consists of a semiconductor sensor, sensor shield and a 10-m measurement cable with a terminal. The equipment uses three kinds of sensors, depending on the point from which the temperature is measured (air sensors, surface sensors and metal jacket sensors). Different sensor types are shown in Figure 2.4.

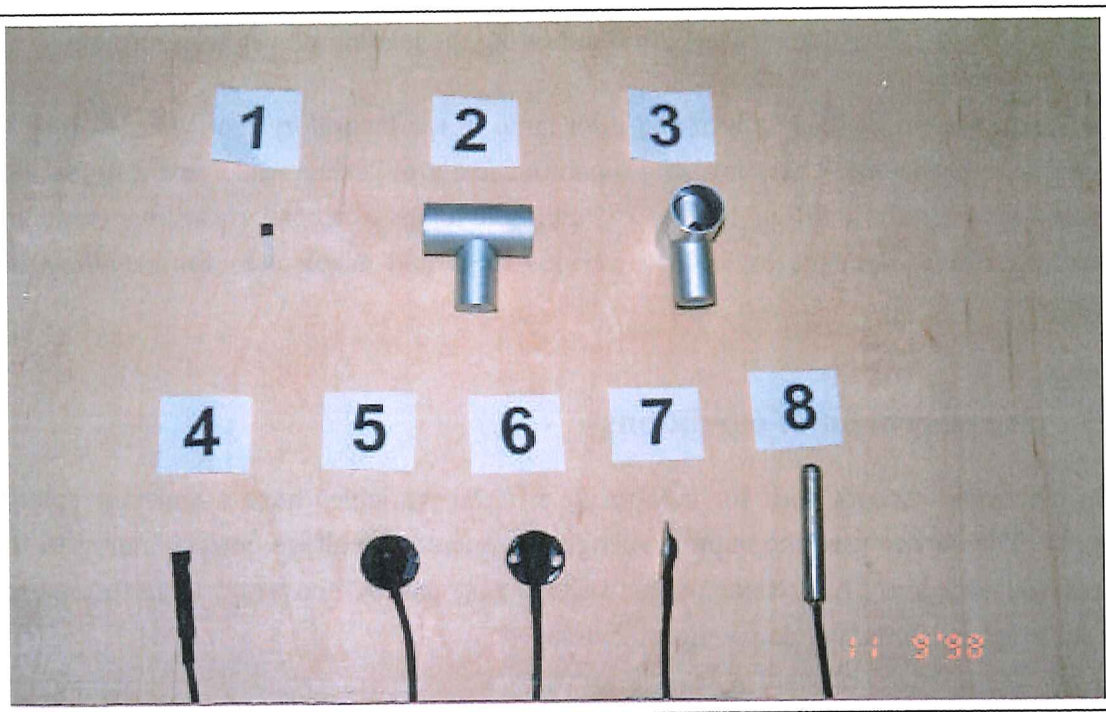


Figure 2.4. Semiconductor sensors used in the equipment. The sensor types listed in numerical order are: 1) semiconductor sensor, 2) and 3) radiation shields of air sensor, 4) air sensor, 5) surface sensor for the structure under study 6) surface sensor for the baffle, 7) surface sensor in side view, and 8) sensor with a metal jacket /17/.

Air sensors are used for measuring air temperatures in the cold room, warm chamber and protective chamber. The sensors are shielded by shrink-on plastic sleeves against humidity in the air. Behind the sensors there are plastic supports that attach the sensors to fibre-glass rods in the baffles. Air sensors are shielded from heat radiation by placing them inside special radiation shields made of aluminium.

Surface sensors are used to measure temperatures from the surfaces of the structure under study and the baffles. A thin aluminium sheet with high thermal conductivity is glued to the bottom of the sensors, which ensures that the sensor temperature will be as close to the surface temperature as possible. The sensors are shielded from the effects of humidity by a chemical metal compound and painted matt black to make their radiation properties match the properties of the mounting surfaces. The aluminium sheets of the sensors to be mounted on the baffles have holes for mounting screws.

Metal jacket sensors are used for measuring temperatures inside the structure under study. They are also used, for example, for monitoring the temperatures of the water vessels used for humidifying air. The sensors are shielded with a stainless steel jacket. Due to the heavy casing the sensor reacts slowly to instantaneous temperature changes. On the other hand, metal jacket sensors resist moisture and mechanical and chemical loads better than other sensor types.

Measuring relative humidity

Relative humidity is measured by HMP 230 series humidity transmitters manufactured by Vaisala Ltd.. The humidity transmitter consists of a sensor part that is connected to the electronics in the measurement room by a 10-m cable. The transmitter's measurement sensor is a capacitive humidity sensor that measures dielectric changes in a medium as a function of humidity.

Relative humidity is measured, for instance, from between the structure under study and the baffle, from the ventilation gap behind the shell and from the insulation space of the structure. Different filters are used at the ends of the humidity sensors depending on whether they are used to measure humidity from air or the porous space in the structure.

Measurement of air flow velocity

The air flow velocity is measured by AFT-1D type air flow transmitters manufactured by Envic Ltd.. The air flow transmitter consists of a sensor part that is connected to the electronics in the measurement room by a 10-m cable. The measurement sensor of the transmitter is a hot-wire anemometer. A hot-wire anemometer measures flow velocity by monitoring changes in heat transfer in a sensor heated by electric current. The sensors measure the highest velocity of air flow irrespective of the direction of the flow. The sensors are small-sized and have a high frequency response, which allows measuring even turbulent flow.

In the test, flow velocity is measured from between the structure under study and the baffle and from the ventilation gap behind the external cladding. The sensors are placed in the centre of the structure in the cross direction.

Measurement of differential pressure

The pressure difference across the structure is measured by FCO 16 type differential pressure transmitters manufactured by Furness Control Ltd. In a differential pressure transmitter gas pressure is converted into mechanical movement, which in turn generates an electrical reading /3/.

Besides the differential pressure transmitter itself, the measurement of pressure difference requires two 10-m plastic hoses with one end connected to the transmitter. The other ends of the hoses are led to opposite sides of the structure under study and shielded with similar shields as air sensors. The shields are equipped with foam plastic filters to even out pressure fluctuations.

Measurement of the air flow rate

The differential pressure transmitter can also be used for measuring the air flow rate if the free ends of the hoses are connected to a laminar pipe. The laminar pipe narrows in the middle, which causes a pressure difference at the ends when air flows through the pipe. The pressure difference corresponds to the air flow rate through the laminar pipe and it can be measured with a differential pressure transmitter. The size of the laminar pipes is varied according to the required laminar flow. At the moment, the test equipment uses laminar pipes manufactured by Furness Control Ltd for 0.02, 0.2, 2.0 and 30 l/min volume flows.

Measuring the weight of the inner evaporation vessel

An electric load cell is used for measuring water evaporation from the vessel used for humidifying the indoor air. The humidifying vessel is suspended from a steel rod whose elongation is directly proportional to the weight of the water vessel. The elongation is measured with wire strain gauges. The change of the weight of the water vessel is needed in calculating amount of humidity fed into the warm chamber.

Voltage measurement

Voltages can be measured in the test by two parallel methods. In the first method, the voltage signals of the measurement channels are sent to the data logger, through which the voltmeter measures each signal in desired order. The second method uses an AD/DA converter card inside the computer to digitalize the analog voltage signals, and the computer converts them back to analog voltage values. The building physical test equipment uses mostly a voltmeter and data logger for measuring the channels. The voltmeter is the HP 34401A Multimeter manufactured by Hewlett Packard.

In measuring heating power, the voltmeter is also used for measuring the electric current as a voltage. This requires a current/voltage converter that uses an electric resistor to convert the current of the power supply circuit to a voltage. The computer uses a conversion formula to reconvert the voltage reading to a current reading.

2.4 Controlling the environmental conditions

The test equipment uses a separate control system to control each environmental factor individually. The controlled variables are indoor and outdoor temperatures, relative humidity levels of indoor and outdoor air, and differential pressure across the structure under study. In addition, the velocity of air flow on the surfaces of the structure and the difference between the cold room temperature and the outdoor temperature are controlled to maintain a constant outdoor temperature. The operation of the control systems is discussed in more detail in references /15/ and /17/.

All environmental factors are controlled by the same kind of formula:

$$a_{new} = a_{prev} + k_1 \,(u_{tar} - u_{meas}) + k_2 \,(u_{meas,prev} - u_{meas}) \tag{2.2}$$

where u_{tar} is the desired value of the controlled variable, $u_{meas,prev}$ is the previous measured value of the variable and u_{meas} is the new measured value. k_1 and k_2 are the control factors of the formula. a_{new} is the new control value of the auxiliary variable used for controlling the condition, and a_{prev} is the previous control value of the auxiliary variable.

The auxiliary variable used in the test equipment is usually the time (t) for which the control device is on during the control period. However, in controlling indoor temperature the auxiliary variable is heating power (P).

The first term of the control formula indicates the current control situation, the second term the difference between the controlled variable and the target value and the third term the direction of change of the variable. Control factors can be selected freely, and they affect the efficiency and speed of control.

Indoor temperature control

The indoor temperature of the warm chamber is controlled by a heater. A certain heating power is required to maintain the temperature of the warm chamber higher than the outdoor temperature. The heating of the warm chamber is implemented using the same principle and mainly the same equipment as in the thermal transmission equipment /17/.

The heater consists of different heating elements and an internal fan. A certain amount of power is supplied to the elements to attain the desired indoor air temperature. The heating power control has two stages so that the basic level of the supplied power is obtained from a stepped additional voltage supply and fine tuning is by a stepless voltage supply. The heating power generated by the internal fan and internal humidifier are also taken into account in controlling the heating power.

Outdoor temperature control

The refrigeration of the cold room uses the same principle and same equipment as the thermal transmittance equipment /17/. The cold room is refrigerated by two cooling compressors that are installed in a separate compressor room beside the cold room. The compressor circuits include the evaporators in the cold room and the condensers on the roof. Air circulation in the cold room is provided by six fans placed in front of the evaporators. The cooling equipment is controlled by control relays connected to a computer that switch cooling power on and then off after the desired time interval.

The temperature in the protective chamber is always somewhat higher than in the cold room. For this reason, the temperature difference between the protective chamber and the cold room is controlled to maintain the desired outdoor air temperature in the protective chamber.

Control of relative humidity

The indoor and outdoor air humidity levels are controlled by electric heating elements in water vessels. The elements heat the water in the vessel, which evaporates into the ambient air. The fans in the warm chamber and protective chamber circulate the air distribute the humidity evenly. Humidifying is controlled by control relays connected to a computer that switch the elements on and then of after the desired interval. The amount of humidity brought in or led out through the air hose is also taken into account in controlling the humidity of the warm chamber.

In the warm chamber humidifying is also controlled by changing the aperture of the water vessel by an electric shutter. This is necessary particularly when the required humidity level is low. Otherwise, the indoor air humidity would rise too high, because the warm chamber has no drying system.

The water vessel of the protective chamber must be properly insulated to avoid wasting the power of the heating element. Moreover, too hot water evaporates rapidly into the protective chamber, and the excess humidity condenses on the inner surfaces of the chamber, which hampers temperature and humidity control.

Control of differential pressure

The differential pressure between the inner and outer chamber is controlled by air pumps. The air hose is connected to the inlet or outlet of the pump, depending on whether the warm chamber should have overpressure or underpressure. The size of air pumps is varied according to the required air flow rate. At the moment, the test equipment uses air pumps with maximum outputs of 4.0, 8.0 and 20 l/min. At low values of volume flow, an additional reduction in the flow is achieved by a throttle in the air hose. The fine tuning of differential pressure takes place by a control relay connected to a computer that switches the pump on and then off after the desired interval.

To attain as even and laminar air flow in the air hose as possible, the switching frequency of the pump is very high. To even out the flow further, an expansion chamber with a filter is connected to the air hose.

Differential pressure differs from the other controlled conditions in that it changes very rapidly. Differential pressure depends strongly on the temperature, thus achieving a steady pressure control requires accurate temperature control. With impermeable test elements, the difference in temperatures on opposite sides of the element may cause high differential pressures. For this reason, the warm chamber has a pressure relief pipe with a magnetic valve. The valve opens if differential pressure exceeds a preset value.

Control of velocity of air flow

The heater has a fan that conveys the heat generated by the heating elements to the indoor air. The fan's speed of rotation can be controlled by varying the supply voltage. However, irrespective of the fan speed the air flow remains within the range of natural convection near the inner surface of the structure under study.

The fans in front of the evaporators produce desired velocity of air flow in the cold room. Fan speed is controlled by a computer through a frequency inverter, which changes the frequency of the fan's supply voltage.

In the protective chamber the velocity of air flow is controlled by two fans. The fans are located in the lower and upper half of the protective chamber, and they are connected to pipes that control the circulation of air in the protective chamber. The fans are controlled by varying their supply voltage.

2.5 Control program

The task of the control program is to measure the conditions of the indoor and outdoor air during the test and bring them to the target values as quickly as possible. The test is controlled by software called CLIMATE, whose operating principle is shown in Figure 2.5. The software consists of input files, the actual measurement and control program, and output files. The program was written in Quick Basic version 4.5. The operating system is DOS 6.22.

The program was designed to be user-friendly and allow monitoring during the test and modification of test arrangements. The measurement arrangements, control conditions and calculated variables can be changed freely by entering new data in the input files either before or during the test. Various monitoring pages, in turn, allow monitoring changes during the test.

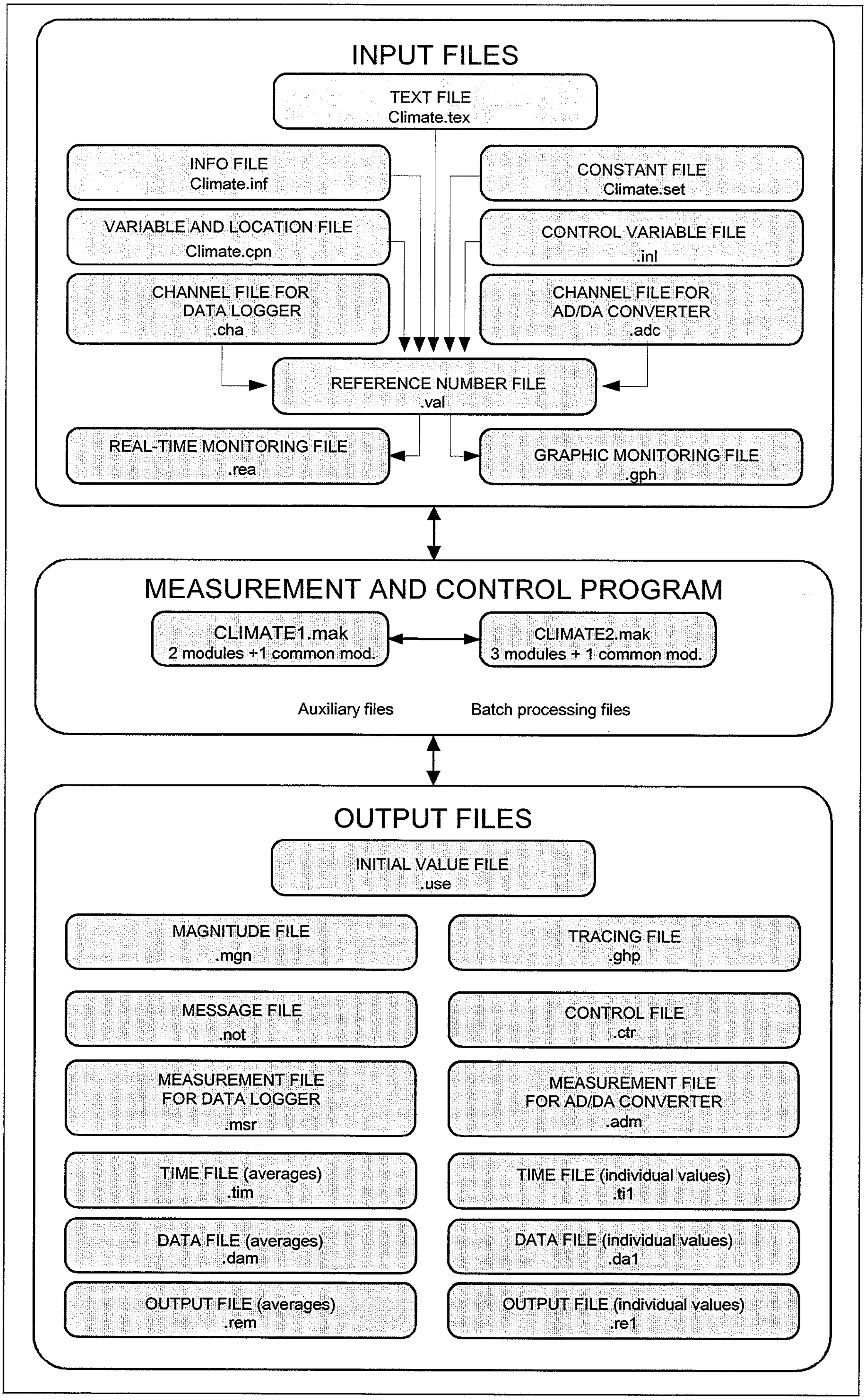


Figure 2.5. Operation of the CLIMATE control program.

Before starting the test, the *input files* (10) of the control program are prepared by entering data on the measurement arrangements, channels, variables to be measured, calibration factors of measurement sensors, test conditions, properties of the tested element, and the measurement values to be monitored during the test. The input files are also divided into constant input files and variable input files. The four constant input files are not usually changed at the beginning of a new test. The six variable input files are always edited at the beginning of a new test, and they are named according to the test under way. The variable input files also contain the initial data needed for monitoring during the test. In practice, all variables to be measured and calculated during the test are entered in these files. All input files must be ready before starting the test.

The *measurement and control* software consists of two programs: CLIMATE1.mak and CLIMATE2.mak, which are divided into a total of 7 modules. Both programs contain the main program section and a great number of various subroutines. In addition, the measurement and control program uses a number of so-called temporary files and batch files.

At the beginning of a test, CLIMATE1.mak runs various checks, creates the required initial files and reads the initial data recorded for the test to virtual memory. CLIMATE2.mak runs various initialization routines, after which it performs the following measurement and control procedures at regular intervals based on the initial data:

- measures the voltage readings of channels and converts them to measured variables
- controls test conditions on the basis of the measurement results
- using the measurement results, calculates a number of values for the structure under study
- stores the measured, calculated and control values in output files
- outputs measured, calculated and control values to the display during the test

The progress of the test is monitored using various graphic and numerical monitoring pages. Real-time monitoring pages display the newest measured, calculated and control values in numerical form. They also show changes in the values from previous values. The advantage of real-time monitoring pages is that one page can show a great number of different values simultaneously. Graphic monitoring pages, in turn, show changes in the measured variables for the desired period using the desired scaling. One graph can show up to 5 measured variables, and the number of graph pages is unlimited. For each graph page there is also a numerical monitoring page that shows the exact values used for plotting the graphs. The channel monitoring pages show the newest measured values of the channels measured through the data logger and the AD/DA converter in numerical order. Besides these pages there are also other pages used for monitoring and controlling the test.

There are 13 *output files* which are used to store the measured, calculated and control values during the test. The initial value file stores the values of the control value file set at the beginning of the test. The serial numbers of variables measured several times a minute are output to the variable file while the page numbers of the graphic monitoring pages for the variables measured and calculated in the test are output to the monitoring file. The message file is used to store changes in the control values made during the test and various error messages. Measurement files store the measuring order of channels in the test. The control file is used to store control events that take place during the test, and the time files store the times of each measurement cycle. Data files store the output voltages read from different measurement channels during the test, and the output files store the variables calculated from the readings.

After the test the output files are processed to be compatible with the Excel spreadsheet software by a special editing program. The editing program also allows dividing the output files into desired parts and compacting them.

The control program includes various checks and limits that steer the control systems of the test. The greatest risk to the progress of the test is probably power failures due to various reasons. To eliminate their effect, the control software has an automatic power-up system that reboots the computer after a power failure and restarts the measurement and control systems. The computer always memorizes the newest control values and restarts control with these values after a power failure. This way, at least the disturbances caused by short power failures can be eliminated rather well.

2.6 Measured and calculated values from the test

Measured values

Examples of variables to be measured during the test are:

- indoor and outdoor temperatures, and temperatures in the structure and on the surfaces T (ºC)
- relative humidity of indoor air, outdoor air and air in the porous space of the structure ϕ (%)
- differential pressure across the structure at the upper and lower section of the tested element Δp_{str} (Pa)
- humidity by volume indoors, outdoors and in the porous space of the structure v (g/m^3)
- velocity of air flow indoors, outdoors and in the ventilation gap r (m/s)
- total air flow rate to and from the warm chamber R_{tot} (l/min)
- total moisture flow rate from the warm chamber G_{tot} (g/day)
- total heat flow rate rate out of the warm chamber Φ_{tot} (W)

In addition, samples taken from the structure yield the following data:

- moisture content of building materials u (%)
- amount of moisture in building materials m (g)
- condensation rate behind the windshield

Calculated values

The measured variables can be used for calculating various other values for the structure using the following formulas:

- *Air flow rate through the structure* R_{str} (l/min)

$$R_{\text{str}} = R_{\text{tot}} - R_{\text{h}} \tag{2.3}$$

where R_{h} is the amount of leakage air from the warm chamber.

- *Density of air flow rate through the structure* r_{str} (l/m^2·min)

$$r_{\text{str}} = \frac{R_{\text{str}}}{A_{\text{str}}} \tag{2.4}$$

where A_{str} is the effective area of the test opening (1150x1150 mm^2).

- *Velocity of air flow through the structure* r_{vel} (m/s)

$$r_{\text{vel}} = \frac{1}{60000} \frac{R_{\text{str}}}{A_{\text{str}}} \tag{2.5}$$

- *Air permeance for the structure* K_{str} (m/s·Pa)

$$K_{\text{str}} = \frac{1}{60000} \frac{R_{\text{str}}}{A_{\text{str}} \Delta p_{\text{str}}} \tag{2.6}$$

- *Air permeability of the entire structure or material* l_{str} (m^2/s·Pa)

$$\ell_{\text{str}} = \frac{1}{60000} \frac{R_{\text{str}} d_{\text{str}}}{A_{\text{str}} \Delta p_{\text{str}}} \tag{2.7}$$

where d_{str} is the thickness of the structure.

The air permeability of individual materials can be measured by placing a specimen of this material in the test opening.

- *Moisture flow rate into the structure* G_{str} (g/day)

$$G_{str} = G_{tot} - G_l \tag{2.8}$$

where G_l is the amount of moisture leak from the warm chamber.

- *Density of moisture flow rate into the structure* g_{str} (g/m^3·day)

$$g_{str} = \frac{G_{str}}{A_{str}} \tag{2.9}$$

- *Moisture flow rate to the structure by convection* G_{conv} (g/day)

$$G_{conv} = \frac{1440}{1000} v_i R_{str} \quad or \quad G_{conv} = \frac{1440}{1000} v_o R_{str} \tag{2.10}$$

where v_i and v_o are the humidity by volume of indoor and outdoor air. Either indoor or outdoor air humidities by volume are used in the calculation, depending on the direction of the differential pressure.

- *Density of moisture flow rate to the structure by convection* g_{conv} (g/m^2·day)

$$g_{conv} = \frac{G_{conv}}{A_{str}} \tag{2.11}$$

- *Moisture flow rate to the structure by diffusion* G_{dif} (g/day)

$$G_{dif} = G_{str} - G_{conv} \tag{2.12}$$

In underpressure test the formula gives the minimum of diffusion value.

- *Density of moisture flow rate to the structure by diffusion* g_{dif} (g/m^2·day)

$$g_{dif} = \frac{G_{dif}}{A_{str}} \tag{2.13}$$

- *Water vapour permeance of the tested structure* $W_{v,str}$ (m/s)

$$W_{v,str} = \frac{1}{86400} \frac{G_{dif}}{(v_s - v_u) A_{str}} \tag{2.14}$$

- *Water vapour permeability of the entire structure or material* $\delta_{v,str}$ (m^2/s)

$$\delta_{v,str} = \frac{1}{86400} \frac{G_{dif} d_{str}}{(v_s - v_u) A_{str}} \tag{2.15}$$

The water vapour permeability of individual materials can be measured by placing a specimen made of this material in the test opening.

- *Heat flow rate through the structure* Φ_{str} (W)

$$\Phi_{str} = \Phi_{tot} - \Phi_h \tag{2.16}$$

where Φ_h is the heat flow rate through the warm chamber.

- *Density of heat flow rate through the structure* q_{str} (W/m^2)

$$q_{str} = \frac{\Phi_{str}}{A_{str2}} \tag{2.17}$$

where A_{str2} is the area of the structure under study.

- *Thermal transmittance of the structure* U_{str} ($W/m^2 \cdot K$)

$$U_{str} = \frac{\Phi_{str}}{A_{str2}(T_i - T_o)} \tag{2.18}$$

where T_i and T_o are indoor and outdoor air temperatures.

- *Thermal conductivity of the entire structure or material* λ_{str} (W/m·K)

$$\lambda_{str} = \frac{d_{str} \Phi_{str}}{A_{str2}(T_{is} - T_{os})} \tag{2.19}$$

where T_{is} and T_{os} are the temperatures of the inner and outer surfaces of the structure.

The thermal conductivity of individual materials can be measured by placing a specimen made of this material in the test opening.

The condition test also tells if the structure has temperatures and RH conditions favourable to the growth of mould. The mould risk can be estimated on the basis of the curves of Figure 2.6 /14/.

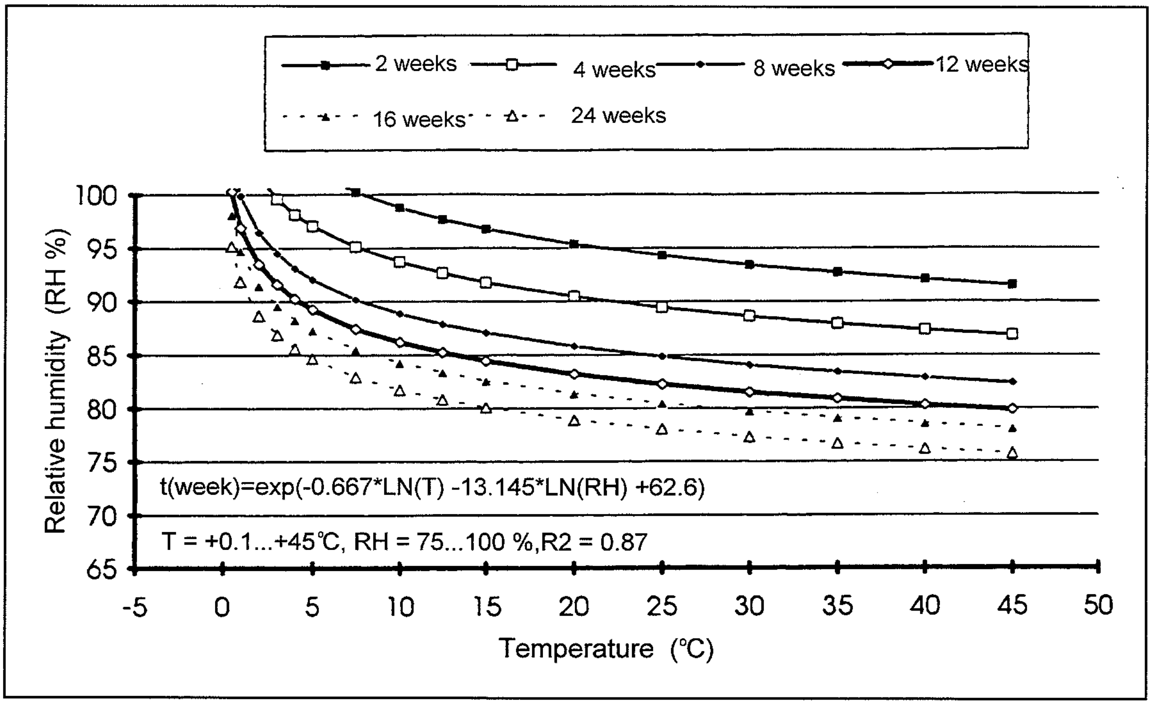


Figure 2.6. The critical durations of action of moisture and temperature for mould growth (level 1, microscopically detectable growth) /14/.

2.7 Calibration and measurement uncertainty of the equipment

Calibration of the measurement sensors and the warm chamber

Temperature sensors are calibrated in a special calibration vessel, where about 70 temperature sensors can be calibrated at a time. Calibration of temperature sensors takes place also in the cold room, and measurements are made using the same equipment as in the actual test. A glass tube thermometer placed in the vessel with the sensors is used as a reference in the calibration. The vessel also has a fan that circulates the air in it to create an even temperature distribution.

There are separate calibration vessels for the calibration of the humidity sensors where about 5 humidity sensors can be calibrated at a time. Humidity sensors are calibrated using saturated solutions of salt that produce certain RH levels in the ambient air. There are two solutions: one produces a high RH and the other a low RH. Calibration takes place using the same equipment as in the actual test.

The load cell is calibrated using different reference weights, whose masses have been determined by an electronic scale. Calibration takes place using the same equipment as in the actual test.

Other measurement sensors and equipment (air flow transmitters, differential pressure transmitters, laminar pipes, and voltmeter) are calibrated either by the manufacturer or an authorized calibration service.

The amount of leakage air from the warm chamber is calibrated by placing a calibration sheet in the test opening and measuring the air flow rate into or from the warm chamber under various differential pressure conditions. The calibration sheet has an area of 1190x1190 mm^2, and it is impermeable to air. The calibration sheet is made of plywood with a steel sheet glued to the inner surface.

The thermal energy consumption of the warm chamber is calibrated by placing calibration elements of different thicknesses and known thermal conductivity in the test opening. Elements with different thicknesses are needed because the share of the heat flow rate transmitted through the perimeter of the test opening changes when element thickness changes /12/. There are 7 calibration elements; their area is 1190 x 1190 mm^2 and their thicknesses are 20 mm, 50 mm, 100 mm, 150 mm, 200 mm, 250 mm and 300 mm. The elements are made of S 25 class polystyrene sheets (EPS) and surfaced with matt black plastic film. The thermal conductivity of EPS sheets was determined at VTT.

Measurement uncertainty of the equipment

The measurement measurement uncertainty and calculation results is determined using the formula presented in reference /2/. The measurement uncertainty of some measured variables was determined on the basis of the manufacturer's calibration.

The uncertainties of the variables measured and calculated in the building physical condition test were as follows:

- individual temperatures ± 0.4 °C
- average temperatures ± 0.2 °C
- relative humidity ± 2.0 RH %
- humidity by volume ± 0.05...0.5 g/m^3 (-20...+20 °C)
- differential pressure across the structure ± 1.0 Pa
- velocity of air flow ± 0.1 m/s
- air flow rate ± 0.1 l/min
- moisture flow rate ± 5.0 g/day
- total heating power ± 0.1 W
- moisture content of materials ± 1.0 wt %

In some tests the uncertainty of differential pressure was about ±2 Pa.

The uncertainty of structural properties (K, W_v, and U) and material properties (ℓ, δ_v and λ) is usually about ±5 % of the result at a safety factor of 2, if only one variable (differential pressure, difference in humidity by volume, or temperature difference) is changed at a time. In the building physical condition test the uncertainty of the results is higher because all condition variables can be changed at the same time.

2.8 Properties of the equipment

The TUT building physical condition test equipment has many properties that together make it an accurate, effective and versatile test apparatus. Examples of these properties are:

- all indoor and outdoor air conditions can be controlled simultaneously during tests
- structures can be tested in real-life indoor and outdoor air conditions (e.g. true RH of outdoor air can be produced also under freezing conditions)
- all controllable condition variables can be set freely within the control range
- all measurements and adjustments are automatic and quick as they are computer-controlled
- In the test, the moisture flows into the structure by diffusion and convection can be measured separately
- structures can be tested under constant conditions or conditions may be changed cyclically
- as a result of the airtightness of the equipment and the installation technique of the element, the air flow through the tested structure is controlled
- the test opening is large (area: 1200x1200 mm^2, depth: 400 mm) which means that the same phenomena occur in the tested structure as in actual structures (e.g. convection inside structure)
- the control and measurement systems of the equipment can be augmented or changed as needed
- the equipment may be rotated as needed so that wall, roofing deck and base floor structures can be tested in the proper position
- the control and measurement systems developed in connection with the building of the equipment can also be used in other laboratory tests

Control ranges of conditions

The following rough control ranges can be specified for the controlled variables:

- indoor temperature 0...+60 °C
- outdoor temperature -40...+20 °C
- indoor humidity 20...80 % RH
- outdoor humidity 50...95 % RH

- differential pressure -50...+50 Pa

The control range of an individual condition varies somewhat depending on what other condition variables are selected and what their properties are. Especially the control range of differential pressure varies considerably with the impermeability of the structure. For instance, when testing insulation boards made of mineral wool or cellulose alone, virtually no differential pressure can be achieved, because the power of the air pumps has not been dimensioned with a view to materials with such high permeability.

3 Tests performed with the equipment

Tests on timber-framed wall structures using the new equipment started in the autumn of 1997. The purpose of these tests was to determine the usefulness of a vapour barrier in wall structures and the effect of differential pressure on the moisture behaviour of the structure. The study focused on two wall structure types: a cellulose insulated wall without moisture barrier and mineral wool insulated wall with a vapour barrier.

A full condition test was run on eight different wall structures. The tests were carried out between 9/1997 and 12/1998. Measurements, controls and test durations varied somewhat as the research team gained knowledge and experiences from the operation of the equipment. However, the target condition control values were attained very quickly, so the moisture behaviours of the wall structures could be compared reliably.

3.1 Building of the test elements

The tested wall structures were assembled in frames made of 9-mm film coated plywood to eliminate air and moisture losses. The size of the frames was 1185 x 1185 mm^2 and their thickness was 176 or 224 mm, depending on the tested wall type. A 31 mm wide bracing was placed in the centre of the tested element and the edges were lined with 18 mm wide mixed plywood sheets. On both sides of the bracing there were 550 mm wide insulation spaces (Figure 3.1).

The elements were usually assembled so that first the inner sheet with the air/vapour barrier was installed on the inner edge of the frame. After this the heat insulation materials and the windshield were installed. The inner sheet, the air/vapour barrier and the windshield were sealed to the rabbets of the frame with silicone. All materials installed in the tested elements were also weighed before the test.

At the beginning of the test, the insulation materials and windshields were either dry (RH 35 %, RH 55 %) or damp (RH 85 %). Some of the tested walls had holes in the air/vapour barrier and inner sheet and a joint at the bracing. The inner surfaces of the structures were unsurfaced. In addition, 22-mm horizontal paneling was used as external cladding in all tests, which was attached to the bracing with screws.

Appendix II shows photographs of the production of the test element.

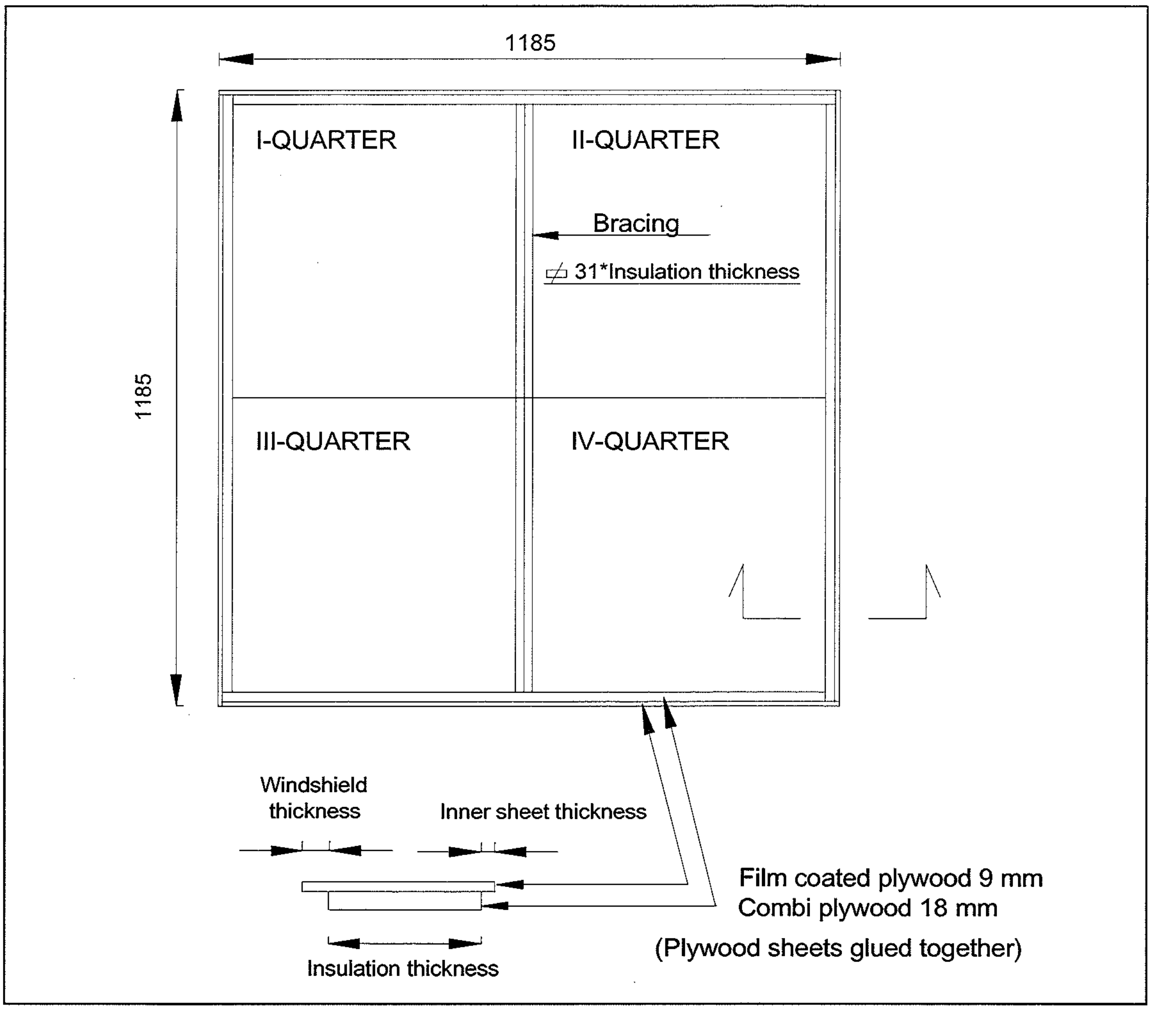


Figure 3.1. Structure of the tested elements

3.2 Location of measurement sensors

Different temperature sensors were used in the tests as follows:

- 5 surface sensors in the inner baffle
- 5 air sensors inside
- 5 surface sensors on the outer surface of the windshield
- 5 surface sensors on the inner surface of the external cladding
- 5 surface sensors on the outer surface of the external cladding
- 5 air sensors outside
- 5 surface sensors on the outer baffle
- 5-6 metal jacket sensors in the structure
- 5 air sensors in the cold room
- 2 metal jacket sensors in the humidifying vessels

Surface sensors were located in the tested element so that each corner had one sensor and one sensor was placed in the middle. The sensors in the corners were attached at a distance of 150 mm from the sides of the tested element. Air sensors and surface sensors of the baffles were placed in corresponding locations outside the tested element. Air sensors were located between the baffles and the element surfaces at a distance of 150 mm from either surface. The temperature sensors installed inside the structure were usually placed beside the bracing or near the edges of the element.

Other measurement sensors and equipment were used as follows:

- number of air flow sensors inside, outside and in the ventilation gap: 3
- number of humidity sensors inside, outside, in the cold room and the pressure equalization chamber: 4
- number of humidity sensors + temperature sensors inside the structure: 7 – 8
- differential pressure transmitters to measure the pressure difference across the structure: 1 – 3
- differential pressure transmitter for measuring the volume flow of the air hose: 1
- laminar pipes for measuring the volume flow of the air hose: 4
- load cell for measuring the weight of the inner humidifier: 1

Humidity sensors (Vaisala HMP 233) were placed inside the structure to measure both temperature and relative humidity (RH). The sensors were generally placed beside the inner sheet and the windshield in the insulation space of the structure. Air flow and humidity sensors were placed in the ventilation gap in the middle of the tested element. The indoor and outdoor air flow and humidity sensors were located between the baffle and the element surfaces at a distance of 150 mm from either surface. Viewed from the front, these sensors were also located in the centre of the structure.

The measurement sensors were installed inside the structure before attaching the windshield. The sensor cables were led through the windshield and the holes were sealed with silicone. Thus, the assembly of the tested element and the installation of the sensors were simultaneous.

Appendix V shows the exact locations of the sensors in the tested elements in each test.

3.3 Installation of the tested element

Before installing the element to be tested, the inner baffle was placed inside the warm chamber, and the measurement sensors needed in the test were mounted on it. The indoor air humidifying vessel was also filled with water and its aperture was set to a suitable size.

Before installation the entire element was weighed. After weighing, the element was lifted into the test opening and centred with it. The element to be tested was sealed to the edge of the test opening by filling the installation gap with polypropylene insulation and sealing the outer edges of the gap with duct tape. The insulation was placed evenly in the installation gap to prevent harmful convection flows. After this the tested element was tightened to the flanges of the test opening with a metal band. Finally, the external cladding was mounted on the outer surface of the element.

The outer baffle with its sensors was mounted outside the warm chamber. The humidifying vessel in the protective chamber was filled with warm water, and the protective chamber was moved beside the warm chamber. Figure 3.2. shows the test arrangement for the wall structures tested in the building physical test equipment.

Appendix III shows photographs of the installation of the tested elements in the test opening of the Warm chamber.

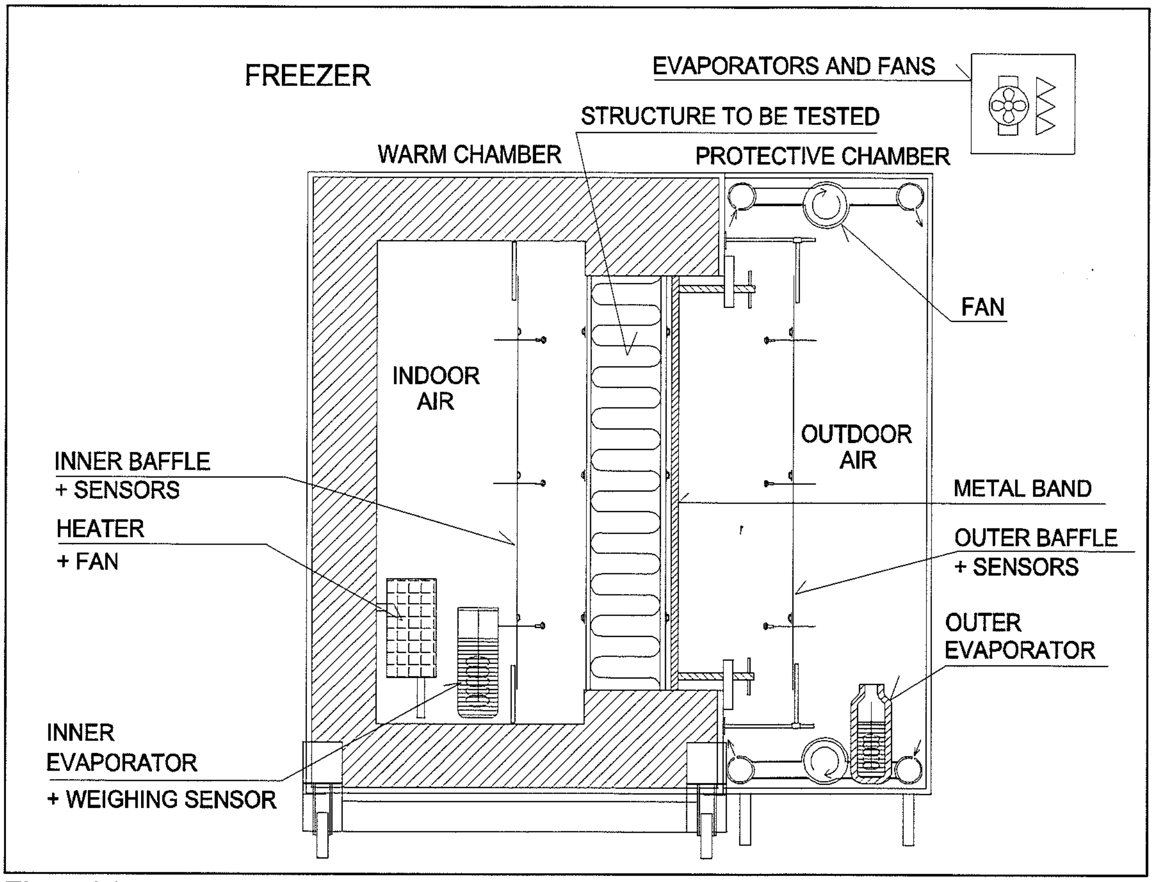


Figure 3.2. Test arrangement for the tests on wall structures in the building physical test equipment.

3.4 Test conditions

The target values of the controllable conditions were the same in all tests: indoor air temperature +20 °C and relative humidity 50 % RH (recommended indoor conditions), outdoor air temperature -10 °C and relative humidity 90 % RH. Winter conditions were selected as the outdoor air conditions, because the need of a vapour barrier is greater in winter.

Wall structures were studied in three different pressure difference situations. In the first period the differential pressure across the structure was –10 Pa (overpressure inside), in the second period it was 0 Pa, and in the third period +10 Pa (underpressure inside) (Figure 3.3). The duration of each pressure difference period was about 9 days, thus the overall test duration was mainly 27 days. Only test wall 7 had a clearly shorter test period (about 9 days) because the moisture behaviour of this structure could be determined in a clearly shorter time. The exact duration of each test is presented in Appendix VI.

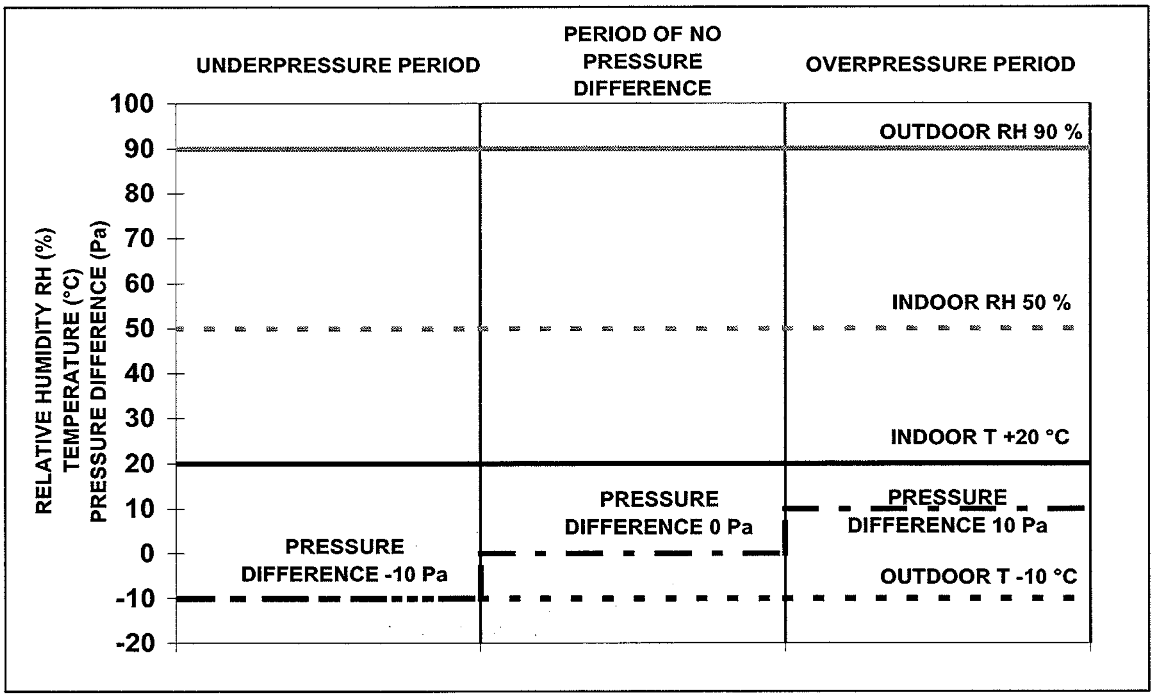


Figure 3.3. Principle of the test and set target values.

3.5 Taking of structure samples and visual observations

In the beginning of the test and after each pressure difference period samples were taken from the windshield and the insulation layer behind it. Behind the windshield there were also thin (40 mm x 40 mm x 2 mm) pieces made of pine, which were changed in connection with taking samples of the structure. For the taking of the samples and installation of the pieces of wood, Ø 75 mm holes were drilled in the outer sheet.

The holes were sealed with plugs as shown in Figure 3.4. The plugs were made of the same material as the windshield, so they did not change the airtightness of the structure in the sampling point. Three pieces of wood were placed in each of the two sampling holes. The locations of the sampling holes are shown in Appendix V.

The moisture contents of the samples were determined by the weighing-drying-weighing method. The results were compared with the humidity values read from RH sensors. In connection with the sampling, visual observations were made to determine possible icing behind the windshield, which would indicate condensation in the structure.

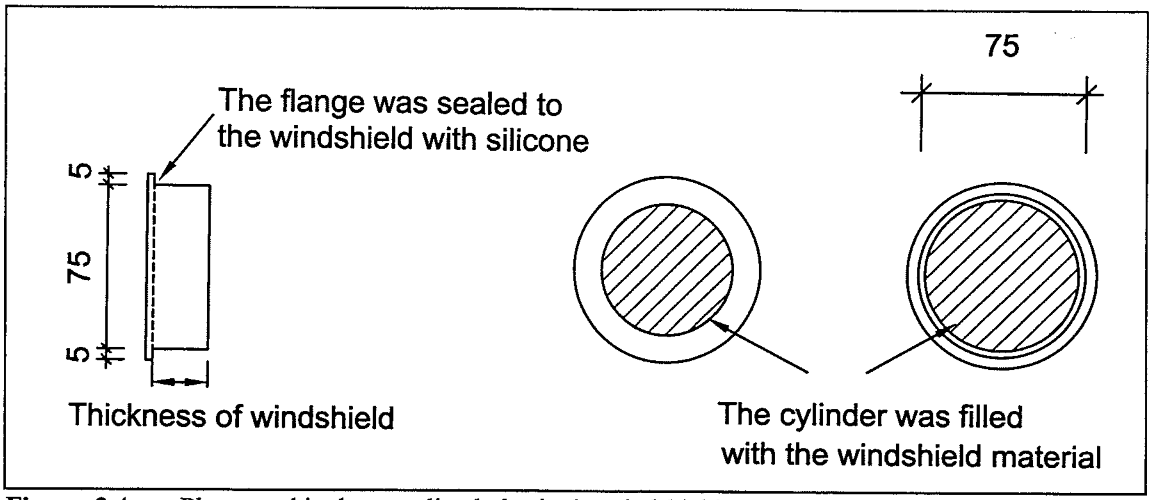


Figure. 3.4. Plugs used in the sampling holes in the windshield.

After the test, the tested element was weighed, after which the materials of the element were weighed separately. The sensor cables in the structure and the freezing of the insulation to the windshield in some structures created problems in weighing. Therefore, the results of the weighing of the element and the materials are only suggestive.

3.6. Tested wall structures

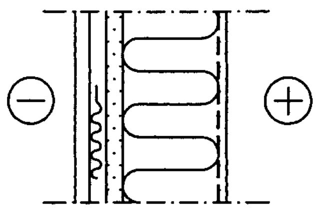
The structure sections of the tested eight wall structures are shown in Figure 3.5 (see also Appendix V).

The original humidity levels of the insulation materials and windshields of test walls 1, 3, 5 and 7 were RH 35 %, in test walls 2 and 4 RH 85 %, and in test walls 6 and 8 RH 55 %. The inner sheets had always the same original humidity (RH about 30...40 %). Here, original humidity refers to the relative humidity of the air in the pores of the material.

Three 3.5-mm holes were drilled to the left of the bracing in test walls 2, 4 and 6; the holes extended through the inner sheet and the air/vapour barrier. Corresponding holes were drilled to the right of the bracing, but they extended only through the air/vapour barrier. These test walls also had a joint of the inner sheet and air/vapour barrier at the bracing. Filler was applied to the joint of the inner sheet and an overlap of 200 mm was used in the air/vapour barrier, but the joints were not taped. In test wall 8, holes were drilled only to the left of the bracing: 6 holes with a diameter of 5.0 mm, which extended through both the inner sheet and the air barrier. Other test walls were not perforated.

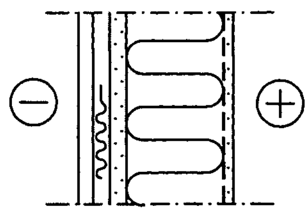
The location of the holes in the test element is shown in more detail in Appendix V.

TEST WALLS 1 AND 2



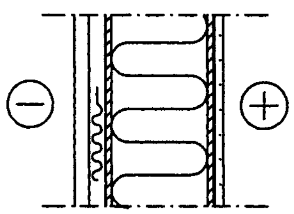
External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (25 mm)
Cellulose-insulation (145 mm)
Bitumen paper
Gypsum board (13 mm)

TEST WALLS 3 AND 4



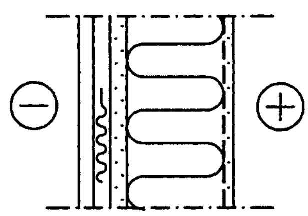
External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Hard mineral wool (30 mm)
Mineral wool (145 mm)
Vapour barrier (0.2 mm PE)
Gypsum board (13 mm)

TEST WALL 5



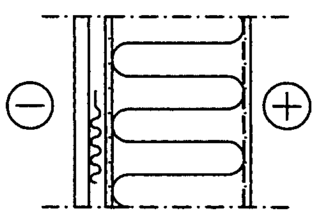
External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Three-ply fir plywood (9 mm)
Cellulose-insulation (145 mm)
Three-ply fir plywood (9 mm)
Bitumen paper
Gypsum board (13 mm)

TEST WALL 6



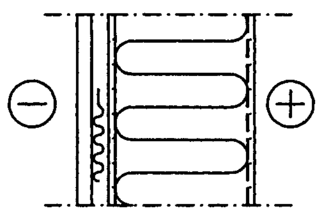
External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (25 mm)
Cellulose-insulation (145 mm)
Vapour barrier (0.2 mm PE)
Gypsum board (13 mm)

TEST WALL 7



External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (12 mm)
Cellulose-insulation (2 x 100 mm)
Building paper
Porous fibreboard (12 mm)

TEST WALL 8



External cladding,
horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (12 mm)
Cellulose-insulation (200 mm)
Building paper
Porous fibreboard (12 mm)

Figure 3.5. Structure sections of examined wall structures.

4 Test results

Test results that are essential from the viewpoint of the moisture behaviour of structures are presented in this connection. All the measurement results of the wall tests and the values computed from them are presented at the end of each test period in Appendix VI. Appendix IV contains photos of the studied wall structures.

4.1 Impact of diffusion and structural moisture

Figures 4.1–4.8 show the RH values and humidity by volume of pore air measured from the examined wall structures at end of testing in the case of solid wall structures and subsequent to the period of no pressure difference for perforated structures. The RH curves of the figures were drawn linear, but actually the changes in the RH of the pore air of the insulation are somewhat nonlinear. This is due the nonlinear temperature dependence of the saturated humidity of air. The measurement results apply to the upper sections of walls. The moisture contents of wall materials, derived from structural samples, also corresponded to measured RH values of pore air.

Test Wall 1

The internal surface of Test Wall 1 had bitumen paper for an air barrier, the insulation was cellulose, and the windshield was porous fibreboard (RH 35 %). The relative humidities and humidities by volume of the porous space of Test Wall 1 rose throughout the test although the rate of increase slowed down towards the end.

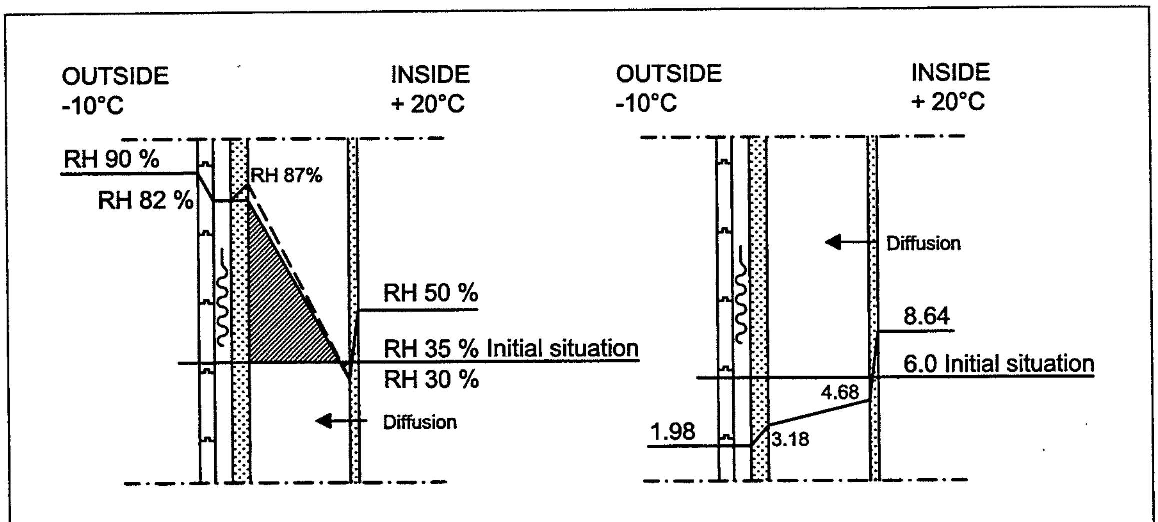


Figure 4.1. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 1 pore air.

The moisture contents of structural samples and pieces of wood were also on the increase. Test Wall 1 did not reach the steady state during the test (Figure 4.1). The broken line of Figure 4.1 indicates the RH values of the steady state estimated on the basis of the rate of increase of RH values.

The windshield and thermal insulation of Test Wall 1 appeared dry throughout the test (34.5 days) and no condensation of water occurred behind the windshield.

The moisture contents of the windshield and thermal insulation were 16 percent by mass at the end of the test. The moisture contents of pieces of wood were 18 percent by mass.

Test Wall 2

Test Wall 2 differed from Test Wall 1 in that the cellulose insulation and windshield had been premoistened (RH 85 %) prior to testing. The steady state was reached in about 14 days and water began to condense on the windshield after about 3 days as the RH values on the external surface of the insulation climbed to over 90 percent (Figure 4.2).

Icing could be detected on the internal surface of the windshield already following the underpressure period, and the amount of ice increased throughout the test. The windshield and the cellulose insulation felt damp to the touch throughout the test.

The moisture contents of the external surface of the thermal insulation were high (approx. 24 mass %) already after the period of no pressure difference, and the overpressure increased them further. The moisture contents of the windshield were quite high throughout the test (approx. 24 mass %). The moisture contents of pieces of wood were also high following the period of no pressure difference (approx. 22 mass %).

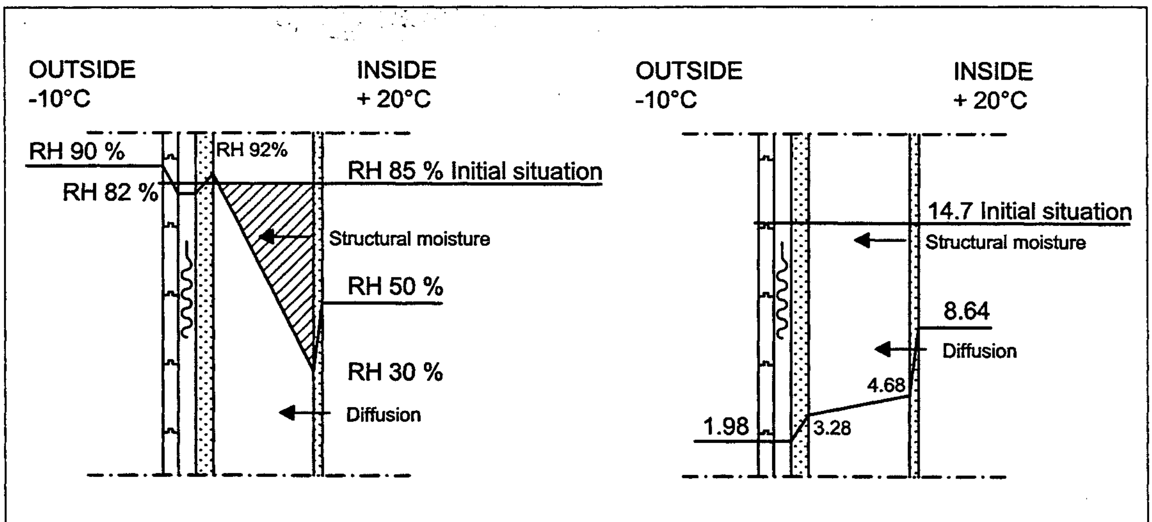


Figure 4.2. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 2 pore air.

Test Wall 3

Test Wall 3 differed from Test Wall 1 only in that the used thermal insulation and windshield were mineral wool (RH 35 %) and the internal surface of the structure had a plastic vapour barrier. In the case of Test Wall 3, the steady state was reached already after about 2 days from starting the test. RH values remained significantly lower than with Test Wall 1 both inside and outside the structure (Figure 4.3).

The windshield and thermal insulation appeared dry throughout the test (27 days) and no condensation of water occurred behind the windshield.

The moisture contents of the windshield and the external surface of the thermal insulation were very low (about 1 mass %). The moisture contents of pieces of wood were also low (about 9 mass %).

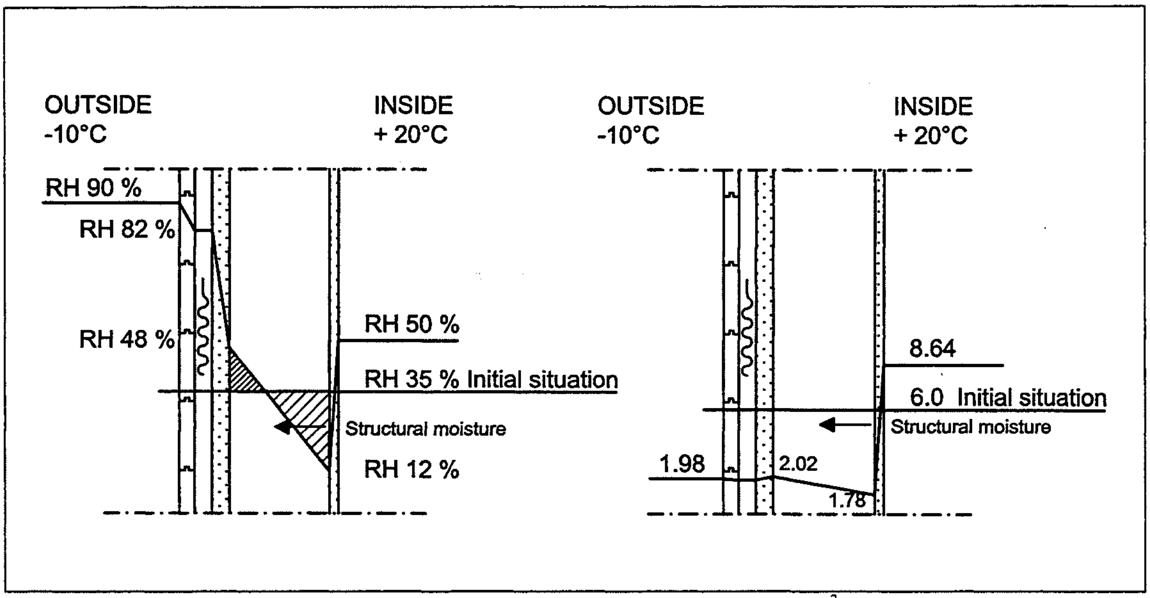


Figure 4.3. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 3 pore air.

Test Wall 4

Test Wall 4 differed from Test Wall 3 in that the thermal insulation and windshield were premoistened (RH 85 %) prior to the test. Thus, Test Wall 4 was similar to Test Wall 2 at beginning of test. In this test, the steady state was reached in about 16 days whereafter the RH values of the structure were on the same level as those of Test Wall 3 (Figure 4.4).

Although the thermal insulation and windshield had been premoistened, they felt dry to the touch already after the underpressure period and all the way until the end of the test (27 days). No ice or condensation of water occurred behind the windshield, either. On the other hand, icing occurred on the external surface of the windshield under the tape used to attach the temperature sensors (see App. IV).

The moisture contents of the external surfaces of the windshield and thermal insulation were low (about 1 mass %) subsequent to the period of no pressure difference. The moisture contents of pieces of wood were also low (about 11 mass %) after the period of no pressure difference. Moisture contents increased due to overpressure near holes.

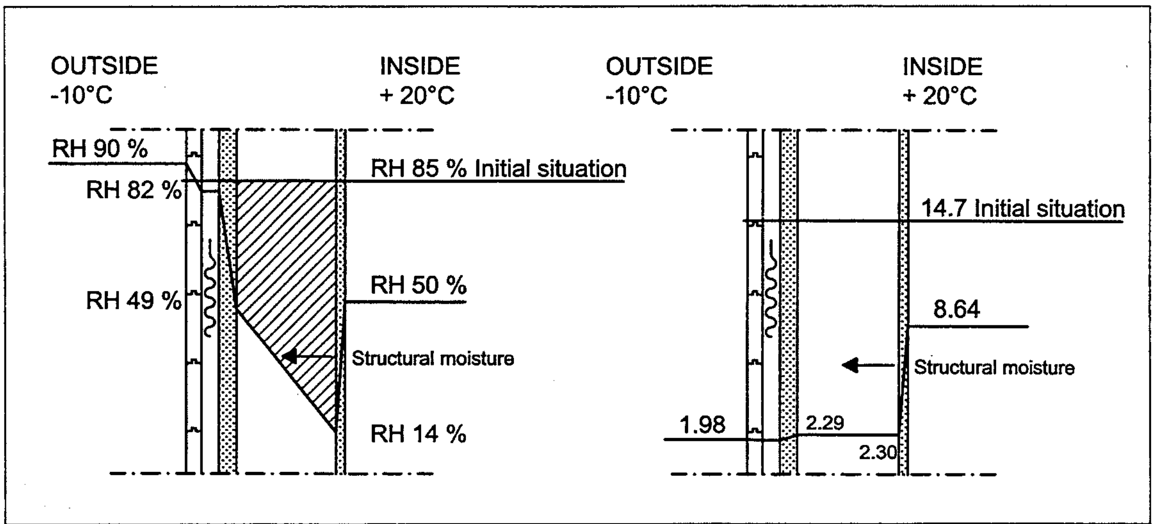


Figure 4.4. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 4 pore air.

Test Wall 5

Test Wall 5 used a different kind of inner sheet and windshield compared to the other tested structures. The internal surface had a 9-mm plywood board in addition to a gypsum board and bitumen paper and the windshield of the external surface was also of 9-mm plywood. Blown-in cellulose was used as insulation (RH 35 %). Changes in RH were highly similar to those of Test Wall 1, but RH values increased even slower in the structure. Also, Test Wall 5 never reached the steady state during testing (Figure 4.5). The broken line in Figure 4.5 shows the estimated steady state RH values, estimated on the basis of the increase in RH values, which are lower than with Test Wall 1.

The windshield and thermal insulation felt dry to the touch after testing (27 days) and no condensation of water occurred behind the windshield.

The moisture content of the windshield was low after the test (about 12 mass %). The moisture contents of pieces of wood were also low (about 11 mass %). On the other hand, the moisture content of the external surface of the thermal insulation was higher (about 19 mass %).

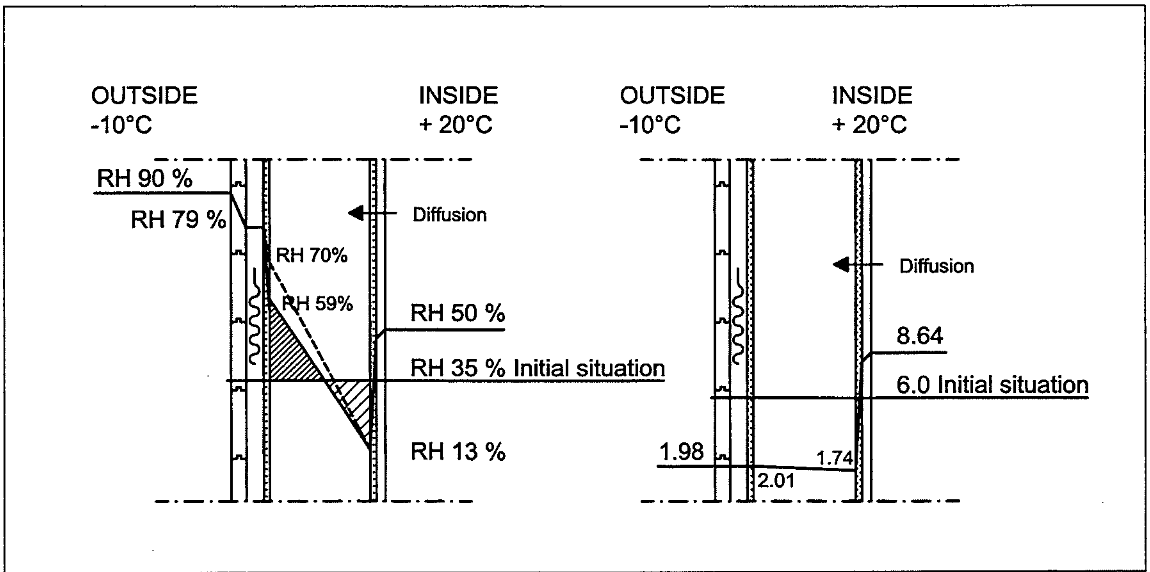


Figure 4.5. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 5 pore air.

Test Wall 6

The internal surface of Test Wall 6 had a plastic vapour barrier, cellulose insulation and porous fibreboard as windshield. The insulation and windshield had been premoistened (RH 55 %). The steady state was reached in 10 days from starting the test and the RH values of the structure stayed low (Figure 4.6).

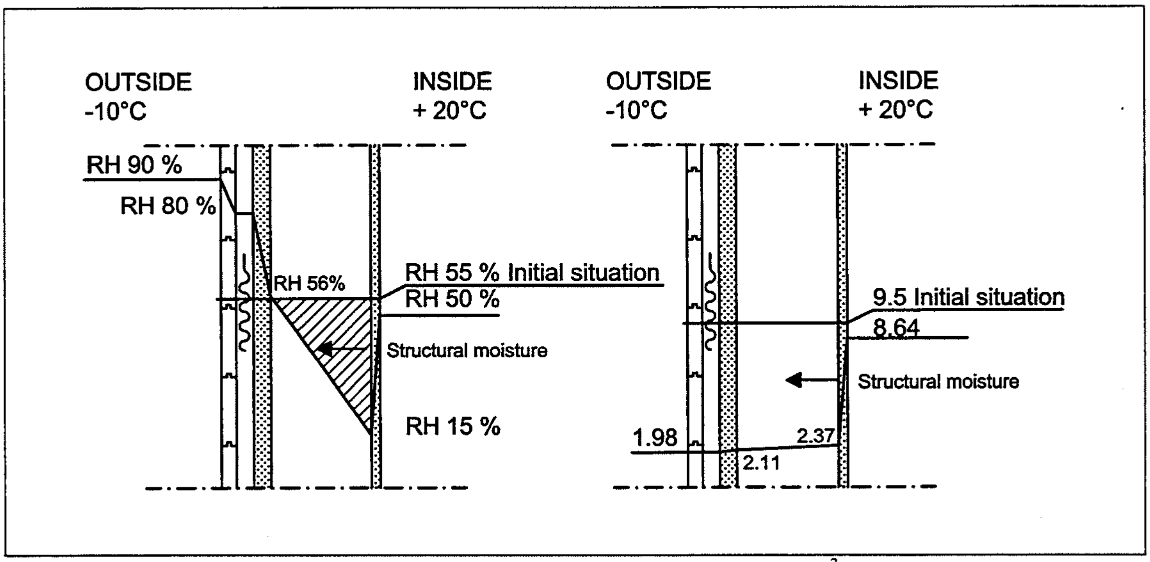


Figure 4.6. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 6 pore air.

The windshield and thermal insulation of Test Wall 6 felt dry to the touch throughout the test (26 days) and no water condensed behind the windshield.

The moisture contents of the windshield and thermal insulation were low after the period of no pressure difference (about 12 mass %). The moisture contents of pieces of wood were also low following the period of no pressure difference (about 11 mass %). Overpressure increased moisture contents near holes.

Test Wall 7

The inner sheet of Test Wall 7 was a porous fibreboard and the air barrier consisted of regular building paper. Consequently, the amount of moisture transmitted by diffusion during the test was significantly higher. The insulation was mineral wool and the windshield was porous fibreboard (RH 35 %). The moisture contents of Test Wall 7 reached the steady state in about 7 days from the beginning of the test, after which water vapour started to condense on the windshield (Figure 4.7).

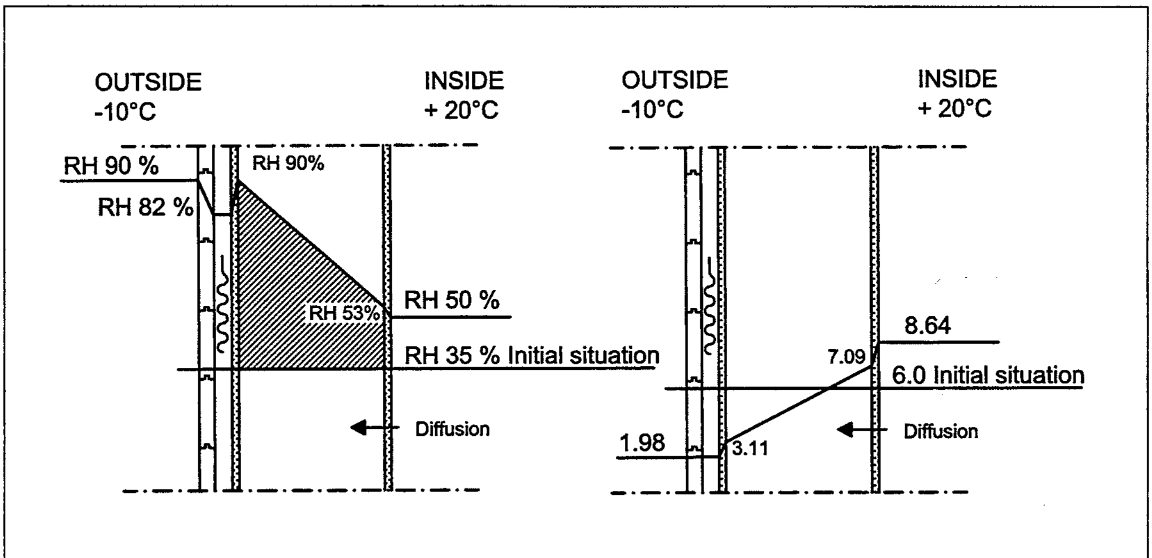


Figure 4.7. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 7 pore air.

The surface of the windshield felt damp to the touch after the underpressure period (3 days from start of test), but no ice formed on the surface. After the period of no pressure difference (6 days), surface moisture was up, but no condensation could yet be detected. Subsequent to the overpressure period (9 days) a layer of ice was clearly detectable on the back of the windshield with the exception of a narrow strip (about 150 mm) in the lower section.

The moisture content of the windshield was high after testing (about 20 mass %). The moisture contents of the pieces of wood were even higher: about 23 % by mass after the period of no pressure difference, and about 28 % by mass following the overpressure period.

Test Wall 8

Test Wall 8 was similar to Test Wall 7 in construction except that it had cellulose as insulation instead of mineral wool. The insulation and windshield had been premoistened (RH 55 %). The moisture contents of Test Wall 8 reached the steady state in about 21 days from launching the test. Thereafter, water vapour started to condense on the windshield (Figure 4.8).

The structure felt damp to the touch already after the underpressure period, but ice began to appear on the windshield only after the period of no pressure difference. As condensation began during the period of no pressure difference, the convection of moisture due to overpressure did not affect the test result. After the test, the cellulose insulation was almost entirely frozen to the windshield.

The moisture content of the external surface of the thermal insulation was very high after the period of no pressure difference (about 32 mass %). The moisture contents of the pieces of wood were also high (about 24 mass %). The moisture content of the windshield was about 20 % by mass following the period of no pressure difference. Moisture contents did not increase further due to overpressure.

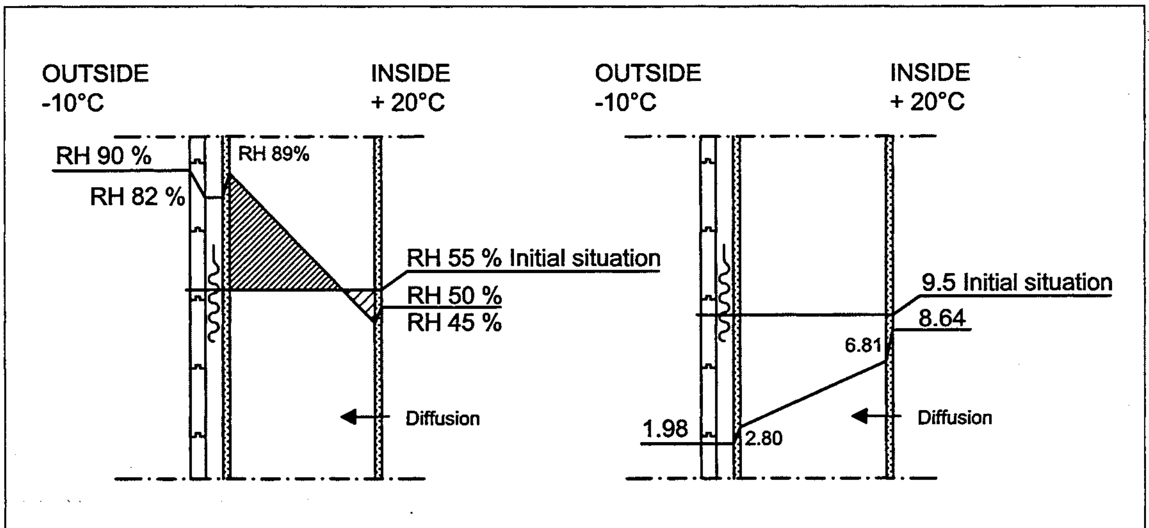


Figure 4.8. Relative humidities (RH %) and humidities by volume (g/m^3) of Test Wall 8 pore air.

4.2 Impact of convection

The impact of convection on structures was determined by drilling holes in the inner sheets and air/vapour barriers of Test Walls 2, 4, 6 and 8. In these walls, a joint was made in inner sheets and air/vapour barriers at the bracing (see Ch. 3.6 and App. V).

The impact of the holes on the RH values of the pore air moisture contents of permeable and impermeable walls is presented in Figures 4.9–4.13. The RH curves of the figures are linear, but in reality the change of pore air RH in the insulation space is somewhat nonlinear. For the purposes of this study, permeable walls are ones where the air barrier is either bitumen paper or building paper. A plastic vapour barrier was attached to the internal surfaces of impermeable walls.

Test results for permeable walls

The external surface of Test Wall 2 had high relative humidity (RH 92 %) in all pressure-difference situations. Overpressure raised internal surface moisture contents primarily near holes. Where the structure was sound or there were holes only in the air barrier, no significant changes occurred in internal-surface RH values during the overpressure period. The joints of air barriers and inner sheets, or the attachment of the inner sheet to the bracing, did not increase RH values, either (Figure 4.9).

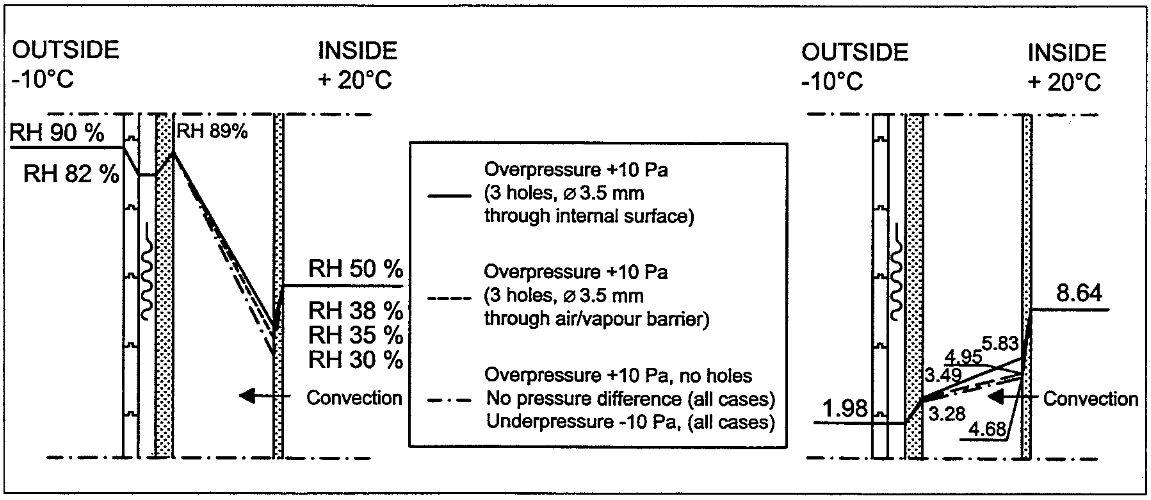


Figure 4.9. Changes in relative humidities and humidities by volume of Test Wall 2 pore air due to convection.

During the overpressure period, the moisture contents of the external surface of the cellulose insulation increased from about 24 % by mass to about 34 % by mass in the section of the structure where the holes extended clear through the internal surface. The moisture contents of pieces of wood followed the same pattern: during the overpressure period they rose from about 22 % by mass to about 29 % by mass when the holes went through the inner sheet. The moisture content of the windshield was about 24 % by mass at the end of the test. Thus, the moisture contents of materials were high just on account of diffusion and structural moisture, while outward convection increased the figures further close to holes. Subsequent to the overpressure period, the moisture content of the cellulose had reached the upper limit of the hygroscopic range on the external surface of the structure.

Test Wall 8 had the highest permeability of all tested structures. Compared to Test Wall 2, it had more and larger holes (6 x ∅ 5 mm). Moreover, the bitumen paper had been replaced with regular building paper and the inner sheet was porous fibreboard.

The RH values of this tested wall rose somewhat also on the external surface of the structure when shifting from underpressure to overpressure: RH 78 % → RH 91 %. In the underpressure situation the RH value was actually increasing at the end of the period, which means that the actual difference in RH values between under- and overpressure situations was smaller than the test results indicate (Figure 4.10).

The moisture content of the external surface of the cellulose insulation did not increase significantly near the holes under overpressure since it was very high to start with (about 32 mass %). The moisture content of the windshield was about 19 % by mass at the end of testing. The moisture contents of pieces of wood increased from about 25 to about 30 % by mass when holes extended through the inner sheet. Moisture contents of materials were high in this test merely due to diffusion and structural moisture and outward convection increased them further near holes. Subsequent to the overpressure situation, the moisture content of the cellulose insulation had reached the upper limit of the hygroscopic range on the external surface of the structure.

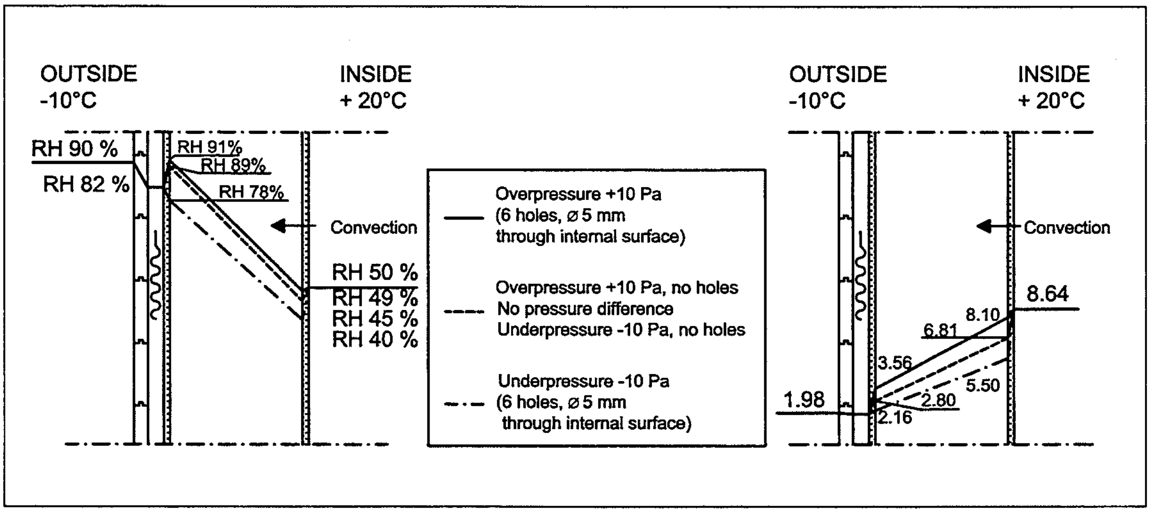


Figure 4.10. Changes in relative humidities and humidities by volume of Test Wall 8 pore air due to convection.

Test results for impermeable walls

In the case of Test Wall 4, overpressure increased the RH value of the external surface of mineral wool to 91 %; it was 48 % at the end of the period of no pressure difference (Figure 4.11). RH rose very rapidly as the steady state was reached already after a 1-day period of overpressure (see Figure 4.13). With holes only through the vapour barrier, untaped joints, and attachment of the inner sheet to the bracing through the vapour barrier did not increase the structure's RH values considerably in an overpressure situation.

During the overpressure situation, the moisture contents of the external surfaces of the windshield and thermal insulation increased from about 1 % to about 3 % by mass in the section of the structure where the holes extended through the thickness of the internal surface. The moisture contents of pieces of wood behaved in a similar manner: during the overpressure period they rose from about 11 % to about 16 % by mass with holes through the inner sheet. Yet, the moisture contents of pieces of wood remained lower than with the permeable Test Wall 2. Thus, the moisture contents of materials in this test were low due to mere diffusion and structural moisture, but outward convection increased them significantly near holes.

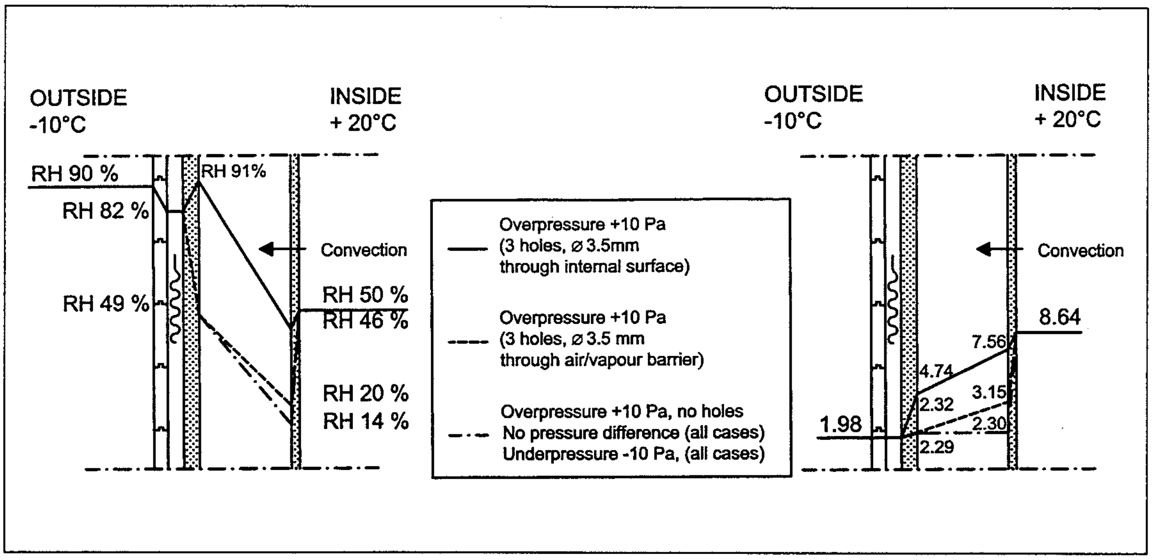


Figure 4.11. Changes in relative humidities and humidities by volume of Test Wall 4 pore air due to convection.

Test Wall 6 was of the same type as Test Wall 4, but the thermal insulation was cellulose. In the case of this wall, overpressure increased the RH value of the external surface of the cellulose insulation to 91 % while it was 56 % at the end of the period of no pressure difference (Figure 4.12). On the other hand, the RH value increased slower than with Test Wall 4 since the steady state was reached about 14 days after the overpressure period (see Figure 4.13). Holes that ran only through the vapour barrier, untaped joints, and attachment of the inner sheet to the bracing through the vapour barrier did not increase the RH values of the structure significantly in an overpressure situation.

During the overpressure period, the moisture contents of the external surfaces of the windshield and the thermal insulation rose from about 12 % to about 23 % by mass in that section of the structure where the holes extended through the internal surface. The moisture contents of pieces of wood followed the same pattern: after the period of no pressure difference they were 11 % by mass, and after the overpressure period 21 % by mass, when the holes extended through the inner sheet. As in the case of Test Wall 4, the moisture contents of materials were low merely due to diffusion and structural moisture, but outward convection increased them considerably near holes.

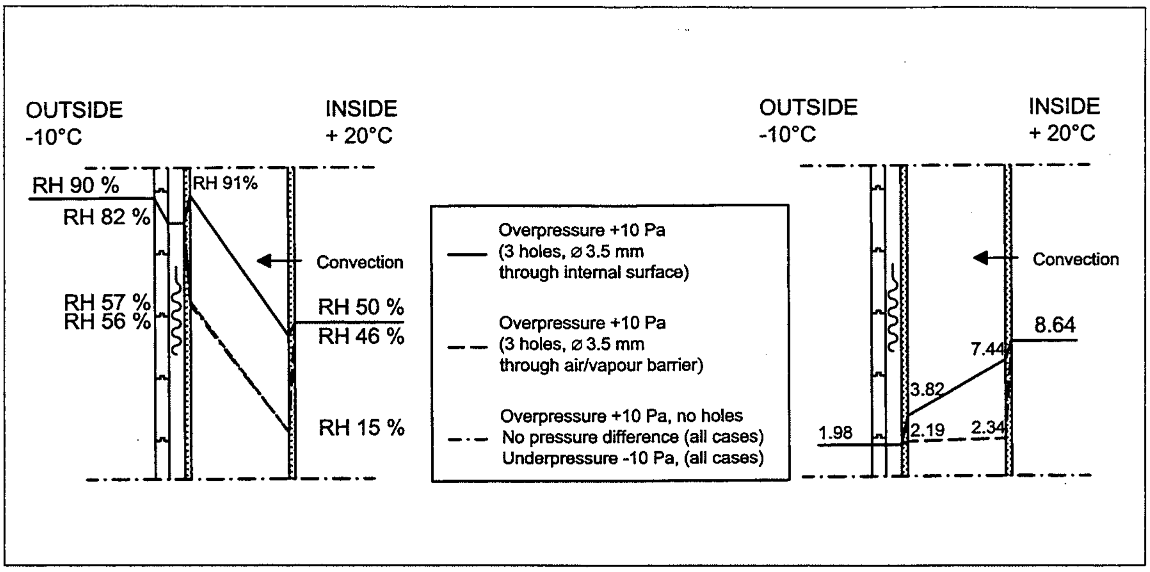


Figure 4.12. Changes in relative humidities and humidities by volume of Test Wall 6 pore air due to convection.

Figure 4.13 presents the development of the relative humidity of the pore air in the insulation space of Test Walls 4 and 6 during the overpressure period at a point where the holes extend through the thickness of the internal surface. The starting point of the curves is at the end of the period of no pressure difference. The figure clearly shows how RH rises slower in a cellulose insulated wall due to the insulation's moisture-retaining capacity

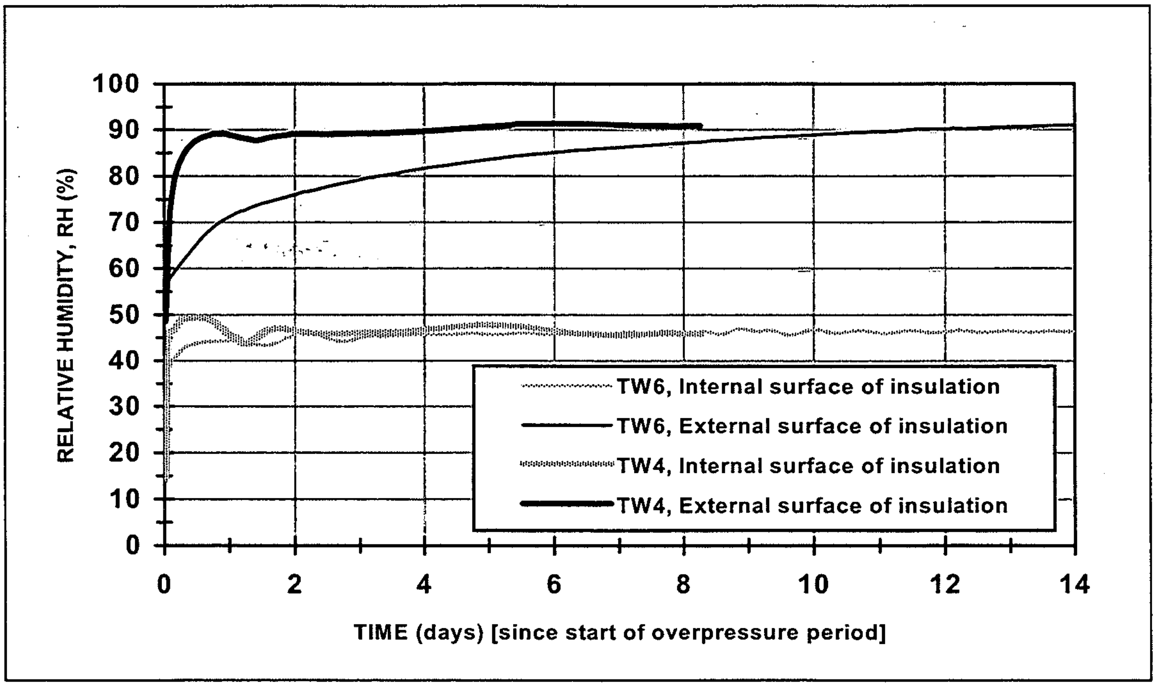


Figure 4.13. Change in relative humidity in Test Walls 4 and 6 during overpressure period. Measurements were made at point where the holes drilled in the structure extended through the inner sheet.

4.3 Comparison of moisture transmitted by diffusion and convection

The tests measured moisture flow rate and air flow rate transmitted to the structure by diffusion and convection in various pressure difference situations. In Figures 4.14–4.17 the sign of the moisture flow rate and the air flow rate is positive when the flow is from the inside out.

The amount of moisture transmitted by diffusion varies somewhat with different pressure difference situations due, for instance, to changes in the moisture contents of the test element, icing on the internal surface of the windshield, and the impact of convection near holes. In the case of Test Walls 2 and 7, the measurement uncertainty concerning diffusion results is higher than usual due to the malfunctions of the load cell of the inner humidifying vessel.

Underpressure situation

Figure 4.14 presents the moisture flow rate created by diffusion and convection in an underpressure situation (-10 Pa).

Convection transmitted moisture through perforated structures to some extent also in the case of Test Wall 7 since the building paper of the internal surface of the structure was quite permeable to air. In most tested walls, the amount of moisture transmitted by convection was, however, quite small compared to transmission by diffusion.

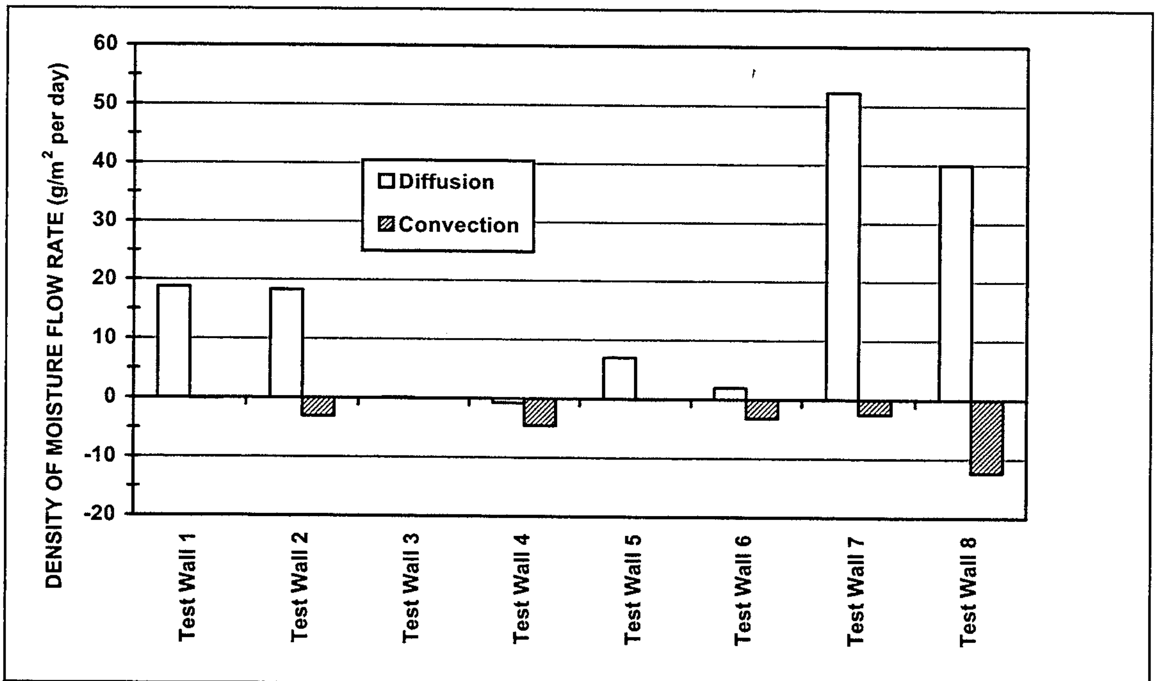


Figure 4.14. Density of moisture flow rate (g/m^2·day) transmitted into structure by diffusion and convection during underpressure period.

Situation during no pressure difference

Figure 4.15 shows the moisture flow rate transmitted by diffusion during the period of no pressure difference.

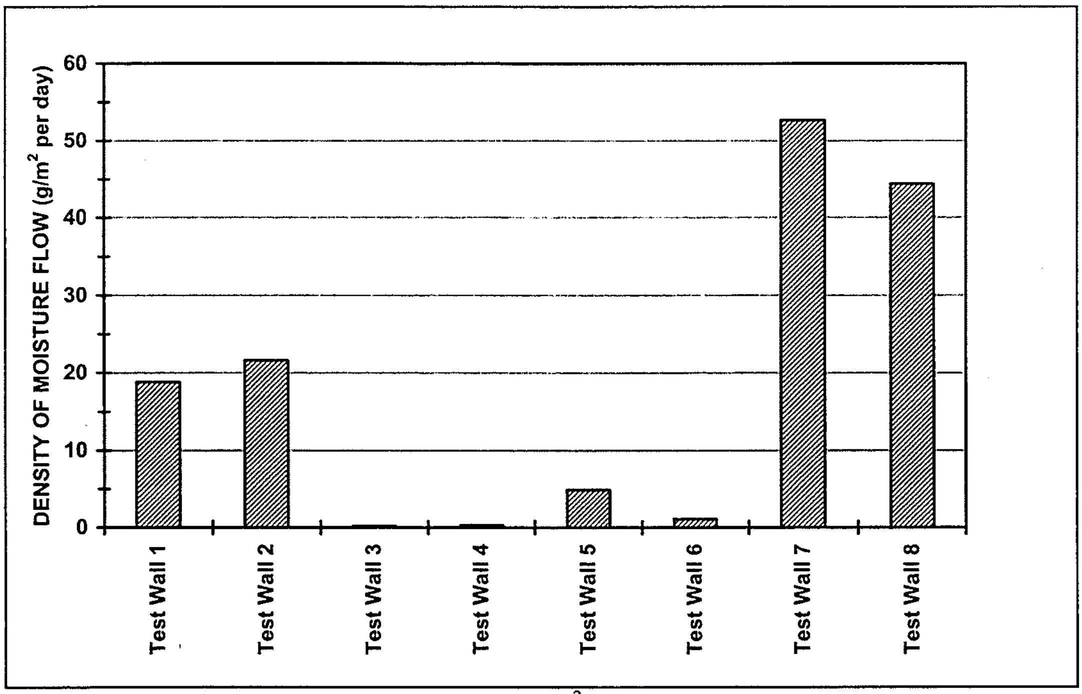


Figure 4.15. Density of moisture flow rate (g/m^2·day) transmitted into structure by diffusion during period of no pressure difference.

The bars of Figure 4.15 indicate the differences in the permeability of building paper, bitumen paper and plastic sheeting. The moisture flow rate transmitted by diffusion divides into three distinct size categories according to the material used. Test Wall 5 also had plywood inside which lessened diffusion.

Overpressure situation

Figure 4.16 shows the transmittance of moisture flow rate by diffusion and convection in an overpressure situation (+ 10 Pa).

In an overpressure situation, the share of moisture transmitted by convection of the total moisture flow rate is significantly larger than with underpressure. This is due the fact that more humid air flows from the inside (v_i = 8.64 g/m^3) into the structure than from the outside (v_o = 1.98 g/m^3). Here, the moisture transmitted through structure 7 by convection is also significant although the structure had a solid air barrier.

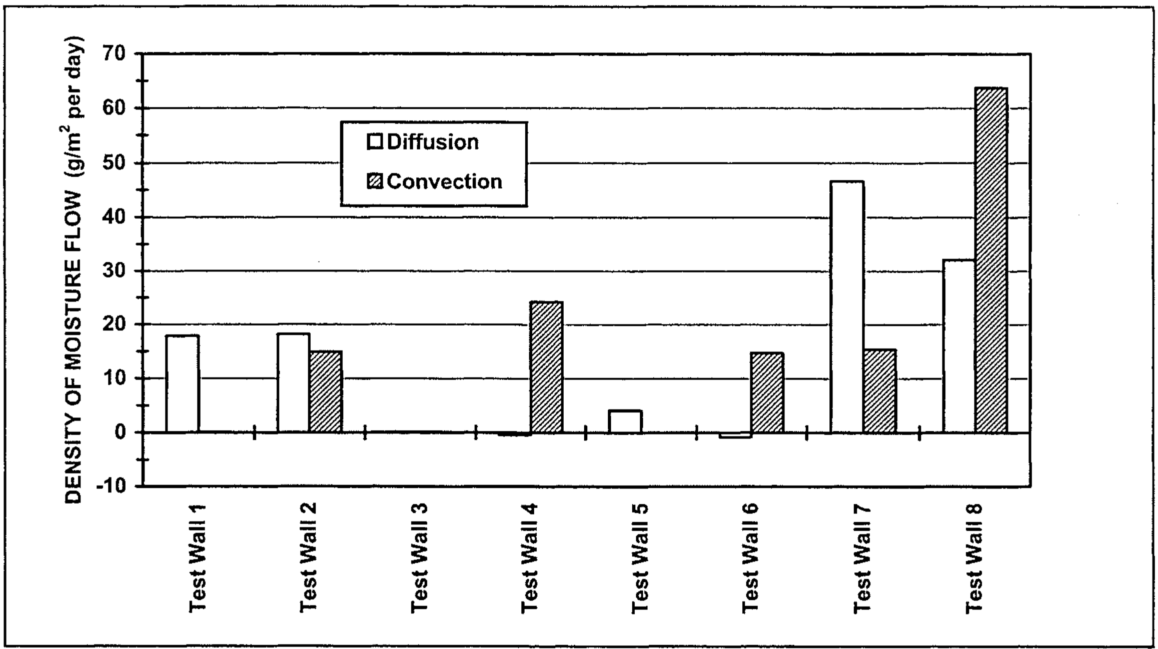


Figure 4.16. Density of moisture flow rate (g/m^2·day) transmitted into structure by diffusion and convection during overpressure period.

Figure 4.17 also shows the volume flow of air transmitted through the structures per square metre in over- and underpressure situations. The volume flow of air through the structure is directly proportional to the moisture transmitted by convection since a certain volume of air always carries the same amount of moisture in a steady state.

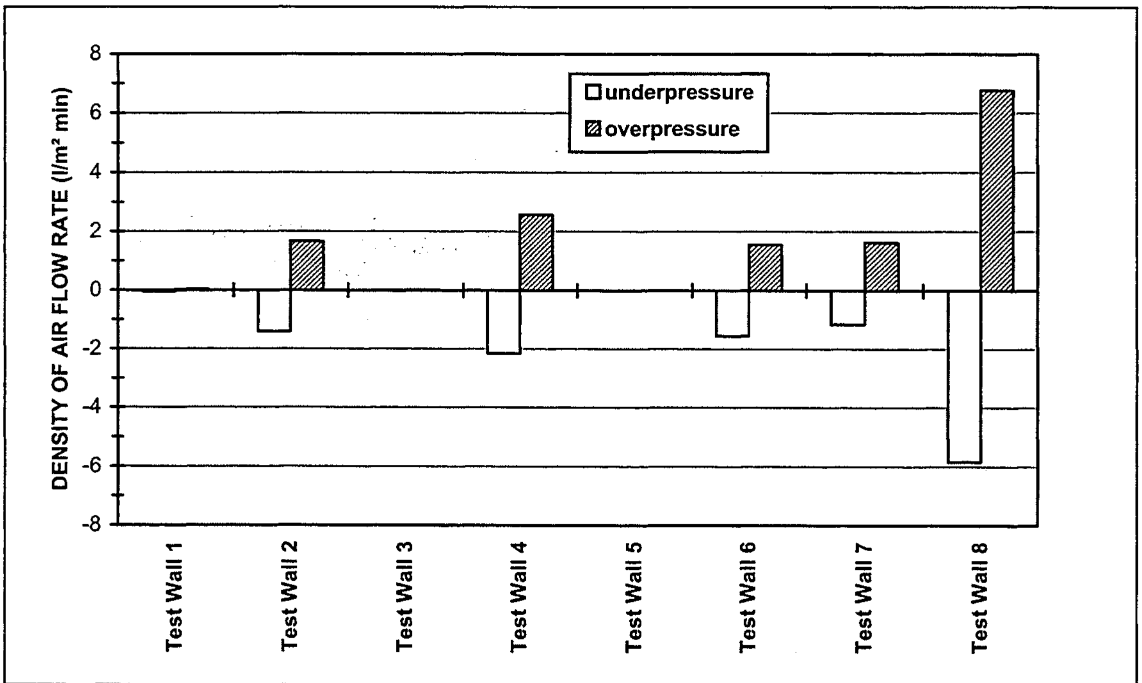


Figure 4.17. Density of air flow rate (l/m^2·min) transmitted through the structure during the over- and underpressure periods.

4.4 Comparison of calculated values and test results

Table 4.1 compares the test results concerning moisture flow rates due to diffusion and convection and calculated values.

Table 4.1. Comparison of densities of moisture flow rates (moisture flow rates per sq.m.) transmitted by diffusion and convection as indicated by tests and calculated estimates.

	TEST RESULT				CALCULATED VALUES			
	Diffusion ($g/m^2 \cdot d$)	Convection ($g/m^2 \cdot d$)		Condensation on external surface	Diffusion ($g/m^2 \cdot d$)	Convection ($g/m^2 \cdot d$)		Condensation on external surface
		Under pressure	Over pressure			Under pressure	Over pressure	
Test Wall 1	18.8	- 0.1	0.1	No condensation	17.6	- 0.1	0.2	**Condensation**
Test Wall 2	21,6	-3,0	14,9	**3 days**	17.6	-	-	**Condensation**
Test Wall 3	0.2	0.0	0.2	No condensation	0.3	0.0	0.0	No condensation
Test Wall 4	0,3	- 4.5	24,2	No condensation	0.3	-	-	No condensation
Test Wall 5	4,9	- 0.1	0.0	No condensation	4.2	0.0	0.0	**Condensation**
Test Wall 6	1,1	- 3,1	14,7	No condensation	0.3	-	-	No condensation
Test Wall 7	52.7	- 2.4	15.4	**7 days**	18.9	- 0.5	2.1	No condensation
Test Wall 8	44,4	-12,3	63,7	**21 days**	18.9	-	-	No condensation

The ratio of internal and external water vapour resistance for Test Walls 1, 2, 5, 7 and 8 was < 5:1, and with Test Walls 3, 4 and 6 it was about 400:1.

Table 4.1 indicates that the largest differences in diffusion values fell on the most permeable Test Walls 7 and 8. Based on the calculations, no condensation should have occurred with these test walls at all. On the other hand, the occurrence of condensation in these test walls depends to a large extent on the water vapour permeability of the building paper used in the calculations.

Test Walls 1 and 5, again, are structures that according to calculations are subject to condensation, but no condensation occurred in the tests. This can partly be explained by the fact that the structures did not reach the steady state during testing.

With regard to Test Wall 2, the calculated values are quite close to the test results, but also here the condensation was mostly due to the excess structural moisture that had not been accounted for in the diffusion assessment.

The calculational survey is based on the following formulas /1, 8, 9/. The density of the moisture flow rates transmitted to a structure, g (kg/m^2·s), can be computed from the following equation:

$$g = \delta_v \frac{\Delta \nu}{\Delta x} \tag{4.1}$$

where δ_v is the water vapour permeability of a material (m^2/s), $\Delta \nu$ is the difference in humidities by volume over the distance x (kg/m^3) and Δx is the diffusion distance (m). The potential difference between the humidities by volume of outdoor and indoor air can also be expressed as a partial pressure difference Δp_p (Pa). The results are converted into the unit (g/m^2·days) used in Table 4.1 with a conversion factor.

The density of a moisture flow rate, g (kg/m^2·s), can be solved from the formula:

$$g = \ell \Delta \nu \frac{\Delta p}{\Delta x} \tag{4.2}$$

where ℓ is the air permeability of a material (m^2/s·Pa), $\Delta \nu$ is the difference in humidity by volume (kg/m^3) over the distance x, Δp is the air pressure difference (Pa) over the distance x, and Δx is the distance over which the pressure changes (m). The results are converted to the unit (g/m^2·days) used in Table 4.1 with a conversion factor.

Several simplifications are made in the calculational diffusion survey which result in errors. Calculations assume a steady state which was not reached in all conducted tests. The calculation model does not take into consideration the moisture-retaining capacity of materials, extra structural moisture, or other forms of moisture transmission. Moreover, the calculation model assumes, for instance, that the transmission of moisture is one-dimensional and that thermal distribution is linear in various material layers.

The biggest computational errors may, however, occur due to incorrect properties of materials (thermal conductivity and water vapour permeability) on which the calculations are based. The determination of the properties of materials is made difficult by the fact that they change as temperature and moisture content change. Moreover, the freezing of the water that condenses behind the windshield alters the water vapour permeability of the boundary layer significantly. However, an effort has been made to select the properties of materials for the calculations of Tables 4.1 and 4.2 on the basis of the most recent research data to ensure the best possible results.

4.5 Impact of permeable wall structure on indoor air humidity

In the test on Test Wall 2, the decrease in indoor RH at the beginning was also examined. The initial RH of the cellulose insulation of Test Wall 2 was 85 % which meant that water vapour was also transmitted to indoor air by diffusion. Moreover, underpressure prevailed inside at the start of the test whereby moisture was transmitted into indoor air also by convection. Humidification of indoor air was begun about after 3 days whereafter diffusion caused only outward flow of air (Figure 4.18). Figure 4.18 shows the change in RH of indoor air and the internal surface of the cellulose insulation.

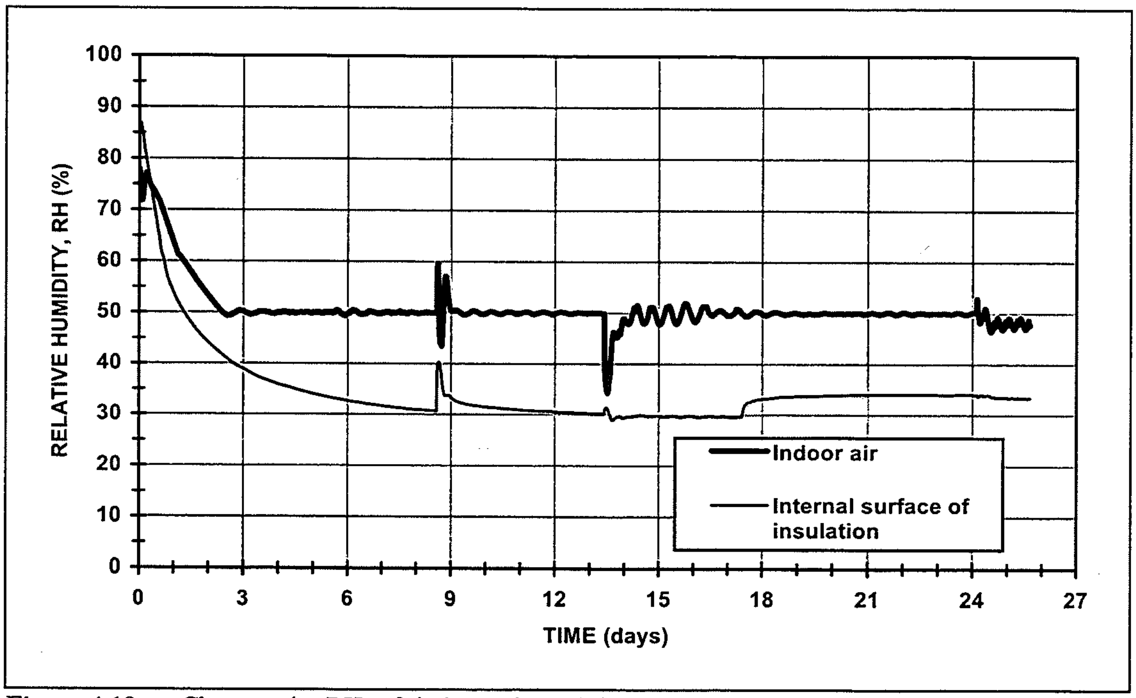


Figure 4.18. Changes in RH of indoor air and internal surface of insulation for Test Wall 2. Measurements regarding internal surface were made at a point where the holes drilled in the structure extended through the inner sheet.

4.6 Change in the temperature field due to pressure difference

Figure 4.19 shows the changes in the temperature field due to fluctuations in pressure difference as regards Test Walls 4 and 6. The changes in temperature have been examined close to the holes in the internal surface and the solid portion of the structure. The only difference between Test Walls 4 and 6 was in thermal insulation. In the case of Test Wall 4, the temperature difference at the external surface of the mineral wool insulation was 6.9 °C between under- and overpressure periods. In Test Wall 6, which had cellulose insulation, it was only 2.6 °C.

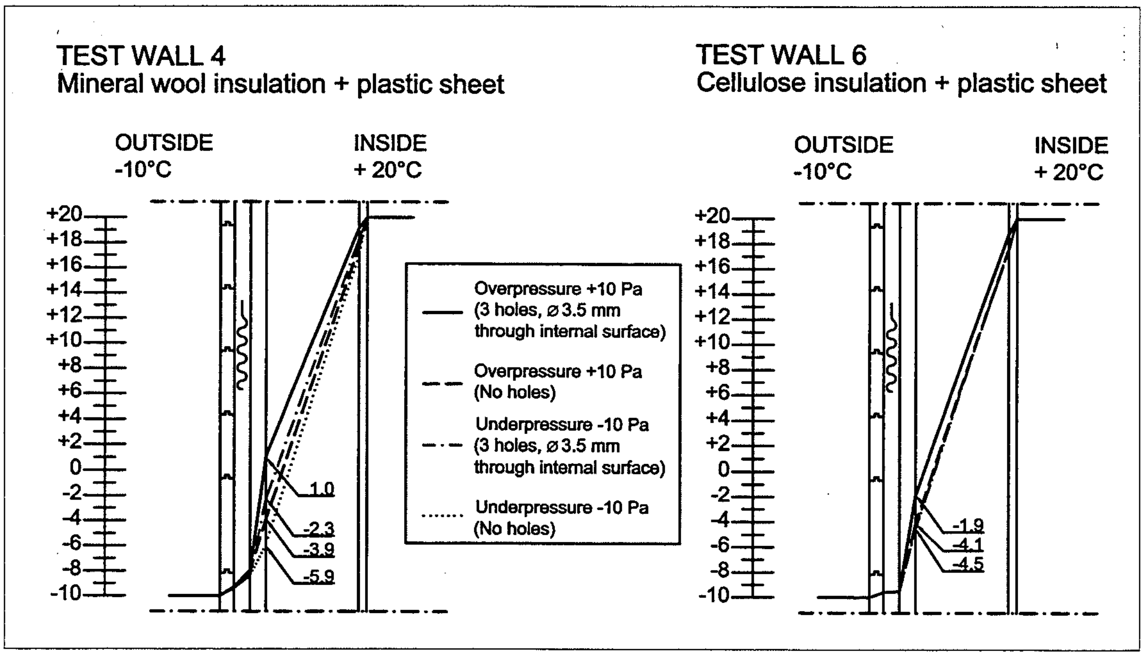


Figure 4.19. Variations in temperature field in different pressure difference situations near holes and in solid structure.

5 Review of test results and conclusions

5.1 Impact of diffusion and structural moisture

Let us start by examining the moisture performance of Test Walls 1, 2 and 8 (Figures 4.1, 4.2 and 4.8). The materials of Test Wall 1 were dry (RH 35 %) at the start of testing, which means that there was no extra moisture in the structure. Due to diffusion, the RH values on the external surface of the structure increased throughout the test. As a result of the low level of initial moisture, the moisture contents in the structure never reached the steady state during the test. In other words, the cellulose insulation had sufficient capacity to retain all the moisture transmitted into the wall and, consequently, there was not enough time for condensation to start forming on the windshield.

In Test Wall 8, the initial moisture content of structures was higher compared to Test 1 (RH 55 %) which meant that the cellulose insulation had less moisture retention capacity left. On the other hand, Test Wall 8 was wider than Test Wall 1 and, thus, its volume of insulation was larger. In this test, the structure reached the steady state after 21 days in the test after which condensation started on the windshield. Condensation began quite quickly since the internal surface of the wall was even more permeable than in Test 1.

The materials of Test Wall 2 were moist (RH 85 %) at the start of testing. Thus, the structure also contained extra moisture which tended to move both inside and out when the test began. The outward transmission was, however, stronger since the outward potential difference was larger. Due to the extra structural moisture, condensation on Test Wall 2 began already about after 3 days. This occurred although there was underpressure inside which caused moisture also to flow from outside in which dried the structure. Nearly all moisture transmitted by diffusion condensed on the windshield since the cellulose insulation had no moisture-retention capacity left after the steady state had been reached.

In summation, it may be stated that the moisture-retention capacity of cellulose insulation delays the start of condensation, but cannot always prevent it. The time it takes for condensation to begin depends of the initial moisture content of the insulation and the windshield, the water vapour and air permeability of the internal wall surface and the moisture load on the wall.

The time it took for condensation to begin with the tested permeable wall structures varied from a few days to three weeks. As the cold period in Finland — that corresponds to the test conditions — typically varies from 2 to 5 months, it can be said that there is clearly a risk for condensation in permeable walls. The extent to which, for instance, solar radiation or wind improve the practical situation is another question.

The risk of condensation is the greater, the more permeable a structure is, the higher the moisture content of the materials of the structure, and the larger the difference between the moisture content of indoor and outdoor air. If water condenses on a structure, it provides favourable conditions for the growth of mould as long as the temperature exceeds 0 °C. Such conditions exist especially in autumn and spring. RH over 80 % in a structure is sufficient to cause mould growth even in the absence of condensation.

Let us then compare Test Walls 7 and 8 with respect to the same issue. The walls were similar in structure except that they had different types of insulation (Figure 4.7 and 4.8). In Test 7 condensation began after 7 days and the initial moisture content corresponded to 35 % RH. In Test 8 condensation started after 21 days and initial moisture content corresponded to 55 % RH. Although the initial moisture content of the cellulose insulation was somewhat higher at the start of testing, it can be concluded that the moisture-retaining capacity provided by the cellulose insulation did not delay the start of condensation significantly. This is due the fact that the internal surface of the wall was highly permeable. In other words, the moisture-retaining capacity of cellulose insulation is limited.

Test Wall 6 was similar in structure to Test Walls 1 and 2 with the exception that the bitumen paper of the inner surface was replaced by a plastic vapour barrier (Figure 4.6). Figure 4.6 shows that RH was essentially lower on the external surface of this wall since no moisture was transmitted to the structure by diffusion. In this test, the cellulose insulation performed flawlessly. In other words, the impermeability of the inner wall surface is much more important for the moisture behaviour of the wall than the insulation used. Both cellulose insulation and mineral wool can be used as insulation if the inner surface of the wall has sufficient air and vapour barriers.

Let us then look at structures 3 and 4 (Figure 4.3 and 4.4) which incorporated mineral wool insulation and vapour barriers. As the test started, Test Wall 3 had the same initial moisture content as Test Wall 1 while the value for Test Wall 4 corresponded to that of Test Wall 2. Structural thicknesses and test conditions were the same for all walls — thus the test results are commensurate. The RH values for Test Wall 3 were very low and moisture contents reached the steady state already after 2 days in the test. Moisture did not move into the structure by diffusion or convection, which means that there was no condensation of water in the structure. The wall structure behaved extremely well in the test.

It took longer (16 days) to reach the steady state in the case of Test Wall 4 since the moisture contents of the insulation and the windshield corresponded to 85 % RH at the start of the test. Yet, no condensation occurred in the structure since the amount of moisture retained by mineral wool is small independent of the RH of pore air. The mineral wool wall had about 40 g/m^2 of extra moisture in the initial situation whereas the cellulose-insulated wall had about 400 g/m^2. This explains why condensation started quite rapidly in Test Wall 2.

The RH values for Test Wall 4 decreased to the same level as with Test Wall 3 in the steady state. Thus, Test Wall 4 also behaved well in the test. The proper behaviour of the structure was partially based on a windshield that was highly permeable to water vapour and allowed the extra moisture to exit the structure. The ice forming under the tapes used to secure surface sensors in place shows that the windshield must be sufficiently permeable to water vapour.

To sum up the results of Tests 3 and 4, it may be stated that walls with plastic sheeting as vapour barrier performed flawlessly with respect to indoor air diffusion. The same applied also to Test Wall 6.

On the basis of the results of Tests 2 and 4, it can be stated that if mineral wool is used as insulation, the moisture content of the insulation has no significance with regard to the behaviour of the structure. On the other hand, if the initial moisture content of cellulose insulation is high, it increases the risk of condensation in the structure considerably. Thus, any extra moisture in cellulose insulation after a rainy summer and autumn has a detrimental effect. The same applies if the cellulose insulation is blown in wet in autumn or winter. Then, the extra moisture in the structure condenses or freezes onto the windshield and dries only the next spring. Accordingly, if insulations that are blown in while wet are used, it is recommended that the work be done in spring or early summer.

Let us finally examine the moisture behaviour of Test Wall 5 (Figure 4.5). The test conditions and material moisture contents for Test Wall 5 prior to testing were the same as for Test 1. The test results indicate that RH values within the structure increased considerably slower than with Test Wall 1 due to the more impermeable inner surface. In this test, much of the moisture-retention capacity of cellulose insulation was still unused a month after the test. The speed of change of RH values at the end of the test further indicates that the moisture contents of the structure would not have presented a risk of condensation (RH < 85 %) even in a steady state situation. According to Table 4.1, Test Wall 5 proved to be a condensing structure which means that the actual water vapour permeability of the external plywood was probably higher than calculated.

We can conclude on the basis of Test 5 that plywood and bitumen paper attached to the inner wall surface are together sufficiently impermeable to resist diffusion of water vapour. The amount of moisture transmitted through the joints of boards by diffusion is so small as to have no practical meaning. The joints are primarily at risk for moisture transmitted by convection, but as long as the bitumen paper is undamaged, it prevents convection into the structure. The test showed that the inner surface of the wall can be made sufficiently impermeable by means other than a plastic vapour barrier. The basic rule is that the inner surface of the wall should have at least five-fold water vapour protection compared to the external surface /6, 11/.

Even if a structure meets the above criterion, it should be kept in mind that the windshield must not be too impermeable (cf. tapes used to attach sensors of Test Wall 4). In this sense, Test Wall 5 is attended with high risk since the external plywood has high water vapour resistance, especially when the temperature is under 0 °C.

5.2 The impact of convection

Let us first examine Test Walls 2 and 4 (Figures 4.9 and 4.11). The RH values of Test Wall 2 rose high close to the outer surface merely due to diffusion while convection had little effect on the values near the holes. The RH values of Test Wall 4 remained low generally, but in an overpressure situation they climbed high in that part of the structure where the holes extended through the internal surface. There, the RH values attained the same level as with a permeable wall structure.

Test 6 was intended to determine how the behaviour of a structure incorporating a vapour barrier changes in the presence of convection, when the mineral wool insulation is replaced by cellulose insulation (Figure 4.12). The end result of this test was similar to that on Test Wall 4: in overpressure conditions RH values were high near holes that penetrated the internal surface. The only difference was that the moisture content values for Test Wall 6 rose somewhat slower (equalization time about 14 days) than those for Test Wall 4 (equalization time 1 day) (Figure 4.13).

It can be concluded on the basis of Tests 2, 4 and 6 that the risk of condensation exists with permeable wall structures merely due to diffusion, and that it is further increased by internal overpressure. On the other hand, the risk of condensation exists with a structure incorporating a vapour barrier only if there are holes extending through the internal surface accompanied with overpressure.

When the holes only go through the air/vapour barrier, the structure's RH values do not change significantly due to convection. This applies also when the inner sheet is fastened to the bracing with screws that penetrate the air barrier. Neither does convection affect the RH values of the wall structure when the joint of the inner sheet and air/vapour barrier is at the bracing.

The use of cellulose insulation is advantageous with a perforated structure under overpressure situations since the insulation can retain the moisture entering through the holes by convection. However, the holes must not be large since the moisture-retention capacity of the insulation is limited.

Pressure difference tests were used to determine the extent to which underpressure can lower the moisture contents of a wall structure. In the case of Test Walls 2, 4 and 6, the RH values of structures did not differ significantly in underpressure and no pressure difference situations. Double the number of holes was drilled in Test Wall 8 — they were also larger than in other tests (Figure 4.10). In this test, the moisture contents of the thermal insulation under equilibrium were somewhat lower in an underpressure situation than when there was no pressure difference. In Test 8, the impact of diffusion was also considerably stronger due to the more permeable wall structure.

Test 8 allows making the conclusion that underpressure lowers the moisture contents of permeable wall structures under equilibrium, provided that they have sufficiently large holes ($A \geq 100$ mm^2/m^2). Moisture contents decrease the more, the greater the pressure difference over the structure and the larger the holes on the internal surface of the structure. However, in actual structures the reduction in moisture contents from underpressure is quite limited. Yet, underpressure ensures that overpressure does not develop in the building.

5.3 Comparison of condensation risks of wall structures

The condensation risks on different wall structures can be compared by examining the humidities by volume of insulation-space pore air in a steady state (Figures 4.1–4.12). Humidity by volume indicates the absolute amount of water in the pore air of thermal insulation — the water tends to become evenly distributed throughout the insulation. In structures prone to condensation, however, the humidity by volume cannot become uniformly distributed since the amount of moisture entering the structure is larger than the amount of moisture the pore air can absorb on the cold side of the insulation. In other words, the condensation risk of a structure is the higher, the greater the difference in the humidities by volume of the internal and external surfaces of the insulation in a steady state.

Figures 4.1–4.12 show that condensation risk is highest for Test Walls 7 and 8 in a diffusion situation (largest humidity by volume differences). On the other hand, the humidities by volume of Test Wall 2 are quite even although condensation also formed on this wall in the test. In the case of Test Wall 2, the condensation was caused primarily by the extra structural moisture of the cellulose insulation.

Let us also examine Test Wall 1, which is of the same type, and was dry at the start of testing. Test Wall 1 did not reach the steady state during the test, but the humidities by volume of the insulation were, however, quite equal at the end. Therefore, Test Wall 1 is a borderline case in that the internal surface of the structure may be just permeable enough to prevent condensation in a diffusion situation under conditions used in the test. The RH values for the structure are, however, so high that in autumn and spring the temperature and RH conditions of the structure are conducive to mould growth. In this structure, condensation begins when it contains extra structural moisture (Test Wall 2) or moisture enters it by convection.

Figures 4.9–4.12 show further that the humidity by volume differences of perforated structures increase due to convection in overpressure situations. Changes in humidity by volume compared to a diffusion situation, again, tell us the extent to which a hole increases the risk of condensation in said structure. In Test Walls 4 and 6, convection increased condensation risk the most compared to a diffusion situation.

5.4 Comparison of moisture transmitted by diffusion and convection

Let us examine the amounts of moisture transmitted through wall structures by diffusion and convection under various pressure difference conditions (Figures 4.14–4.16). Figures 4.14 and 4.16 show that the role of convection is generally insignificant provided that the structure has no holes. An exception is Test Wall 7 where convection occurred although the structure had solid building paper as an air barrier. Convection occurred because the porous fibreboard on the internal surface had high air permeability and the building paper used for air barrier was untreated (no bituminization or plastic coating). Test Wall 7 proves that in an extreme case mere building paper may not provide a sufficient air barrier, even if it is solid. However, in reality the internal surface of the structure can easily be provided a sufficiently tight air barrier by using, for instance, bitumen paper.

The impact of holes on the amount of moisture transmitted by convection can be determined by comparing Tests 1 and 2, Tests 3 and 4, and Tests 7 and 8. In the case of Test Wall 8, the transmission of moisture due to convection is four times that of Test Wall 7 — thus, three quarters of the convection in Test 8 occurs through holes and one quarter through the building paper.

A comparison of Figures 4.14 and 4.16 reveals that the amount of moisture transmitted into the structure by overpressure are considerably larger than those transmitted by underpressure. This is primarily due to the higher humidity by volume of indoor air. In other words, overpressure is much more detrimental to wall structures than underpressure is beneficial. Consequently, overpressure increases considerably the flow of moisture into a perforated wall structure.

In general, it may be said that the moisture flow rate due to diffusion was larger than that due to convection in the case of permeable structures while it was correspondingly smaller in structures incorporating a vapour barrier and holes. Yet, in the case of permeable structures, the total moisture transmission to the structure was considerably larger than with structures incorporating a vapour barrier.

A comparison of the air flow rate values of Figure 4.17, reveals that the coefficient of air permeability for building paper + porous fibreboard (Test Wall 7) was clearly higher than for, let's say, bitumen paper + gypsum board (Test Wall 1). In other words, even the coefficients of air permeability of solid structures may vary significantly as already stated before. The figure also shows that the air permeability of the cellulose insulation used in the tests was nearly 40 % lower than that of mineral wool (Test Walls 4 and 6) as the test walls were similar in other respects.

5.5 Comparison of calculated values and test results

A comparison of the test results of Table 4.1 and the calculated diffusion and convection values reveals that the calculated values differ from actual test results the more, the more permeable the wall structures. This is primarily due the fact that the water vapour permeabilities of the materials used in the calculations under different conditions are not known in sufficient detail. If moisture enters a structure from the inside, the properties of all material layers need to be known in order to arrive at the correct end result. Thus, the water vapour permeabilities of materials should be tested at different RH and temperature conditions and, especially, at under 0 °C.

The values calculated for structures incorporating a vapour barrier are correct because the water vapour resistance of plastic sheeting is manyfold compared to all other materials. Consequently, the true properties of other materials need not be known in detail.

The moisture contents of the external surfaces of Test Walls 1, 2, 7 and 8 were high in a diffusion situation, and the lowest ratios between internal and external surface water vapour resistances were also calculated for the walls. Of these structures, Test Walls 2, 7 and 8 also condensed vapour in the test. The test results indicated that the lower the ratio between the water vapour resistances of the internal and external surface, the higher the risk of condensation in the structure in winter. The ratio between internal and external water vapour resistances should, therefore, be at least 5:1, as stated earlier (Ch. 5.1).

5.6 Impact of permeable wall structure on indoor air humidity in winter

Figure 4.18 shows that very moist cellulose insulation could humidify indoor air under winter conditions only for a few days. Thereafter, humidifiers had to be used to maintain the target humidity (RH 50 %). In reality, there is even more air space per square metre of wall in a building to humidify than in the test, which means that cellulose humidifies indoor air for an even shorter period. Moreover, ventilation removes moisture from indoor air much more efficiently than in the test.

This test allows us to draw the conclusion that a permeable wall structure incorporating cellulose insulation is incapable of increasing the moisture content of indoor air in winter. Instead, indoor air tends to dry up as the moisture moves into wall structures.

5.7 Change in temperature field of structure due to pressure difference

Figure 4.19 shows the changes in the temperature fields of Test Walls 6 and 4 due to a pressure difference behind the windshield. The figures show that an overpressure of 10 Pa has a significant impact on the temperature field of a structure near holes that extend through the internal surface.

In Test Wall 4 (mineral wool-insulated) the temperature changed more behind the windshield than in Test Wall 6 (cellulose-insulated). This, for its part, tells that the permeability of the cellulose insulation used in the test was lower than that of mineral wool (cf. Ch. 5.4).

A rise in temperature next to a hole increases the saturated humidity content of pore air, which reduces the risk of condensation. On the other hand, the moisture load in the hole area increases since moisture is transmitted into the wall also by convection. In addition, as temperature rises sufficiently, the structure may provide conditions conducive to mould growth.

5.8 Impact of ventilation gap on behaviour of wall structure

The tests showed that the air in the ventilation gap was, on average, about 1.15 °C higher than outdoor air. As temperature rises, the capacity of air to retain moisture increases. Thus, the RH values of impermeable structures were even smaller on the internal surface of the windshield. On the other hand, in the case of permeable wall structures, the moisture transmitted by diffusion from the inside raised moisture contents high independent of temperature. The increased temperature in the ventilation gap also shows that exterior cladding improves the thermal insulation of a wall structure.

5.9 Moulding risk of wall structures

The risk of moulding of wall structures under winter conditions was also examined in the conducted tests. Temperatures and RH values measured from walls were used to assess whether conditions conducive to growth of mould existed in walls. None of the studied wall structures were, however, found to have RH conditions under winter conditions that were favourable for mould growth. This is natural since the temperature was below 0 °C in areas of high RH values. The risk for mould is highest in autumn and spring when outdoor temperature is over 0 °C while the relative humidity of outdoor air is still high.

6 Conclusions for the design of moisture behaviour of structures

6.1 Moisture loads

Diffusion

The moisture behaviour of wall structures depends on the moisture load they are subjected to. In relation to diffusion, the most essential thing to know is the design difference in humidity by volume of indoor and outdoor air in various seasons. If RH value of 50 % is selected as the design value in winter, as in this study, the difference between inside and outside humidities by volume is about 6.5 g/m^3. This is such a high value that many of the permeable wall structures in use today are at risk for moisture damage. With a moisture increase of, for instance, 3.5 g/m^3 (typical design value), the RH of indoor air will be 25...35 % in winter. Then, most of the presently used wall structures function sufficiently well. Yet, in the case of permeable wall structures, this increase in indoor air humidity may cause moisture-related problems.

Actually, the humidity of the indoor air of most buildings drops in winter, but there are also many buildings where that does not happen. In some instances people also have to maintain higher humidity with an air humidifier due to, for example, health reasons. In buildings that house families with many children, the humidity of indoor air is naturally much higher than, for instance, in dwellings occupied by a single person. The ventilation system and the moisture retained by wooden wall surfaces and furniture also affect the RH of indoor air.

Considering the above reasons, it is recommended that an indoor RH value of 35...50 % is selected for winter. That is also in line with the recommendation of health authorities since it has been found that indoor RH should be in the 25...45 % range the year round. If the RH value of indoor air is 35...50 % and the indoor temperature ≤ 20°C, the internal surface of the wall must have a water vapour resistance that is at least five-fold compared to the layers of materials outside the insulation as well as a windshield sufficiently permeable to water vapour.

Convection

There is no need to examine convection separately if underpressure prevails in the building, or if the structures have a solid air barrier. The aim is to install and adjust ventilation systems so as to create underpressure throughout the building, but that is not necessarily the case in real life. If we assume that overpressure prevails in the building, we must know the amount of overpressure and the size of the holes in the structures for dimensioning.

The amount of overpressure may be significantly higher in the upper parts of high buildings due to thermic pressure difference. On the other hand, there may also be overpressure in low buildings if the mechanical supply ventilation flow exceeds the exhaust air flow. Overpressure may range from 0...20 Pa depending on the situation. However, pressure differences are generally smaller (0...5 Pa).

The size and number of holes in shell structures is very difficult to estimate since the amount depends to a high degree on the carefulness and skill of the builders. Significant from the viewpoint of overpressure are holes in the upper sections of a building extending through the internal surface of the structure. Most critical spots in this respect are various corners and joints and edges of penetrations. The assumption is, however, that holes and gaps are stopped tightly e.g. with tape. Then, separate dimensioning with respect to convection is not needed.

Other forms of moisture transmission besides diffusion and convection are gravitational and capillary transmission. The situation vis-à-vis gravitational and capillary transmission is clear - a structure must be protected from them by sufficient moisture barriers.

6.2 Properties of materials

Water vapour permeabilities, air permeabilities and thermal conductivities of materials under varying conditions must be known for moisture performance dimensioning. Water vapour permeability, especially, can vary significantly as a function of temperature and relative humidity.

Today, only a single water vapour permeability value, at a certain temperature and RH, has been determined for many materials. Additional research data on the behaviour of materials is thus needed.

If the vapour barrier is made considerably tighter than called for by the 5:1 rule, the accurate water vapour permeability of other material layers need not be known.

6.3 Calculation models describing moisture transmission

From the viewpoint of moisture behaviour, structures are designed to have separate layers of materials to protect them from moisture loads while, on the other hand, the structures are designed so as to allow them to dry as necessary. With respect to diffusion, the 5:1 rule is applied in dimensioning to ensure sufficient vapour tightness of the internal surface. With respect to convection, airtightness is ensured by an air barrier and more detailed calculations are usually not made.

It can be said on the basis of the conducted tests and earlier experiences that the 5:1 rule applied in diffusion calculations is generally sufficient for ensuring the proper moisture performance of wall structures. Consequently, it will be a useful rule of thumb for dimensioning also in the future. An undamaged air barrier, or underpressure inside, ensure the reliable functioning of a structure in convection analysis. It is another matter how this can be realized in practice.

Shell structures can also be dimensioned by more accurate calculation models that take into consideration several other factors besides temperature, moisture and pressure difference conditions and material properties. These include, for instance, the impacts of solar radiation, orientation of the structure and wind, the alternation of the time of day and seasons, various means of moisture transmission within a structure, as well as the moisture-retention capacity and drying rate of materials.

Accurate calculation models can be used in special cases to determine whether more effective water vapour resistance is required on the internal surface of a structure than called for by the 5:1 rule. They can also be used to examine, for instance, the impact of external rain on structures and the increased risk of moulding in autumn and spring. The need for accurate calculation models increases in proportion to the degree of permeability desired of a wall structure.

The weakness of accurate calculation models lies in that they require a lot of initial data and a computerized dimensioning program. As the amount of initial data increases, the amount of mistakes in it increases meaning that the dimensioning may produce an essentially false result. The reliability of the end result depends then to a high degree on the magnitude of the used safety factors.

To be sure, diffusion studies may produce an incorrect end result also when applying the 5:1 rule, if the properties of various layers of materials are not known in sufficient detail. The problems can, however, be avoided by using more impermeable vapour barriers since the water vapour resistance of the internal surface is then sufficient. In other words, if we wish to ensure the performance of a structure with respect to diffusion, it is much safer and simpler to increase the water vapour resistance of the inner surface than to use a more accurate calculation model to study the structure.

The design of structures with good moisture behaviour does not require complicated calculations, if the properties of the materials are known under different conditions, and if the designers have available good standardized structural solutions. Also, the use of a more accurate calculation method does not reduce construction costs since structures are not optimized to cut materials consumption. Design can still be implemented on the basis of old principles: the structure is protected from moisture by different layers of materials, and it is seen to that the structure can dry.

Accurate calculation models are useful especially when used by research institutes and product-development units in the development and testing of structures. They are a handy tool for examining new structural solutions under different exposure conditions. When the results of calculations are combined with experimental testing and empirical data, designers can be given new ready-made structural alternatives or protection methods that have already been tested reliably under varying conditions.

7 Summary

An equipment for building physics tests has been built by the Laboratory of Structural Engineering at Tampere University of Technology (TUT) which allows studying the moisture behaviour of shell structures under different conditions. The equipment has been developed on the basis of earlier thermal transmittance testing equipment and has taken altogether some 4 years.

The equipment consists of a warm and a cold chamber — the examined structure is placed between them. The warm chamber is used to model indoor air conditions while the cold chamber models outdoor air conditions. The equipment incorporates numerous measurement and control instruments that are computer-controlled. Accurate and fast regulation of conditions requires an effective control program that continually maintains an equilibrium between various factors.

In tests, the controllable variables are indoor and outdoor temperature and relative humidity (RH) as well as the pressure difference across the examined structure. Tests can be conducted either under constant or varying conditions.

During testing, a computer measures and computes the values of different variables, controls test conditions accordingly, and saves measurement results to files. The progress of a test can also be monitored on various pages on the computer screen. In addition to the values measured by sensors, samples are taken from the examined structure to determine, for instance, moisture contents of materials and the extent of condensation in a structure. Measurement uncertainties of measured variables are determined on the basis of a calibration by manufacturers or TUT.

The building physics test equipment has many features that together make it a novel and versatile apparatus such as:

- all indoor and outdoor air conditions can be controlled simultaneously during tests
- structures can be tested in indoor and outdoor air conditions that correspond to real-life situations (e.g. RH of outdoor air can be made to correspond to the actual value also under freezing conditions)
- all controllable condition variables can be set freely within the control range
- all measurements and adjustments are automatic, accurate and quick as they are computer-controlled
- in the test, the moisture flow rates into the structure by diffusion and convection can be measured separately.
- structures can be tested under constant conditions or conditions may be changed cyclically

- as a result of the airtightness of the equipment and the installation technique of the element, the air flow rate through the tested structure is controlled
- the test opening is large (area: 1200 x 1200 mm^2, depth: 400 mm) which means that the same phenomena occur in the tested structure as in actual structures (e.g. convection inside structure)
- the control and measurement systems of the equipment can be augmented or changed as needed
- the equipment may be rotated as needed so that wall, roofing deck and base floor structures can be tested in the proper position
- the control and measurement systems developed in connection with the building of the equipment can also be used in other laboratory tests

The new test equipment was used to study the transmission of water vapour in timber-framed external wall structures due to diffusion and convection. The emphasis was on determining the need for a vapour barrier and the impact of pressure difference on the behaviour of structures. In addition, the behaviour of mineral wool and wood-fibre insulation in structures was compared. A total of eight different wall structures were tested under winter conditions: the indoor temperature was +20 °C and RH 50 % while the outdoor temperature was -10 °C and RH 90 %. The pressure difference across the structure was varied in tests so that initially there was underpressure inside (-10 Pa) followed by a period of no pressure difference and, finally, overpressure (+10 Pa). A single test generally took about a month.

Conducted tests gave the following results:

Effect of diffusion

1. All wall structures perform well from the viewpoint of diffusion, if
   - the moisture increase of indoor air is small **and**
   - water cannot enter the structure as a result of moisture leaks
2. A structure permeable to moisture is clearly more at risk for condensation than one with a vapour barrier.
   →The internal wall surface must have sufficient water vapour resistance (5:1 rule).
3. If the internal wall surface has proper air and vapour barriers, both cellulose and mineral wool insulation can be used.
4. The moisture-retention capacity of wood-based materials delays the onset of condensation but is not always enough to prevent condensate from forming.
5. Surplus moisture retained by materials increases the risk of condensation of a structure. In the case of wood-based materials the risk is high since they can retain a lot of moisture.
6. A windshield sufficiently permeable to water vapour must be attached to the external wall surface in order to allow surplus moisture to exit. There must also be a functioning ventilation gap outside the windshield.

Effect of convection

1. All wall structures perform safely with regard to convection if
   - underpressure prevails in the building **or**
   - the structure has a solid air barrier
2. Internal underpressure does not reduce moisture contents of a perforated wall structures significantly compared to a situation where there is no pressure difference. However, underpressure prevents the build-up of overpressure in a building.
3. Internal overpressure increases the equilibrium moisture contents of a perforated wall structure and increases its risks for condensation and moulding.
4. Condensation is possible in a moisture-permeable wall structure despite pressure difference (diffusion).
5. The risk of condensation exists for a wall structure with a vapour barrier only if the structure has holes clear through the internal surfaces and there is overpressure.
6. The use of cellulose insulation slows down increases in RH values in overpressure situations at holes, but in the final end the moisture rates of the structure correspond to those of a mineral wool wall.
7. When holes penetrate only the air/vapour barrier, RH values are not affected by pressure difference. This applies also to the attachment of the inner sheet to the bracing through an air/vapour barrier.
8. Joints of the inner sheet and air/vapour barrier at the bracing have no effect on the RH values of the wall structure in over- or underpressure situations. A 200-mm overlap is sufficient at the joint of an air/vapour barrier. Taping of joints is always recommended but is not necessary at the bracing.

Other test results

1. Calculated values differ from the real-life situation the more, the more permeable the wall structure is.

   →It is difficult to determine the moisture specifications of a wall structure permeable to moisture.
2. A permeable wall structure is incapable of increasing the indoor air humidity in winter.
3. Overpressure raises significantly temperatures on the internal surface of the windshield in structures with holes clear through the internal surface.
4. Exterior cladding increases the temperature in the ventilation gap compared to outdoors whereby the RH values on the internal surface of the windshield drop in the case of airtight and vapourtight structures.
5. Under winter conditions the wall structures do not generally provide temperature or RH conditions conducive to mould growth.

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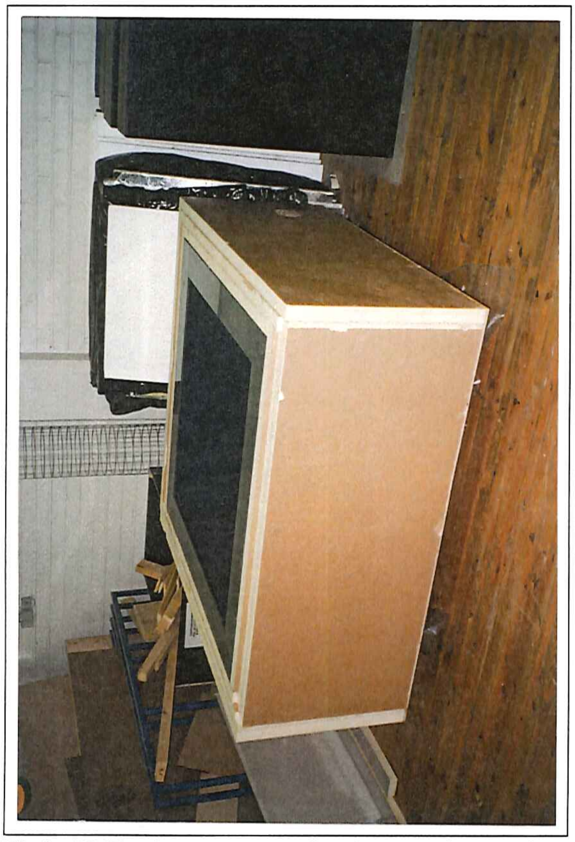
List of appendices

Appendix I

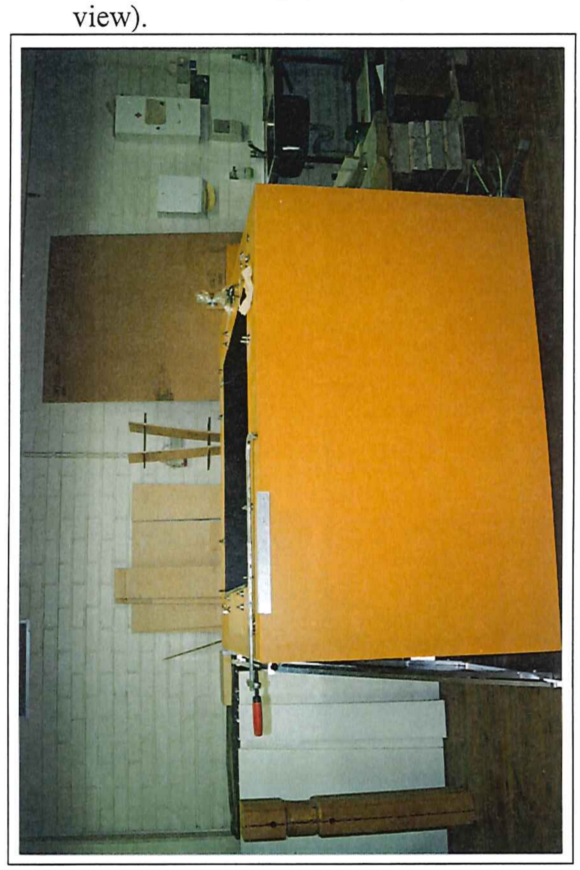
Photographs of the building of the warm chamber



Ill 1. PUR sheets were glued onto the enclosurewelded of PVC sheets (rotate to view).

Ill 2. The support structure of the test opening was made of wood and the faces of laminated plywood (rotate to view).

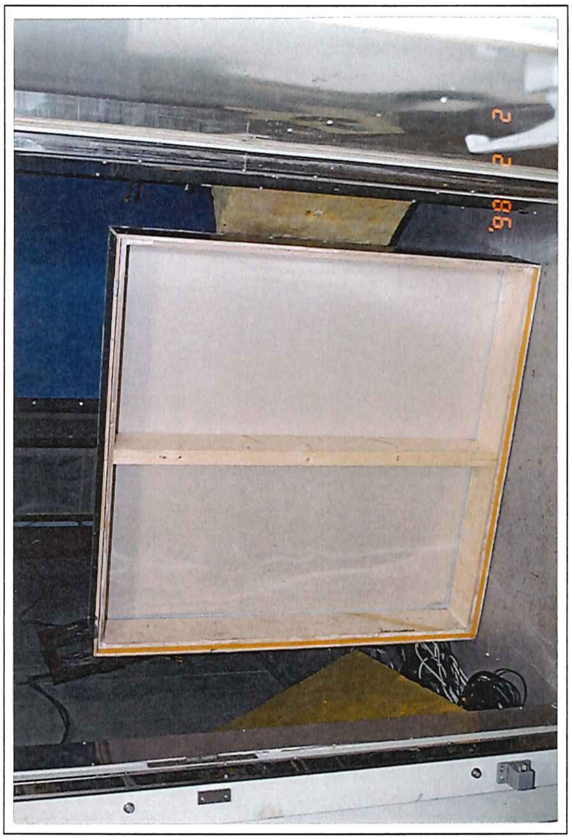
Ill 3. All external surfaces of the warm chamber were made of film faced plywood (rotate to view).



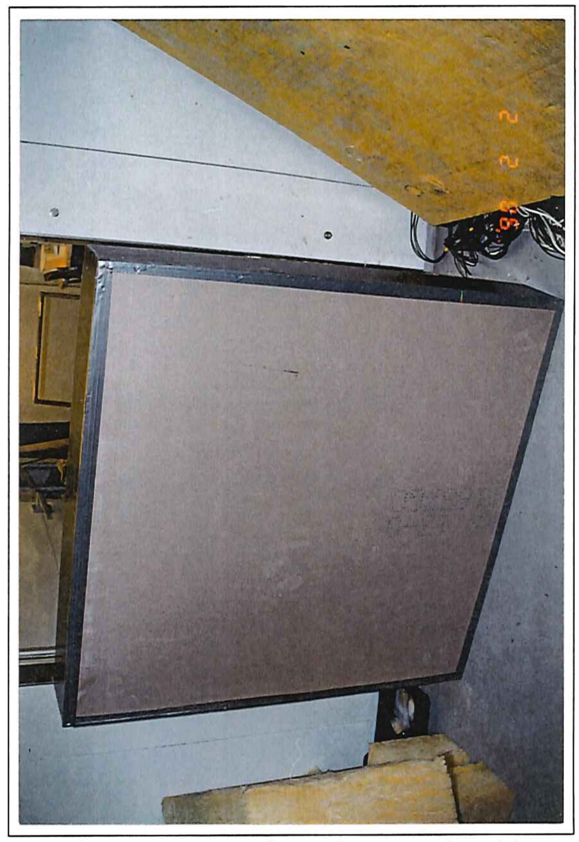
Ill 4. Finished warm chamber except for external moisture insulation and aluminium frame (rotate to view).

Appendix II

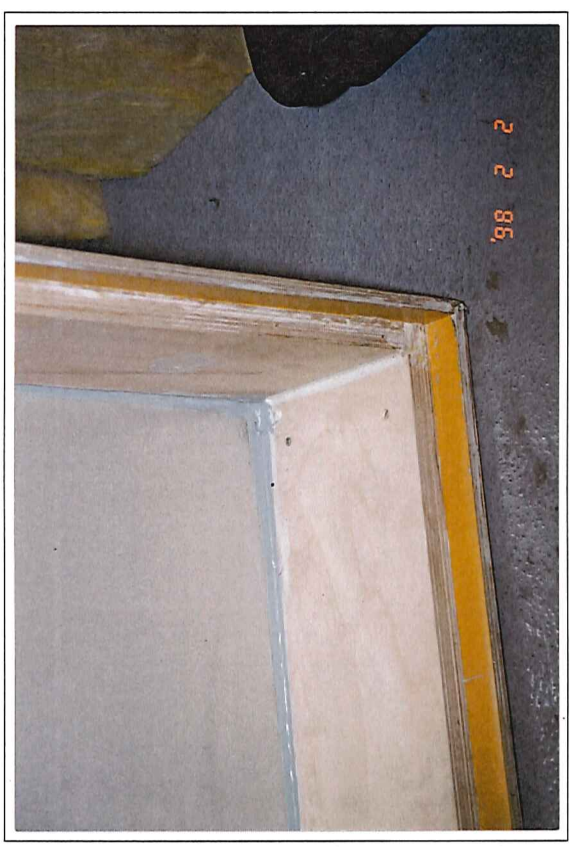
Photographs of test wall construction



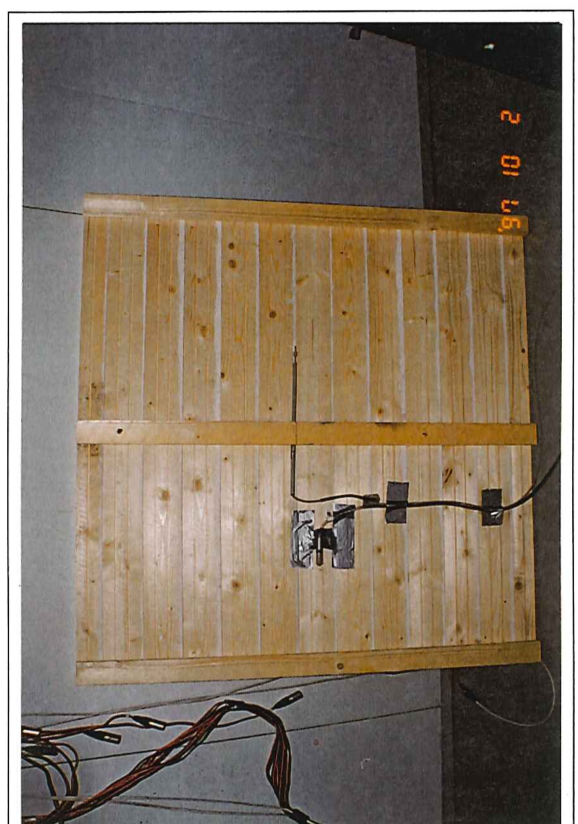
Ill 1. Frame and bracing of test element to which vapour barrier and inner sheet have been attached (rotate to view).



Ill 2. Same structure from the opposite side as in Ill. 1. The inner sheet used here was a gypsum board (rotate to view).



Ill 3. Structural principle of enclosure. All joints were sealed with frost-resistant silicone compound (rotate to view).

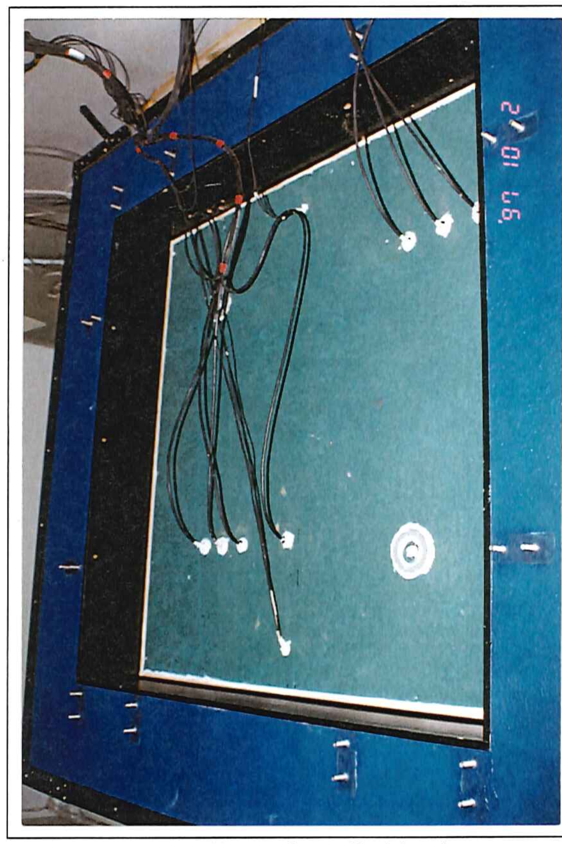


Ill 4. Detachable horizontal paneling was used as exterior cladding in test walls. An air-flow and a moisture sensor were attached to the cladding; the surface temperature sensors are missing (rotate to view).

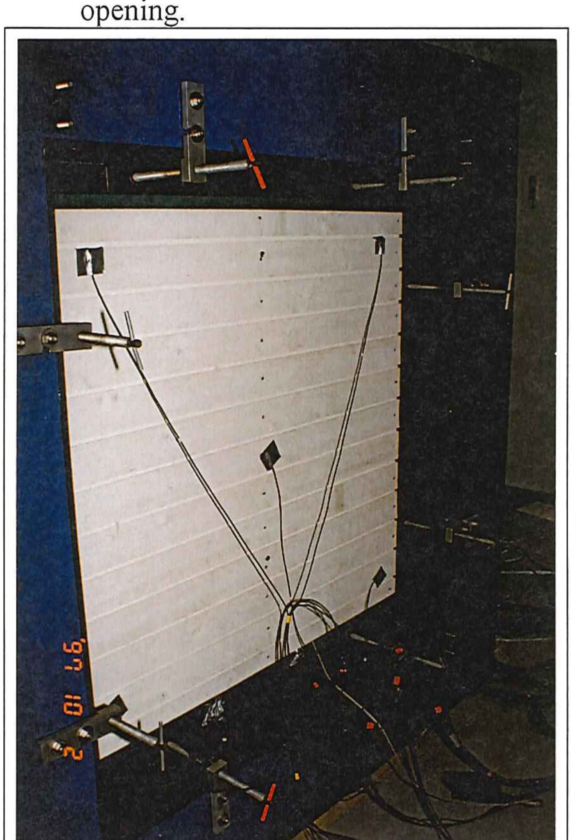
Appendix III

Photographs of test wall installation

Ill 1. Surface temperature sensors were installed on the internal surface of finished test wall. Subsequently, the wall was ready for installation in the test opening.



Ill 2. The test wall was installed in the test opening and the edges were sealed. The photo shows the leads of sensors placed in the structure and the pluggings of sampling holes.

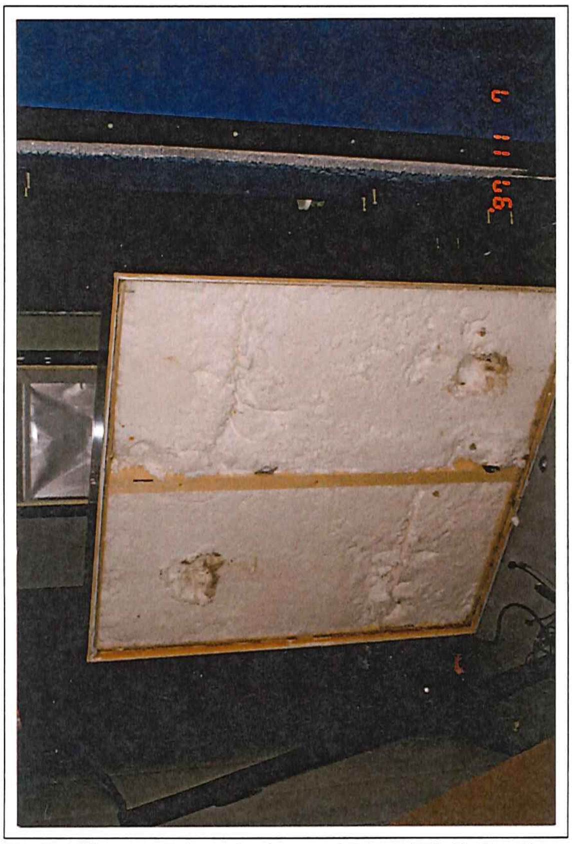


Ill 3. The test wall was tightened into place with a band clamp and the exterior cladding was attached.

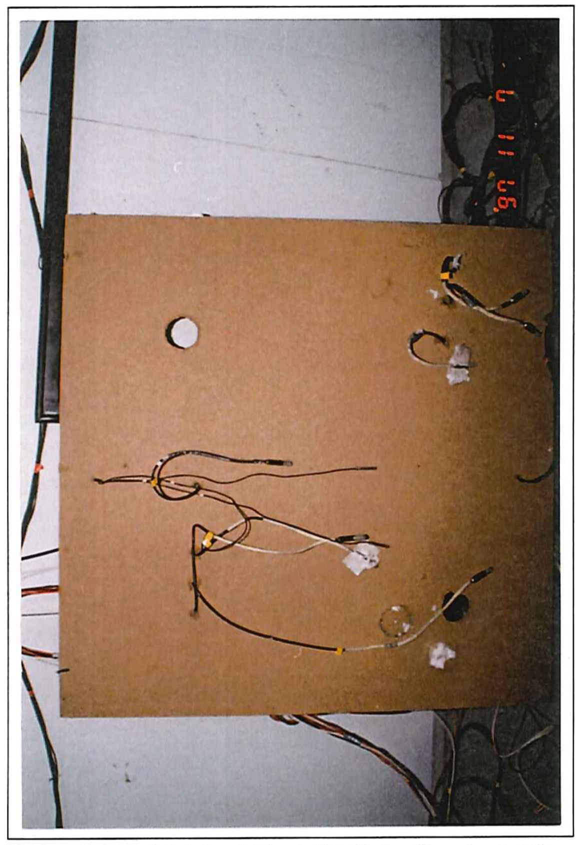
Ill 4. The external protective board with sensors was attached.

Appendix IV

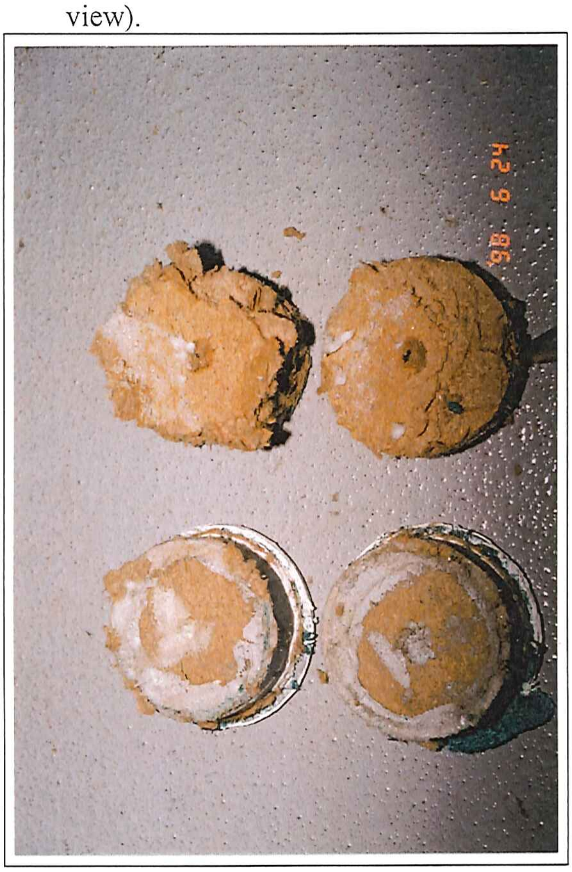
Photographs of conducted tests



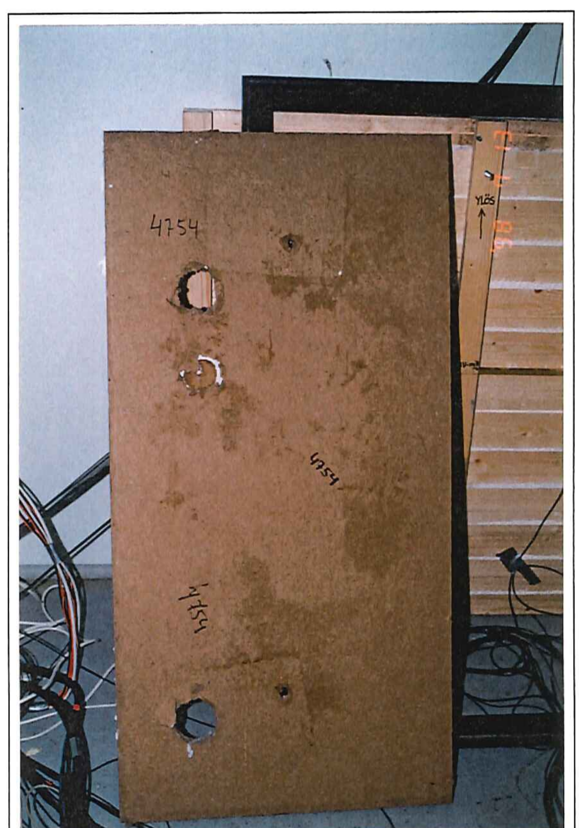
Ill 1. Thermal insulation of Test Wall 1 after test. Thermal insulation was installed in similar fashion in all test walls (rotate to view).



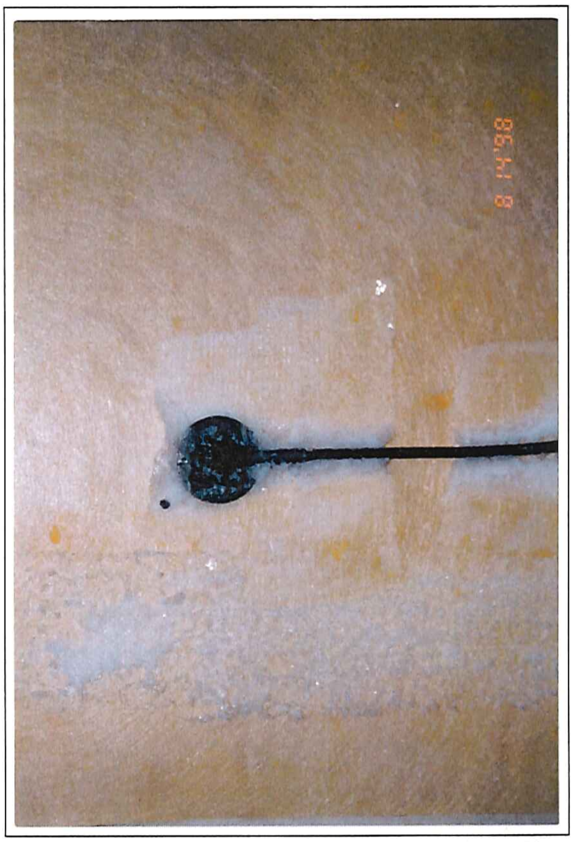
Ill 2. Windshield of Test Wall 1 after test. No water condensed on the windshield during testing (rotate to view).



Ill 3. Samples taken from Test Wall 2 after underpressure period. Ice had already formed on windshield (rotate to view).



Ill 4. The windshield of Test Wall 2 appeared wet all over after the test.



Ill 5. In Test Wall 4, icing occurred on the outer surface of the windshield under the tape holding the temperature sensors in place (rotate to view).

Ill 6. The wood fibre insulation of Test Wall 5 was stuffed in place manually. Appearance of insulation after test (rotate to view).

Ill 7. In Test Wall 8 heavy condensation occurred on the backside of the windshield (rotate to view).

Ill 8. In Test Wall 8 the thermal insulation froze to the windshield almost everywhere (rotate to view).

Appendix V

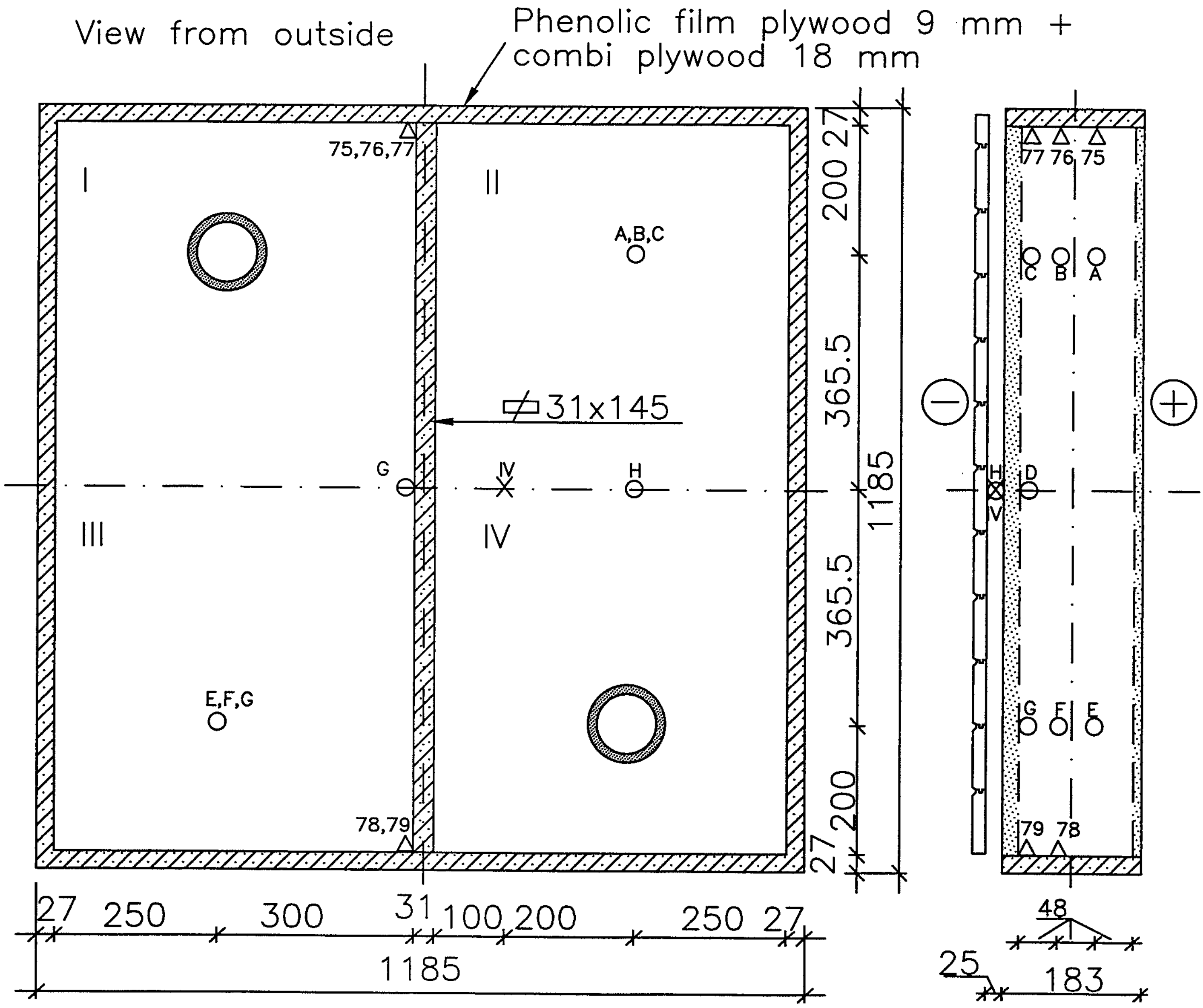
Structure sections of test walls and placement of sensors

TUT/BC Building physical test equipment	Subject: TEST WALL 1	Content: Dimensions of test element and positioning of measuring sensors	Test period: 03.10–07.11.97

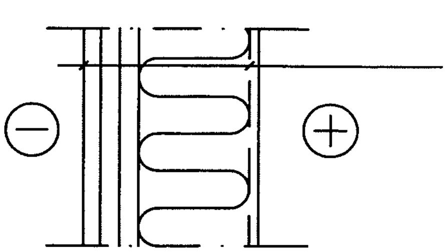
LEGEND

RH/temperature sensor A...H ○   Air flow transmitter X
Temperature sensor 75...79 △   Pieces of wood ◯

ELEMENT SIZE: 1185*1185, thickness 183 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)



STRUCTURE



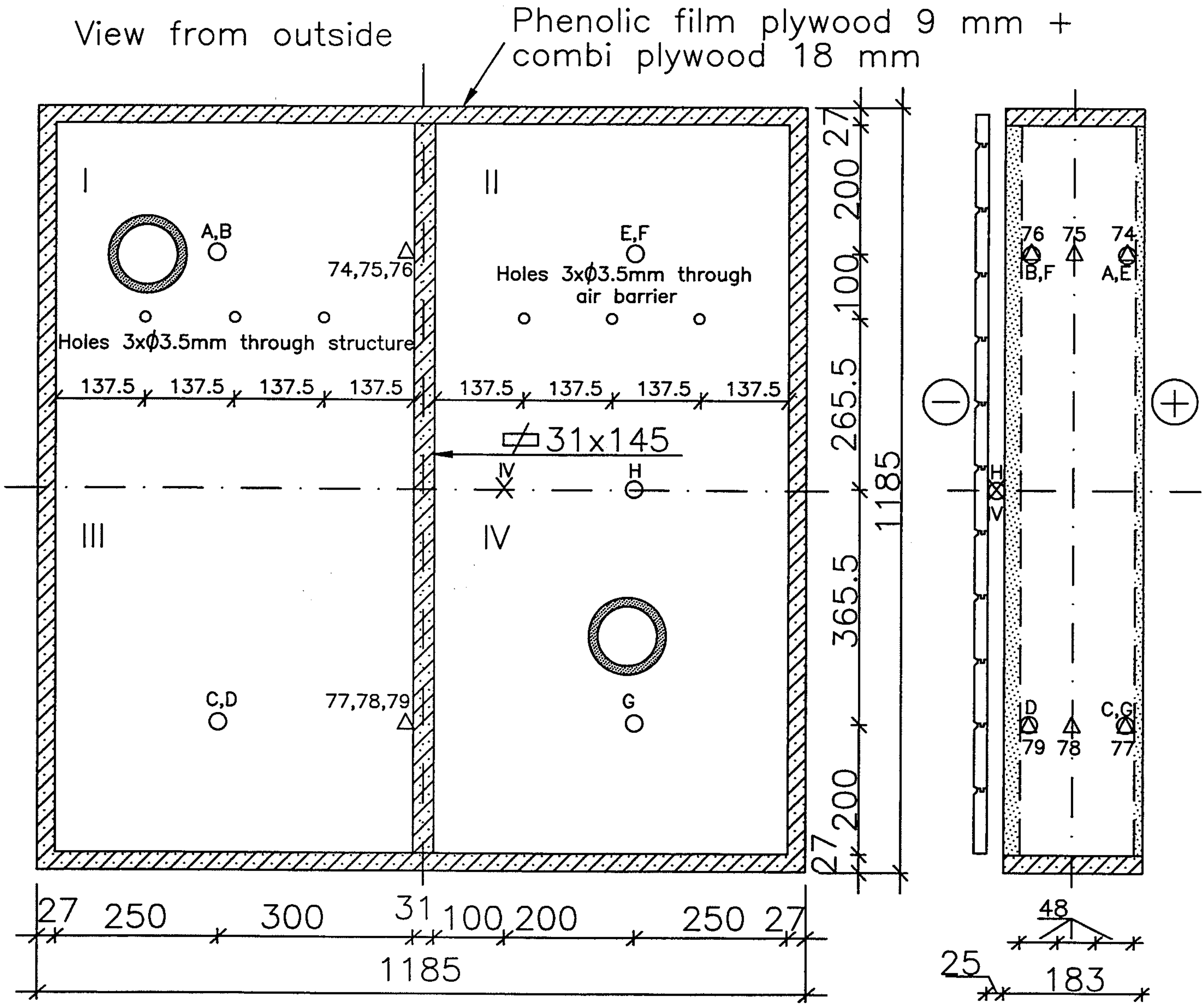
External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (25 mm)
Cellulose–insulation (145 mm)
Bitumen paper
Gypsum board (13 mm)

TUT/BC Building physical test equipment	Subject TEST WALL 2	Dimensions of test element and positioning of measuring sensors	Test period 15.06–13.07.98

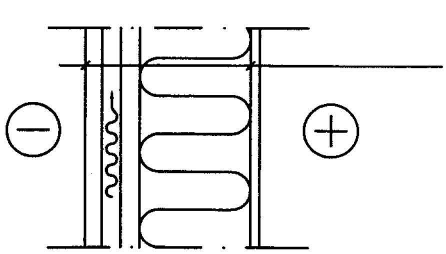
LEGEND

RH/temperature sensor A...H ○ — Air flow transmitter X
Temperature sensor 75...79 △ — Pieces of wood ◯

ELEMENT SIZE: 1185*1185, thickness 183 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)



STRUCTURE



External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (25 mm)
Cellulose–insulation (145 mm)
Bitumen paper
Gypsum board (13 mm)

TUT/BC Building physical test equipment	Subject TEST WALL 3	Dimensions of test element and positioning of measuring sensors	Test period 05.01– 02.02.98

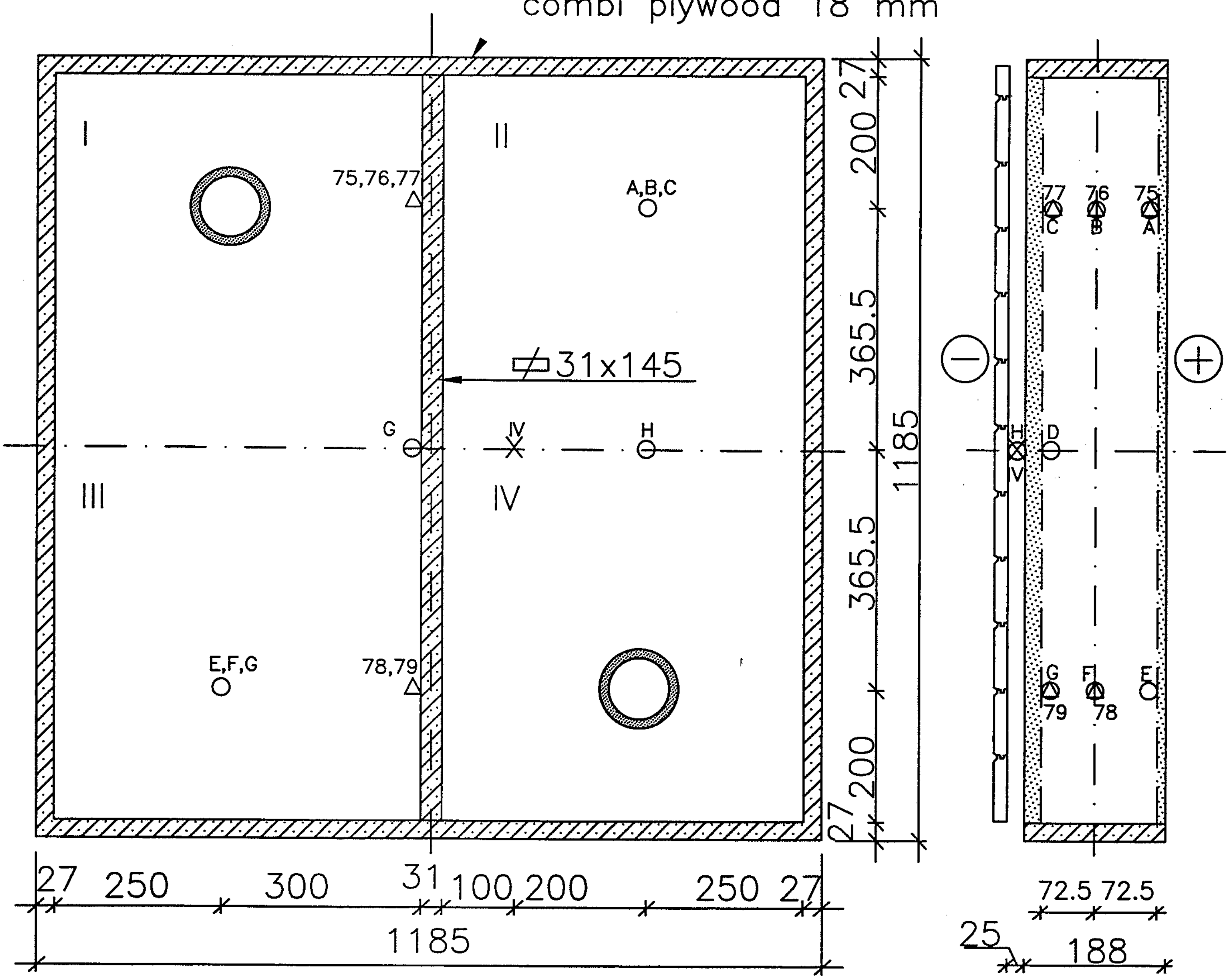
LEGEND

RH/temperature sensor A...H ○ — Air flow transmitter X
Temperature sensor 75...79 △ — Pieces of wood ○

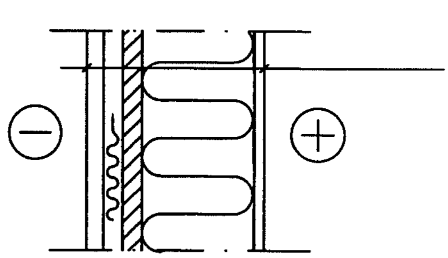
ELEMENT SIZE: 1185*1185, thickness 188 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)

View from outside

Phenolic film plywood 9 mm + combi plywood 18 mm



STRUCTURE



External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Hard mineral wool (30 mm)
Mineral wool (145 mm)
Vapour barrier (0.2 mm PE)
Gypsum board (13 mm)

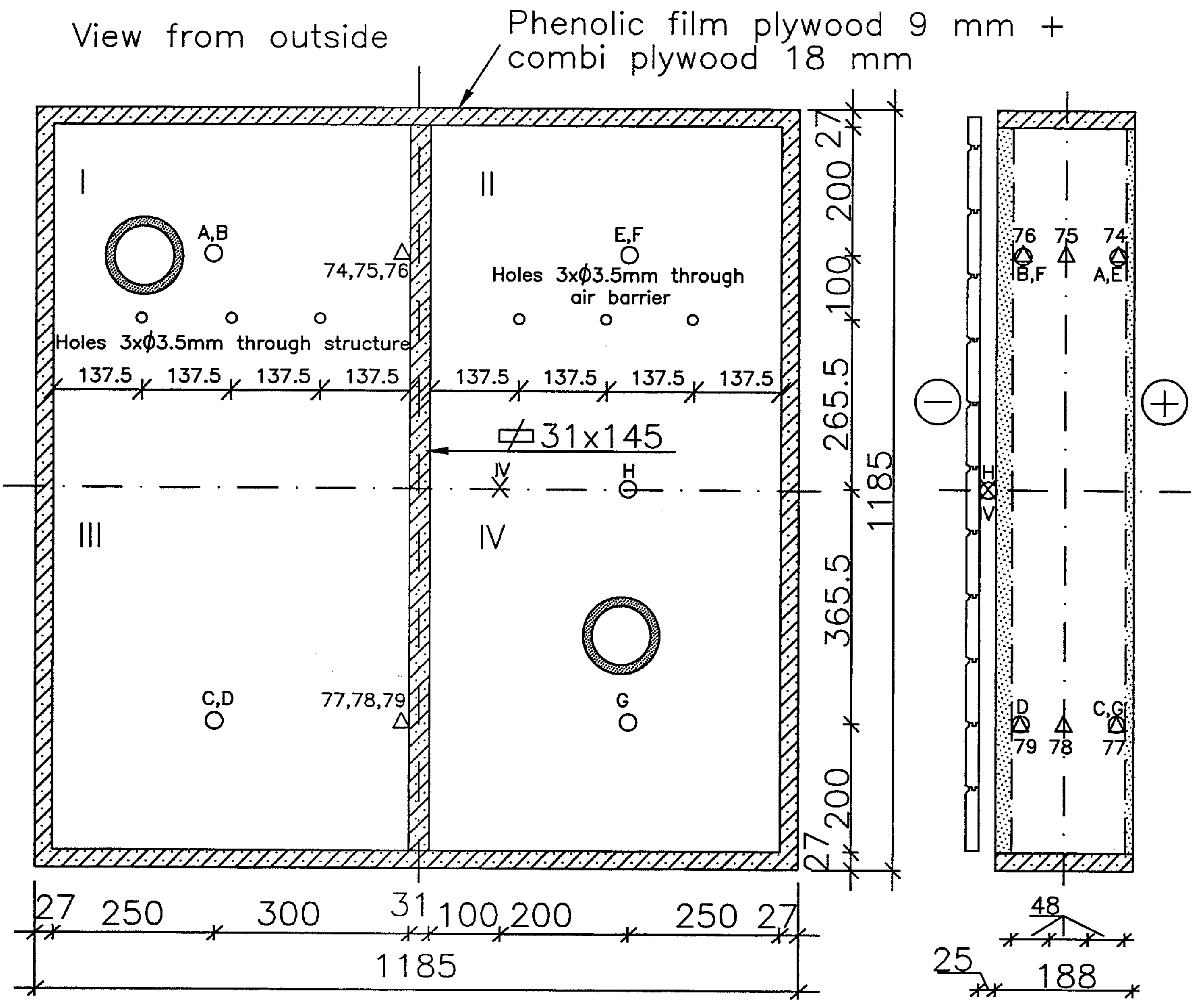
TUT/BC Building physical test equipment	Subject TEST WALL 4	Dimensions of test element and positioning of measuring sensors	Test period 17.07–14.08.98

LEGEND

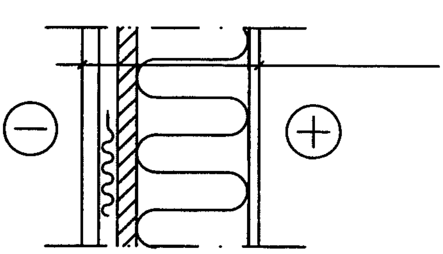
RH/temperature sensor A...H ○ Air flow transmitter X
Temperature sensor 75...79 △ Pieces of wood ◯

ELEMENT SIZE: 1185*1185, thickness 188 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)

View from outside



STRUCTURE



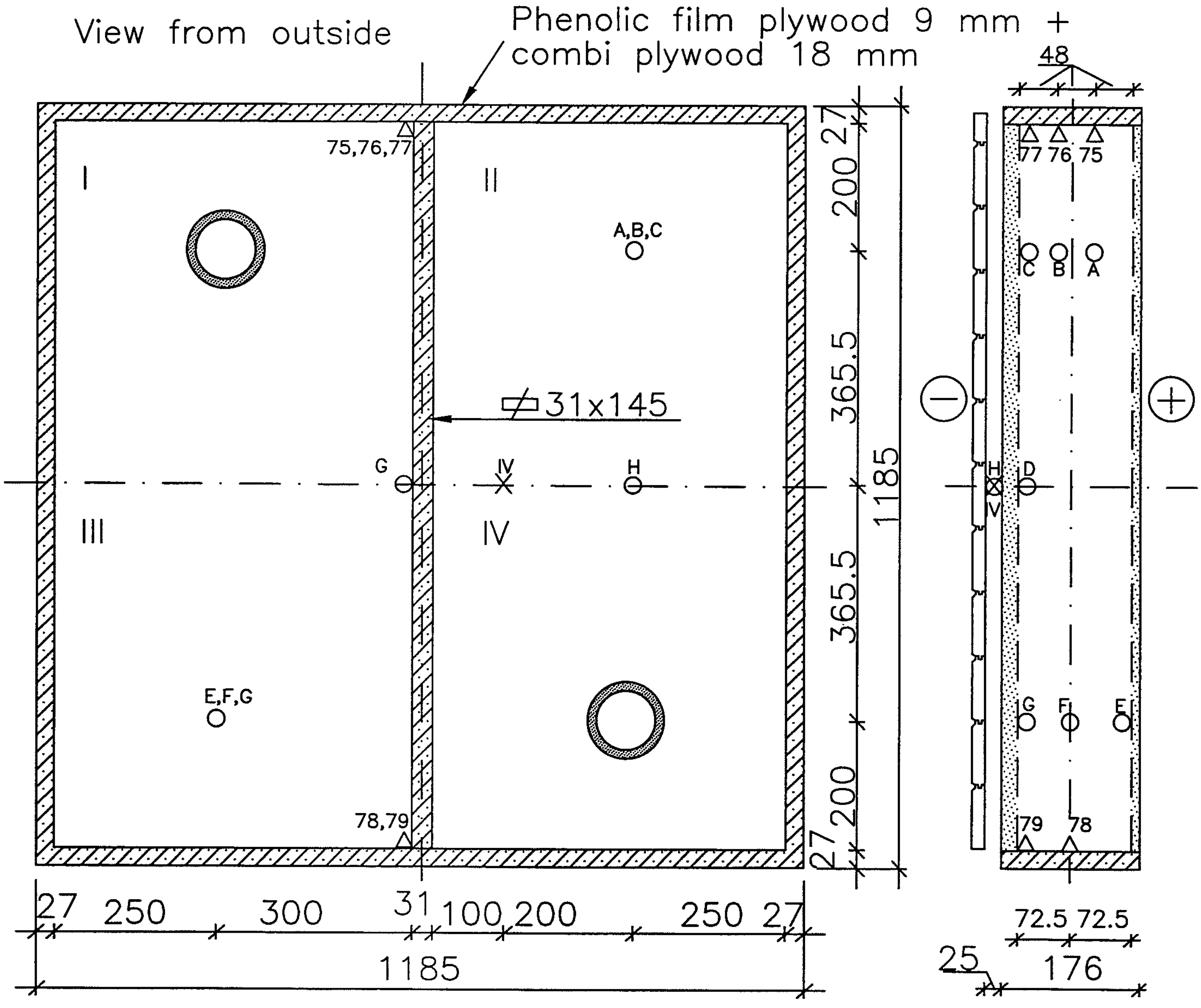
External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Hard mineral wool (30 mm)
Mineral wool (145 mm)
Vapour barrier (0.2 mm PE)
Gypsym board (13 mm)

TUT/BC Building physical test equipment	Subject: TEST WALL 5	Dimensions of test element and positioning of measuring sensors	Test period: 22.11–19.12.97

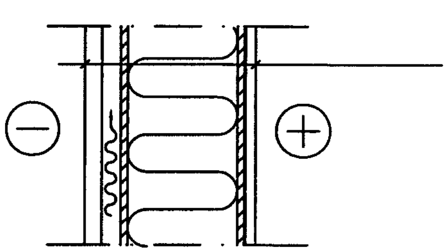
LEGEND

RH/temperature sensor (A...H) ○ — Air flow transmitter X
Temperature sensor (75...79) △ — Pieces of wood ◯

ELEMENT SIZE: 1185*1185, thickness 176 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)



STRUCTURE



External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Three–ply fir plywood (9 mm)
Cellulose–insulation (145 mm)
Three–ply fir plywood (9 mm)
Bitumen paper
Gypsum board (13 mm)

TUT/BC Building physical test equipment	Subject TEST WALL 6	Dimensions of test element and positioning of measuring sensors	Test period 30.09.– 26.10.98

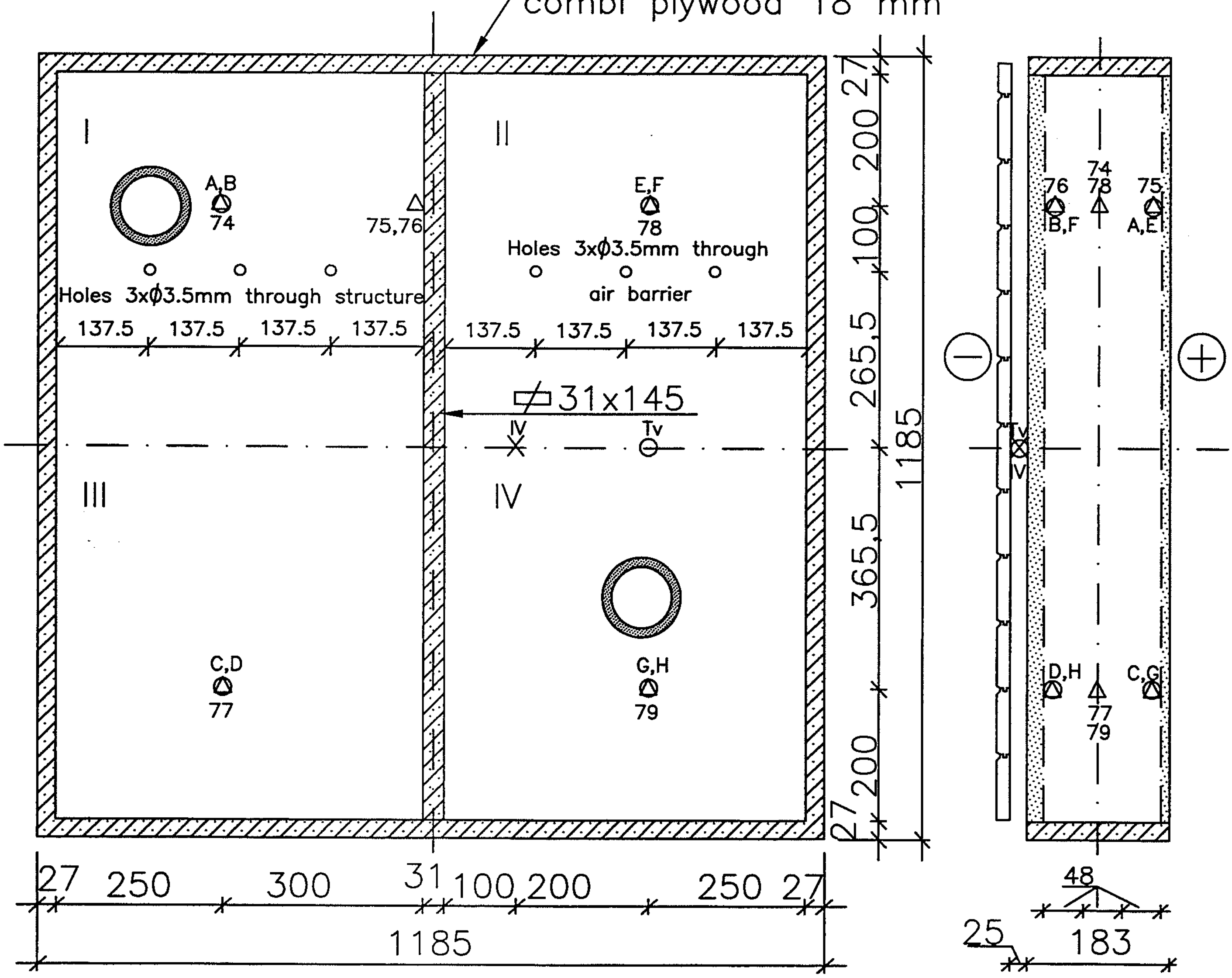
LEGEND

RH/temperature sensor A...H ○ — Air flow transmitter X
Temperature sensor 75...79 △ — Pieces of wood ○

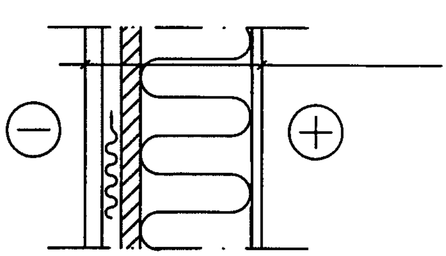
ELEMENT SIZE: 1185*1185, thickness 183 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)

View from outside

Phenolic film plywood 9 mm + combi plywood 18 mm



STRUCTURE



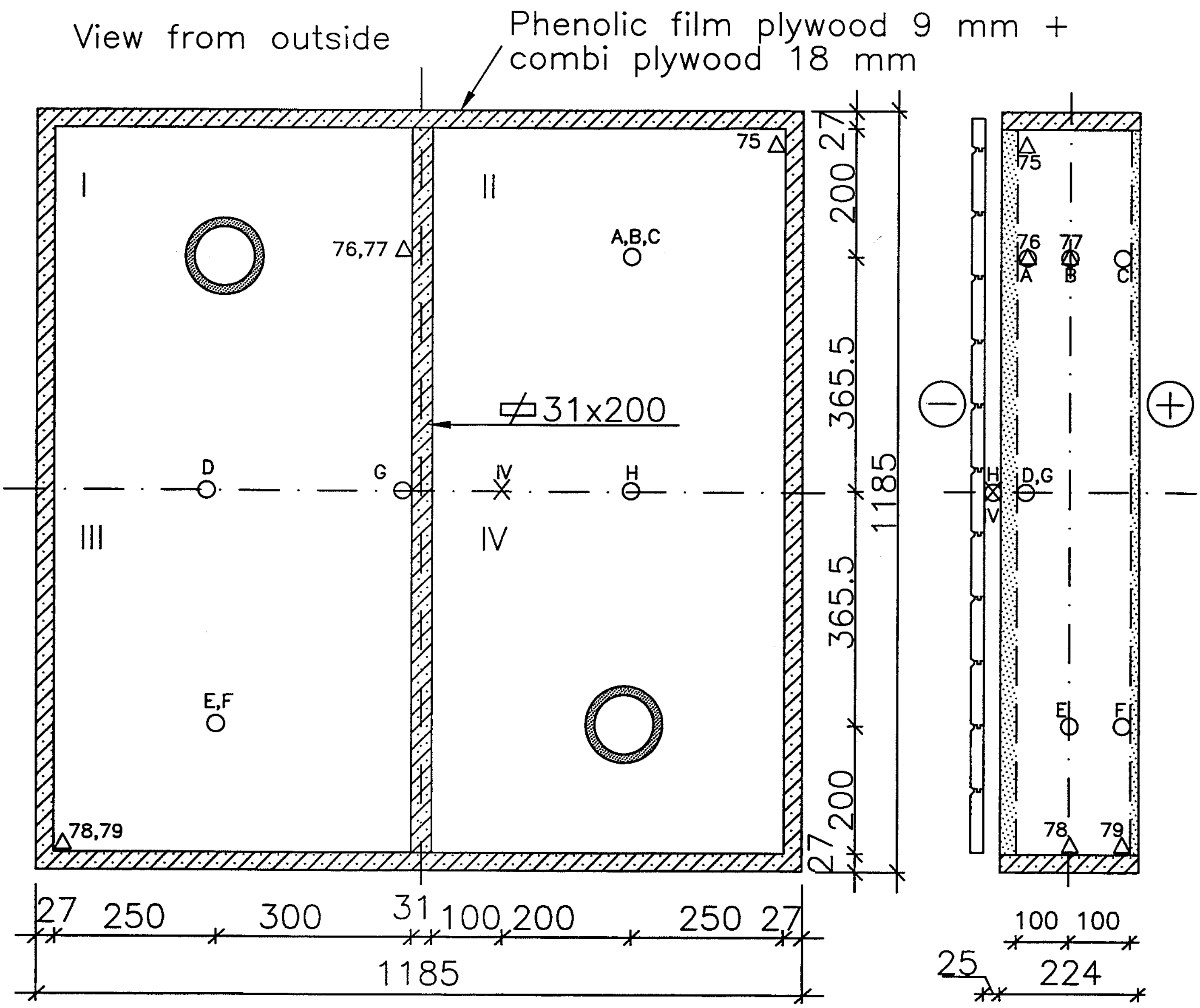
External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (25 mm)
Cellulose–insulation (145 mm)
Vapour barrier (0.2 mm PE)
Gypsum board (13 mm)

TUT/BC Building physical test equipment	Subject: TEST WALL 7	Dimensions of test element and positioning of measuring sensors	Test period: 19.09.– 29.09.97

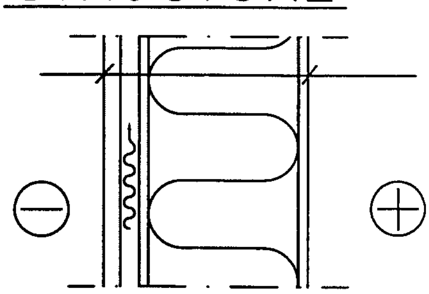
LEGEND

RH/temperature sensor	○ A...H	Air flow transmitter	X
Temperature sensor	△ 75...79	Pieces of wood	◯

ELEMENT SIZE: 1185*1185, thickness 224 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)



STRUCTURE



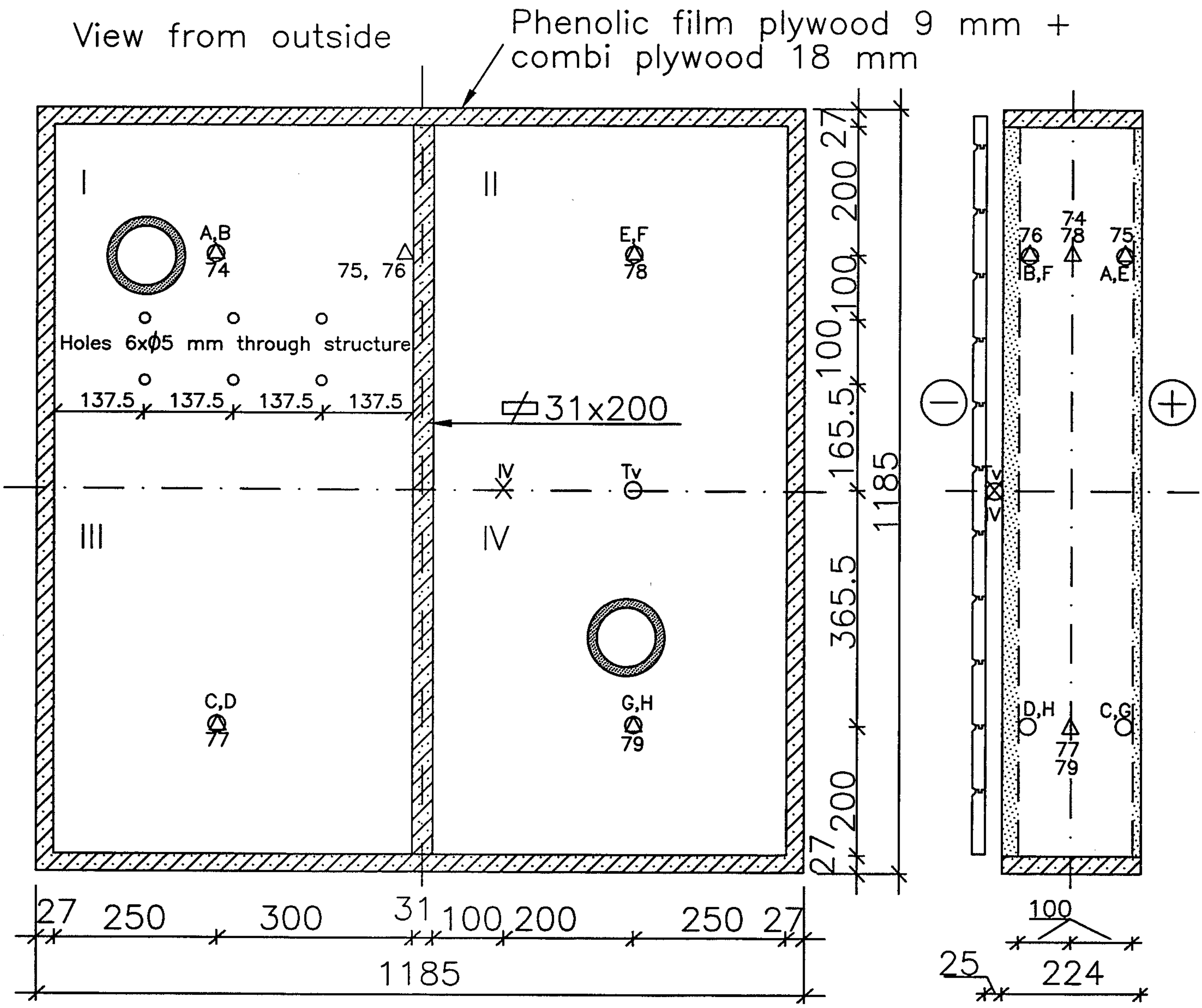
External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (12 mm)
Mineral wool (2x100 mm)
Building paper
Porous fibreboard (12 mm)

TUT/BC Building physical test equipment	Subject TEST WALL 8	Dimensions of test element and positioning of measuring sensors	Test period 25.08.– 28.09.98

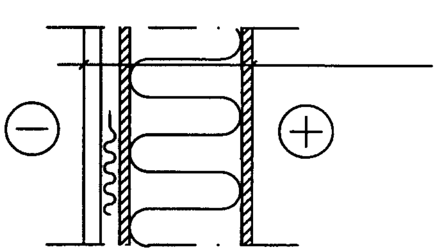
LEGEND

RH/temperature sensor (A...H)
Temperature sensor (75...79)
Air flow transmitter X
Pieces of wood

ELEMENT SIZE: 1185*1185, thickness 224 mm (excl. external cladding)
Pretest storage of windshield and thermal insulation: RH 35 % (+20 °C)



STRUCTURE



External cladding, horizontal paneling (22 mm)
Ventilation gap (25 mm)
Porous fibreboard (12 mm)
Cellulose insulation (200 mm)
Building paper
Porous fibreboard (12 mm)

Appendix VI

Results of tests

TEST RESULTS (Test Wall 1)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**257,3**	**308,3**	**264,0**
Indoor air temperature	T_i	°C	20,01	20,01	20,04
Outdoor air temperature	T_o	°C	-10,00	-10,00	-9,99
Indoor air relative humidity (RH)	ϕ_i	%	50,0	49,6	49,8
Outdoor air relative humidity (RH)	ϕ_o	%	90,0	90,0	90,0
Pressure difference across structure	Δp_{str}	Pa	-10,0	0,2	9,9
Temp. on inner surface of structure	T_{ip}	°C	18,87	18,48	18,51
Temp. on outer surface of windshield	T_{ws}	°C	-8,49	-8,52	-8,48
Temp. on inner baffle	T_{ib}	°C	19,64	19,62	19,65
Temp. on outer baffle	T_{ob}	°C	-10,17	-10,18	-10,16
Environmental inside temperature	T_{ei}	°C	19,90	19,88	19,88
Environmental outside temperature	T_{eo}	°C	-10,03	-10,02	-10,01
Cold room temperature	T_{cr}	°C	-12,80	-12,73	-12,76
Cold room relative humidity (RH)	ϕ_{cr}	%	66,1	63,5	64,8
Indoor air humidity by volume	ν_i	g/m³	8,64	8,58	8,63
Outdoor air humidity by volume	ν_o	g/m³	1,97	1,98	1,98
Cold room humidity by volume	ν_{cr}	g/m³	1,12	1,09	1,11
Heat flow rate from outside in	Φ_{tot}	W	51,8	51,4	51,5
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,20	0,21	0,21
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,19	0,19	0,16
Air flow rate through structure	R_{str}	l/min	-0,047	0	0,030
Density of air flow rate through structure	r_{str}	l/min•m²	-0,036	0	0,023
Velocity of air flow through structure	r_{vel}	m/s	-5,95E-07	0	3,82E-07
Volume of air transmitted through structure	V_{str}	l	-779	0	365
Moisture flow rate to structure	G_{str}	g/day	24,8	24,8	23,7
Moisture flow rate to structure by convection	G_{con}	g/day	-0,1	0	0,1
Moisture flow rate to structure by diffusion	G_{dif}	g/day	24,9	24,8	23,6
Density of moisture flow rate to structure	g_{str}	g/day•m²	18,7	18,8	17,9
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-0,1	0	0,1
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	18,8	18,8	17,9
Moisture transmitted to structure	m_{str}	g	266	325	264
Moisture retained by windshield (*	m_{ws}	g	471	129	103
Water vapour permeance of structure(**	$W_{v,str}$	m/s	3,27E-05	3,29E-05	3,11E-05

Variable	Symbol	Unit	Underpres.	$\Delta p = 0$	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-8,70	-8,76	-8,80
Temperature at point A	T_{strA}	°C	10,46	10,35	10,36
Temperature at point B	T_{strB}	°C	3,46	3,31	3,28
Temperature at point C	T_{strC}	°C	-2,80	-2,93	-2,97
Temperature at point D	T_{strD}	°C	-1,53	-1,62	-1,61
Temperature at point E	T_{strE}	°C	9,65	9,53	9,61
Temperature at point F	T_{strF}	°C	1,59	1,46	1,51
Temperature at point G	T_{strG}	°C	-4,70	-4,76	-4,73
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	79,4	81,2	81,6
Relative humidity at point A (RH)	ϕ_{strA}	%	36,9	39,6	40,3
Relative humidity at point B (RH)	ϕ_{strB}	%	51,8	56,3	57,8
Relative humidity at point C (RH)	ϕ_{strC}	%	72,0	79,3	81,7
Relative humidity at point D (RH)	ϕ_{strD}	%	60,9	66,8	68,8
Relative humidity at point E (RH)	ϕ_{strE}	%	34,3	37,1	37,9
Relative humidity at point F (RH)	ϕ_{strF}	%	51,6	56,4	58,0
Relative humidity at point G (RH)	ϕ_{strG}	%	70,1	77,2	79,8
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,95	1,98	1,99
Humidity by volume at point A	v_{strA}	g/m³	3,59	3,83	3,90
Humidity by volume at point B	v_{strB}	g/m³	3,20	3,44	3,52
Humidity by volume at point C	v_{strC}	g/m³	2,85	3,10	3,18
Humidity by volume at point D	v_{strD}	g/m³	2,64	2,88	2,97
Humidity by volume at point E	v_{strE}	g/m³	3,17	3,40	3,49
Humidity by volume at point F	v_{strF}	g/m³	2,80	3,03	3,13
Humidity by volume at point G	v_{strG}	g/m³	2,39	2,62	2,72

MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES

Moisture content of pieces of wood (top of structure)	u_{wd}	%	13,8	16,7	18,0
Moisture content of pieces of wood (bottom of structure)	u_{wd}	%	13,8	16,8	17,9
Moisture content of cellulose insulation on outside (top)	u_{ins}	%	13,8	14,5	14,5
Moisture content of cellulose insulation on outside (bottom)	u_{ins}	%	12,5	14,7	16,5
Moisture content of windshield (top of structure)	u_{ws}	%	13,5	15,0	16,2
Moisture content of windshied (bottom of structure)	u_{ws}	%			
Moisture content of bracing (9.0 % at start of test)	w_{br}	%			9,9
Moisture retained by thermal insulation	m_{ins}	g			
Water retained by frame	m_f	g			
Moisture retained by windshield	m_{ws}	g			

*) Value derived from moisture contents of windshield

**) The moisture contents of the structure were not at equilibrium

Visual observations

No condensation or icing could be detected on the inner surface of the windshied at any phase.
The sheet felt dry to the touch throughout the test. The cellulose insulation also appeared dry.

TEST RESULTS (Test Wall 2)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**206,0**	**211,8**	**197,8**
Indoor air temperature	T_i	°C	20,01	20,04	19,92
Outdoor air temperature	T_o	°C	-9,92	-9,89	-9,98
Indoor air relative humidity (RH)	ϕ_i	%	50,0	50,6	47,6
Outdoor air relative humidity (RH)	ϕ_o	%	89,9	89,9	90,0
Pressure difference across structure	Δp_{str}	Pa	-9,9	-0,5	10,2
Temp. on inner surface of structure	T_{ip}	°C	18,62	18,70	18,61
Temp. on outer surface of windshield	T_{ws}	°C	-7,81	-7,81	-7,74
Temp. on inner baffle	T_{ib}	°C	19,24	19,27	19,16
Temp. on outer baffle	T_{ob}	°C	-10,30	-10,22	-10,36
Environmental inside temperature	T_{ei}	°C	19,67	19,73	19,72
Environmental outside temperature	T_{eo}	°C	-10,20	-10,11	-10,15
Cold room temperature	T_{cr}	°C	-12,77	-12,28	-12,93
Cold room relative humidity (RH)	ϕ_{cr}	%	69,3	71,3	70,4
Indoor air humidity by volume	ν_i	g/m³	8,64	8,76	8,19
Outdoor air humidity by volume	ν_o	g/m³	1,99	1,99	1,98
Cold room humidity by volume	ν_{cr}	g/m³	1,18	1,29	1,18
Heat flow rate from outside in	Φ_{tot}	W	48,5	53,1	54,9
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,16	0,01	0,01
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,09	0,07	0,08
Air flow rate through structure	R_{str}	l/min	-1,41	0	1,67
Density of air flow rate through structure	r_{str}	l/min•m²	-1,07	0	1,26
Velocity of air flow through structure	r_{vel}	m/s	-1,78E-05	0	2,10E-05
Volume of air transmitted through structure	V_{str}	l	-15000	0	19740
Moisture flow rate to structure	G_{str}	g/day	20,2	28,8	43,8
Moisture flow rate to structure by convection	G_{con}	g/day	-3,9	0	19,7
Moisture flow rate to structure by diffusion	G_{dif}	g/day	24,2	28,8	24,1
Density of moisture flow rate to structure	g_{str}	g/day•m²	15,3	21,8	33,1
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-3,0	0	14,9
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	18,3	21,8	18,2
Moisture transmitted to structure	m_{str}	g	174	254	361
Air permeance of structure	K_{str}	m/s•Pa	1,79E-06	0	2,05E-06
Water vapour permeance of structure(*	$W_{v,str}$	m/s	3,18E-05	3,72E-05	3,39E-05

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-9,18	-9,08	-9,03
Temperature at point A	T_{strA}	°C	18,00	18,21	18,16
Temperature at point B	T_{strB}	°C	-4,00	-3,66	-2,96
Temperature at point C	T_{strC}	°C	17,45	17,63	17,52
Temperature at point D	T_{strD}	°C	-4,77	-4,38	-3,98
Temperature at point E	T_{strE}	°C	16,49	16,63	16,45
Temperature at point F	T_{strF}	°C	-3,15	-3,27	-3,29
Temperature at point G	T_{strG}	°C	16,84	16,93	16,70
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	82,0	81,8	81,8
Relative humidity at point A (RH)	ϕ_{strA}	%	30,4	30,1	37,5
Relative humidity at point B (RH)	ϕ_{strB}	%	88,5	88,6	89,5
Relative humidity at point C (RH)	ϕ_{strC}	%	31,0	29,2	29,3
Relative humidity at point D (RH)	ϕ_{strD}	%	90,9	91,2	91,6
Relative humidity at point E (RH)	ϕ_{strE}	%	39,5	36,0	35,3
Relative humidity at point F (RH)	ϕ_{strF}	%	91,8	92,0	91,8
Relative humidity at point G (RH)	ϕ_{strG}	%	34,2	30,8	29,8
Humidity by volume of ventilation gap	ν_{vg}	g/m³	1,94	1,95	1,95
Humidity by volume at point A	ν_{strA}	g/m³	4,68	4,68	5,83
Humidity by volume at point B	ν_{strB}	g/m³	3,19	3,28	3,49
Humidity by volume at point C	ν_{strC}	g/m³	4,62	4,40	4,37
Humidity by volume at point D	ν_{strD}	g/m³	3,09	3,19	3,30
Humidity by volume at point E	ν_{strE}	g/m³	5,55	5,10	4,95
Humidity by volume at point F	ν_{strF}	g/m³	3,53	3,51	3,49
Humidity by volume at point G	ν_{strG}	g/m³	4,91	4,44	4,24
MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES					
Moisture content of pieces of wood (top of structure)	u_{wd}	%	26,5	22,7	29,1
Moisture content of pieces of wood (bottom of structure)	u_{wd}	%	26,2	22,0	18,4
Moisture content of pieces of cellulose insulation at the start of test	u_{wd}		25,3		
Moisture content of windshield at the start of test	u_{ws}		21,9		
Moisture content of cellulose insulation on outside (holes through internal surface)	u_{ins}	%	34,9	24,4	33,6
Moisture content of cellulose insulation on outside (holes through air barrier)	u_{ins}	%	42,8	24,2	20,1
Moisture content of windshield (holes through int. surf.)	u_{ws}	%	21,8	32,9	24,5
Moisture content of windshied (holes through air barrier)	u_{ws}	%	24,8	21,9	21,1
Moisture content of bracing (12.5 % at start of test)	w_{br}	%			outs. 15.5 ins. 10.5
Moisture retained by thermal insulation (holes through internal surface) (holes through air barrier)	m_{ins}	g			- 325 - 434
Water retained by frame	m_f	g			171
Moisture retained by windshield (holes through int.surf.) (holes through air barrier)	m_{ws}	g			229 135

*) Measurement result reflects effect of holes

Visual observations

Condensation and icing could be detected on the inner surface of the windshield already after the underpressure period. The sheet and thermal insulation felt damp to the touch throughout the test.

TEST RESULTS (Test Wall 3)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**209,0**	**216,3**	**216,3**
Indoor air temperature	T_i	°C	20,00	20,00	20,00
Outdoor air temperature	T_o	°C	-9,97	-10,01	-9,99
Indoor air relative humidity (RH)	ϕ_i	%	50,2	50,5	50,0
Outdoor air relative humidity (RH)	ϕ_o	%	89,9	90,1	90,0
Pressure difference across structure	Δp_{str}	Pa	-10,5	0,2	9,9
Temp. on inner surface of structure	T_{ip}	°C	18,51	18,53	18,57
Temp. on outer surface of windshield	T_{ws}	°C	-8,42	-8,50	-8,42
Temp. on inner baffle	T_{ib}	°C	19,42	19,42	19,43
Temp. on outer baffle	T_{ob}	°C	-10,34	-10,35	-10,35
Environmental inside temperature	T_{ei}	°C	19,78	19,78	19,79
Environmental outside temperature	T_{eo}	°C	-10,02	-10,05	-10,04
Cold room temperature	T_{cr}	°C	-15,06	-14,38	-14,31
Cold room relative humidity (RH)	ϕ_{cr}	%	49,0	57,3	58,7
Indoor air humidity by volume	ν_i	g/m³	8,68	8,73	8,65
Outdoor air humidity by volume	ν_o	g/m³	1,98	1,97	1,98
Cold room humidity by volume	ν_{cr}	g/m³	0,67	0,84	0,87
Heat flow rate from outside in	Φ_{tot}	W	51,0	51,3	51,2
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,14	0,19	0,20
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,11	0,11	0,10
Air flow rate through structure	R_{str}	l/min	-0,013	0	0,020
Density of air flow rate through structure	r_{str}	l/min•m²	-0,010	0	0,015
Velocity of air flow through structure	r_{vel}	m/s	-1,59E-07	0	2,46E-07
Volume of air transmitted through structure	V_{str}	l	-128	0	242
Moisture flow rate to structure	G_{str}	g/day	0,14	0,26	0,41
Moisture flow rate to structure by convection	G_{con}	g/day	-0,03	0	0,29
Moisture flow rate to structure by diffusion	G_{dif}	g/day	0,17	0,26	0,12
Density of moisture flow rate to structure	g_{str}	g/day•m²	0,10	0,20	0,31
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-0,02	0	0,22
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	0,13	0,20	0,09
Moisture transmitted to structure	m_{str}	g	1,20	2,39	3,66

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-8,84	-8,88	-8,95
Temperature at point A	T_{strA}	°C	18,26	18,20	18,15
Temperature at point B	T_{strB}	°C	6,77	6,42	6,18
Temperature at point C	T_{strC}	°C	-1,41	-1,70	-1,91
Temperature at point D	T_{strD}	°C	-0,96	-0,87	-0,82
Temperature at point E	T_{strE}	°C	17,49	17,56	17,70
Temperature at point F	T_{strF}	°C	5,93	6,24	6,83
Temperature at point G	T_{strG}	°C	-1,89	-1,66	-1,14
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	80,5	81,2	82,4
Relative humidity at point A (RH)	ϕ_{strA}	%	11,0	10,8	10,9
Relative humidity at point B (RH)	ϕ_{strB}	%	24,4	24,6	25,2
Relative humidity at point C (RH)	ϕ_{strC}	%	46,1	46,8	47,8
Relative humidity at point D (RH)	ϕ_{strD}	%	44,1	43,8	44,0
Relative humidity at point E (RH)	ϕ_{strE}	%	12,4	12,3	12,3
Relative humidity at point F (RH)	ϕ_{strF}	%	26,6	25,8	24,8
Relative humidity at point G (RH)	ϕ_{strG}	%	47,5	46,6	45,0
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,95	1,97	1,98
Humidity by volume at point A	v_{strA}	g/m³	1,71	1,68	1,69
Humidity by volume at point B	v_{strB}	g/m³	1,87	1,85	1,86
Humidity by volume at point C	v_{strC}	g/m³	2,02	2,00	2,02
Humidity by volume at point D	v_{strD}	g/m³	2,00	2,00	2,01
Humidity by volume at point E	v_{strE}	g/m³	1,85	1,84	1,86
Humidity by volume at point F	v_{strF}	g/m³	1,93	1,92	1,91
Humidity by volume at point G	v_{strG}	g/m³	2,01	2,00	2,01

WATER VAPOUR CONTENTS MEASURED FROM STRUCTURAL SAMPLES

Moisture content of pieces of wood (top of structure)	u_{wd}	%	8,2	8,2	7,7
Moisture content of pieces of wood (bottom of structure)	u_{wd}	%	10,3	11,7	10,9
Moisture content of mineral wool on outside (top)	u_{ins}	%	2,7	0,8	1,2
Moisture content of mineral wool on outside (bottom)	u_{ins}	%	0,4	0,7	1,0
Moisture content of windshield (top of structure)	u_{ws}	%	1,9	0,7	0,8
Moisture content of windshied (bottom of structure)	u_{ws}	%			
Moisture content of bracing (7.7 % at start of test)	w_{br}	%			9,9
Moisture retained by thermal insulation	m_{ins}	g			17
Water retained by frame	m_f	g			74
Moisture retained by windshield	m_{ws}	g			11

Visual observations

No condensation or icing could be detected on the inner surface of the windshield at any phase. The sheet felt dry to the touch throughout the test. The mineral wool also appeared dry.

TEST RESULTS (Test Wall 4)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**228,5**	**207,5**	**211,5**
Indoor air temperature	T_i	°C	20,00	20,00	20,00
Outdoor air temperature	T_o	°C	-9,99	-10,00	-9,99
Indoor air relative humidity (RH)	ϕ_i	%	50,0	50,8	50,0
Outdoor air relative humidity (RH)	ϕ_o	%	90,0	90,0	90,0
Pressure difference across structure	Δp_{str}	Pa	-9,9	-0,5	10,0
Temp. on inner surface of structure	T_{ip}	°C	18,60	18,61	18,80
Temp. on outer surface of windshield	T_{ws}	°C	-8,40	-8,29	-8,03
Temp. on inner baffle	T_{ib}	°C	19,27	19,18	19,35
Temp. on outer baffle	T_{ob}	°C	-10,33	-10,34	-10,35
Environmental inside temperature	T_{ei}	°C	19,72	19,68	19,77
Environmental outside temperature	T_{eo}	°C	-10,14	-10,17	-10,20
Cold room temperature	T_{cr}	°C	-12,13	-12,29	-12,54
Cold room relative humidity (RH)	ϕ_{cr}	%	70,8	72,6	72,1
Indoor air humidity by volume	ν_i	g/m³	8,64	8,77	8,64
Outdoor air humidity by volume	ν_o	g/m³	1,98	1,98	1,98
Cold room humidity by volume	ν_{cr}	g/m³	1,28	1,30	1,26
Heat flow rate from outside in	Φ_{tot}	W	51,9	50,3	51,1
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,10	0,08	0,08
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,26	0,24	0,22
Air flow rate through structure	R_{str}	l/min	-2,15	0	2,57
Density of air flow rate through structure	r_{str}	l/min•m²	-1,63	0	1,94
Velocity of air flow through structure	r_{vel}	m/s	-2,71E-05	0	3,24E-05
Volume of air transmitted through structure	V_{str}	l	-17460	0	24334
Moisture flow rate to structure	G_{str}	g/day	-6,8	0,4	31,4
Moisture flow rate to structure by convection	G_{con}	g/day	-5,9	0	32,0
Moisture flow rate to structure by diffusion	G_{dif}	g/day	-0,9	0,4	-0,6
Density of moisture flow rate to structure	g_{str}	g/day•m²	-5,2	0,3	23,7
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-4,5	0	24,2
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	-0,7	0,3	-0,4
Moisture transmitted to structure	m_{str}	g	-65	3	277
Air permeance of structure (*	K_{str}	m/s•Pa	2,73E-06	0	3,24E-06

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-9,35	-9,31	-9,29
Temperature at point A	T_{strA}	°C	18,27	18,73	19,14
Temperature at point B	T_{strB}	°C	-2,28	-0,41	1,03
Temperature at point C	T_{strC}	°C	17,05	17,13	17,63
Temperature at point D	T_{strD}	°C	-5,92	-4,59	-3,89
Temperature at point E	T_{strE}	°C	18,31	18,36	18,36
Temperature at point F	T_{strF}	°C	-0,60	-0,36	-0,29
Temperature at point G	T_{strG}	°C	17,24	17,20	17,30
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	82,2	82,1	82,2
Relative humidity at point A (RH)	ϕ_{strA}	%	18,0	14,3	46,0
Relative humidity at point B (RH)	ϕ_{strB}	%	77,4	48,6	90,9
Relative humidity at point C (RH)	ϕ_{strC}	%	17,8	13,6	13,0
Relative humidity at point D (RH)	ϕ_{strD}	%	92,9	62,3	58,6
Relative humidity at point E (RH)	ϕ_{strE}	%	15,0	14,6	20,1
Relative humidity at point F (RH)	ϕ_{strF}	%	48,8	46,0	48,9
Relative humidity at point G (RH)	ϕ_{strG}	%	15,7	13,7	13,1
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,91	1,92	1,92
Humidity by volume at point A	v_{strA}	g/m³	2,81	2,30	7,56
Humidity by volume at point B	v_{strB}	g/m³	3,18	2,29	4,74
Humidity by volume at point C	v_{strC}	g/m³	2,59	1,99	1,95
Humidity by volume at point D	v_{strD}	g/m³	2,88	2,14	2,13
Humidity by volume at point E	v_{strE}	g/m³	2,35	2,29	3,15
Humidity by volume at point F	v_{strF}	g/m³	2,26	2,18	2,32
Humidity by volume at point G	v_{strG}	g/m³	2,31	2,01	1,94
MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES					
Moisture content of pieces of wood (top of structure, holes through internal surface)	u_{wd}	%	16,8	11,4	15,7
Moisture content of pieces of wood (bottom of structure, holes through air barrier)	u_{wd}	%	12,6	10,1	10,5
Moisture content of mineral wool insulation on outside (holes through internal surface)	u_{ins}	%	6,7	0,9	1,2
Moisture content of mineral wool insulation on outside (holes through air barrier)	u_{ins}	%	0,5	0,7	3,3
Moisture content of windshield (holes through int. surf.)	u_{ws}	%	1,4	0,9	1,6
Moisture content of windshield (holes through air barrier)	u_{ws}	%	3,4	0,8	1,4
Moisture content of bracing (12.5 % at start of test)	w_{br}	%			14,0
Moisture retained by thermal insulation	m_{ins}	g			-
Water retained by frame	m_f	g			-
Moisture retained by windshield	m_{ws}	g			-

*) Measurement result reflects effect of holes

Visual observations

No condensation or icing could be detected on the inner surface of the windshield at any phase.
The sheet and thermal insulation felt dry to the touch throughout the test.
There was ice under the tapes on the outer surface of the windshield after the overpressure period.

TEST RESULTS (Test Wall 5)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**211,5**	**214,8**	**216,8**
Indoor air temperature	T_i	°C	20,00	20,00	20,01
Outdoor air temperature	T_o	°C	-9,96	-9,99	-9,99
Indoor air relative humidity (RH)	ϕ_i	%	52,3	50,1	50,0
Outdoor air relative humidity (RH)	ϕ_o	%	89,9	90,0	90,0
Pressure difference across structure	Δp_{str}	Pa	-10,0	0,9	10,0
Temp. on inner surface of structure	T_{ip}	°C	18,92	18,22	18,24
Temp. on outer surface of windshield	T_{ws}	°C	-8,22	-8,28	-8,31
Temp. on inner baffle	T_{ib}	°C	19,52	19,52	19,53
Temp. on outer baffle	T_{ob}	°C	-10,25	-10,14	-10,14
Environmental inside temperature	T_{ei}	°C	19,88	19,78	19,80
Environmental outside temperature	T_{eo}	°C	-10,01	-10,01	-10,01
Cold room temperature	T_{cr}	°C	-13,43	-13,04	-13,03
Cold room relative humidity (RH)	ϕ_{cr}	%	64,4	67,7	64,9
Indoor air humidity by volume	v_i	g/m³	9,05	8,66	8,65
Outdoor air humidity by volume	v_o	g/m³	1,98	1,98	1,98
Cold room humidity by volume	v_{cr}	g/m³	1,03	1,13	1,08
Heat flow rate from outside in	Φ_{tot}	W	53,5	52,5	53,2
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,16	0,21	0,22
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,19	0,23	0,20
Air flow rate through structure	R_{str}	l/min	-0,004	0	-0,00026
Density of air flow rate through structure	r_{str}	l/min•m²	-0,003	0	-0,00020
Velocity of air flow through structure	r_{vel}	m/s	-4,90E-08	0	-3,28E-09
Volume of air transmitted through structure	V_{str}	l	-160	0	223
Moisture flow rate to structure	G_{str}	g/day	9,3	6,5	5,5
Moisture flow rate to structure by convection	G_{con}	g/day	-0,02	0	-0,005
Moisture flow rate to structure by diffusion	G_{dif}	g/day	9,3	6,5	5,5
Density of moisture flow rate to structure	g_{str}	g/day•m²	7,0	4,9	4,1
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-0,02	0	-0,004
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	7,0	4,9	4,1
Moisture transmitted to structure	m_{str}	g	82	62	49
Moisture retained by windshield (*	m_{ws}	g	181	44	100
Water vapour permeance of structure (**	$W_{v,str}$	m/s	1,15E-05	8,53E-06	7,18E-06

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-8,34	-8,40	-8,53
Temperature at point A	T_{strA}	°C	8,65	8,19	8,24
Temperature at point B	T_{strB}	°C	0,88	0,65	0,65
Temperature at point C	T_{strC}	°C	-4,50	-4,68	-4,72
Temperature at point D	T_{strD}	°C	-3,35	-3,66	-3,53
Temperature at point E	T_{strE}	°C	15,20	15,32	15,33
Temperature at point F	T_{strF}	°C	1,10	1,48	1,40
Temperature at point G	T_{strG}	°C	-6,09	-6,06	-6,06
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	75,8	77,4	78,8
Relative humidity at point A (RH)	ϕ_{strA}	%	19,6	21,2	22,4
Relative humidity at point B (RH)	ϕ_{strB}	%	35,9	39,0	41,4
Relative humidity at point C (RH)	ϕ_{strC}	%	50,1	55,2	59,1
Relative humidity at point D (RH)	ϕ_{strD}	%	48,1	52,1	55,5
Relative humidity at point E (RH)	ϕ_{strE}	%	11,6	12,5	13,3
Relative humidity at point F (RH)	ϕ_{strF}	%	27,3	29,0	31,1
Relative humidity at point G (RH)	ϕ_{strG}	%	43,3	48,3	52,5
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,92	1,95	1,97
Humidity by volume at point A	v_{strA}	g/m³	1,70	1,78	1,89
Humidity by volume at point B	v_{strB}	g/m³	1,86	1,98	2,10
Humidity by volume at point C	v_{strC}	g/m³	1,74	1,89	2,01
Humidity by volume at point D	v_{strD}	g/m³	1,82	1,93	2,07
Humidity by volume at point E	v_{strE}	g/m³	1,51	1,64	1,74
Humidity by volume at point F	v_{strF}	g/m³	1,43	1,56	1,66
Humidity by volume at point G	v_{strG}	g/m³	1,32	1,48	1,61

MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES

Moisture content of pieces of wood (top of structure)	u_{wd}	%	10,9	10,3	12,0
Moisture content of pieces of wood (bottom of structure)	u_{wd}	%	9,1	9,2	10,9
Moisture content of windshield at start of test	u_{ws}	%	6,6		
Moisture content of cellulose insulation on outside (top)	u_{ins}	%	18,3	19,8	19,0
(bottom)	u_{ins}	%	16,2	18,1	18,6
Moisture content of windshield (top of structure)	u_{ws}	%	9,5	10,2	11,8
Moisture content of windshied (bottom of structure)	u_{ws}	%			
Moisture content of bracing (8.0 % at start of test)	w_{br}	%			11,1
Moisture retained by thermal insulation	m_{ins}	g			-
Water retained by frame	m_f	g			-
Moisture retained by windshield	m_{ws}	g			-

*) Value derived from moisture contents of windshield

**) The moisture contents of the structure were not at equilibrium

Visual observations

No condensation or icing could be detected on the inner surface of the windshied at any phase.
The sheet felt dry to the touch throughout the test. The cellulose insulation also appeared dry.

TEST RESULTS (Test Wall 6)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**180,8**	**97,8**	**335,5**
Indoor air temperature	T_i	°C	20,00	20,00	19,99
Outdoor air temperature	T_o	°C	-10,06	-9,97	-9,92
Indoor air relative humidity (RH)	ϕ_i	%	51,0	53,2	49,9
Outdoor air relative humidity (RH)	ϕ_o	%	90,2	89,2	89,4
Pressure difference across structure	Δp_{str}	Pa	-10,1	-0,3	10,0
Temp. on inner surface of structure	T_{ip}	°C	18,72	18,64	18,71
Temp. on outer surface of windshield	T_{ws}	°C	-9,50	-9,35	-9,42
Temp. on inner baffle	T_{ib}	°C	19,32	19,19	19,25
Temp. on outer baffle	T_{ob}	°C	-10,41	-10,24	-10,40
Environmental inside temperature	T_{ei}	°C	19,73	19,69	19,74
Environmental outside temperature	T_{eo}	°C	-10,28	-10,13	-10,18
Cold room temperature	T_{cr}	°C	-12,07	-12,47	-14,44
Cold room relative humidity (RH)	ϕ_{cr}	%	-	-	-
Indoor air humidity by volume	ν_i	g/m³	8,82	9,19	8,62
Outdoor air humidity by volume	ν_o	g/m³	1,98	1,96	1,98
Cold room humidity by volume	ν_{cr}	g/m³	-	-	-
Heat flow rate from outside in	Φ_{tot}	W	49,0	51,0	52,8
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,13	0,13	0,03
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,15	0,13	0,11
Air flow rate through structure	R_{str}	l/min	-1,55	0	1,56
Density of air flow rate through structure	r_{str}	l/min•m²	-1,17	0	1,18
Velocity of air flow through structure	r_{vel}	m/s	-1,95E-05	0	1,97E-05
Volume of air transmitted through structure	V_{str}	l	-15957	0	32254
Moisture flow rate to structure	G_{str}	g/day	-1,4	1,4	18,3
Moisture flow rate to structure by convection	G_{con}	g/day	-4,1	0	19,4
Moisture flow rate to structure by diffusion	G_{dif}	g/day	2,6	1,4	-1,1
Density of moisture flow rate to structure	g_{str}	g/day•m²	-1,1	1,1	13,8
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-3,1	0	14,7
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	2,0	1,1	-0,8
Moisture transmitted to structure	m_{str}	g	-11	24	256
Air permeance of structure (*	K_{str}	m/s•Pa	-1,93E-06	0	1,97E-06

Variable	Symbol	Unit	Underpres.	$\Delta p = 0$	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-8,97	-8,93	-8,98
Temperature at point A	T_{strA}	°C	17,64	18,25	18,76
Temperature at point B	T_{strB}	°C	-4,50	-3,41	-1,92
Temperature at point C	T_{strC}	°C	17,67	17,45	17,62
Temperature at point D	T_{strD}	°C	-4,58	-4,32	-4,11
Temperature at point E	T_{strE}	°C	18,00	18,05	18,02
Temperature at point F	T_{strF}	°C	-3,62	-3,23	-3,09
Temperature at point G	T_{strG}	°C	17,37	17,41	17,51
Temperature at point H	T_{strH}	°C	-5,03	-4,42	-4,25
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	76,3	79,5	77,9
Relative humidity at point A (RH)	ϕ_{strA}	%	13,0	15,2	46,3
Relative humidity at point B (RH)	ϕ_{strB}	%	54,9	56,0	90,7
Relative humidity at point C (RH)	ϕ_{strC}	%	12,6	12,5	12,6
Relative humidity at point D (RH)	ϕ_{strD}	%	57,8	57,1	57,3
Relative humidity at point E (RH)	ϕ_{strE}	%	14,4	14,2	15,2
Relative humidity at point F (RH)	ϕ_{strF}	%	56,3	55,2	56,6
Relative humidity at point G (RH)	ϕ_{strG}	%	12,7	12,6	12,4
Relative humidity at point H (RH)	ϕ_{strH}	%	57,8	56,8	55,8
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,83	1,92	1,87
Humidity by volume at point A	v_{strA}	g/m³	1,96	2,37	7,44
Humidity by volume at point B	v_{strB}	g/m³	1,90	2,11	3,82
Humidity by volume at point C	v_{strC}	g/m³	1,91	1,87	1,89
Humidity by volume at point D	v_{strD}	g/m³	1,99	2,01	2,05
Humidity by volume at point E	v_{strE}	g/m³	2,22	2,18	2,34
Humidity by volume at point F	v_{strF}	g/m³	2,09	2,11	2,19
Humidity by volume at point G	v_{strG}	g/m³	1,89	1,87	1,85
Humidity by volume at point H	v_{strH}	g/m³	1,92	1,98	1,97
MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES					
Moisture content of pieces of wood (top of structure, holes through internal surface)	u_{wd}	%	9,6	10,3	20,5
Moisture content of pieces of wood (bottom of structure, no holes)	u_{wd}	%	10,2	10,8	10,4
Moisture content of cellulose insulation on outside before test	u_{ins}	%	9,0		
Moisture content of windshield before test	u_{ws}	%	10,5		
Moisture content of cellulose insulation on outside (holes through internal surface)	u_{ins}	%	12,5	11,6	25,2
Moisture content of cellulose insulation on outside (no holes)	u_{ins}	%	12,5	11,6	11,0
Moisture content of windshield (holes through int. surf.)	u_{ws}	%	11,8	11,9	21,1
Moisture content of windshied (no holes)	u_{ws}	%	-	-	-
Moisture content of bracing (10.0 % at start of test)	u_{br}	%			14,9
Moisture retained by thermal insulation	m_{ins}	g	-	-	-
Water retained by frame	m_f	g	-	-	-
Moisture retained by windshield	m_{ws}	g	-	-	-

*) Measurement results reflect effect of holes

Visual observations

No condensation could be detected at any phase. The insulation and windshield did, however, feel damp to the touch around holes.

TEST RESULTS (Test Wall 7)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	$\Delta p = 0$	Overpres.
Test time (hours)	t	h	**67,5**	**64,0**	**67,5**
Indoor air temperature	T_i	°C	20,00	20,00	20,00
Outdoor air temperature	T_o	°C	-9,99	-9,99	-9,98
Indoor air relative humidity (RH)	ϕ_i	%	50,0	50,0	50,0
Outdoor air relative humidity (RH)	ϕ_o	%	90,0	90,0	89,8
Pressure difference across structure	Δp_{str}	Pa	-9,9	-0,1	9,8
Temp. on inner surface of structure	T_{ip}	°C	19,39	19,44	19,48
Temp. on outer surface of windshield	T_{ws}	°C	-7,43	-7,44	-7,95
Temp. on inner baffle	T_{ib}	°C	19,63	19,66	19,66
Temp. on outer baffle	T_{ob}	°C	-10,01	-10,04	-10,12
Environmental inside temperature	T_{ei}	°C	19,94	19,94	19,95
Environmental outside temperature	T_{eo}	°C	-10,00	-10,02	-10,05
Cold room temperature	T_{cr}	°C	-12,15	-12,06	-12,53
Cold room relative humidity (RH)	ϕ_{cr}	%	81,2	83,2	73,6
Indoor air humidity by volume	ν_i	g/m³	8,65	8,64	8,64
Outdoor air humidity by volume	ν_o	g/m³	1,98	1,98	1,98
Cold room humidity by volume	ν_{cr}	g/m³	1,47	1,52	1,29
Heat flow rate from outside in	Φ_{tot}	W	50,3	49,8	50,3
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,05	0,07	0,11
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,08	0,06	0,09
Air flow rate through structure	R_{str}	l/min	-1,15	0	1,63
Density of air flow rate through structure	r_{str}	l/min•m²	-0,87	0	1,24
Velocity of air flow through structure	r_{vel}	m/s	-1,45E-05	0	2,06E-05
Volume of air transmitted through structure	V_{str}	l	-4014	0	6494
Moisture flow rate to structure	G_{str}	g/day	66,0	69,7	82,0
Moisture flow rate to structure by convection	G_{con}	g/day	-3,2	0	20,3
Moisture flow rate to structure by diffusion	G_{dif}	g/day	69,2	69,7	61,7
Density of moisture flow rate to structure	g_{str}	g/day•m²	49,9	52,7	62,0
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-2,4	0	15,4
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	52,3	52,7	46,6
Moisture transmitted to structure	m_{str}	g	186	214	308
Moisture retained by windshield (*	m_{ws}	g	220	130	190
Air permeance of structure	K_{str}	m/s•Pa	1,47E-06	0	2,10E-06
Water vapour permeance of structure	$W_{v,str}$	m/s	9,08E-05	9,15E-05	8,10E-05

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-7,93	-8,04	-8,28
Temperature at point A	T_{strA}	°C	-4,90	-4,48	-4,28
Temperature at point B	T_{strB}	°C	5,12	5,80	6,28
Temperature at point C	T_{strC}	°C	15,55	15,82	15,95
Temperature at point D	T_{strD}	°C	-5,77	-5,42	-5,14
Temperature at point E	T_{strE}	°C	3,22	3,47	3,49
Temperature at point F	T_{strF}	°C	14,95	15,12	15,08
Temperature at point G	T_{strG}	°C	-5,04	-5,02	-5,15
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	71,3	75,3	80,2
Relative humidity at point A (RH)	ϕ_{strA}	%	84,6	89,6	91,8
Relative humidity at point B (RH)	ϕ_{strB}	%	67,3	70,0	71,6
Relative humidity at point C (RH)	ϕ_{strC}	%	51,2	52,5	53,5
Relative humidity at point D (RH)	ϕ_{strD}	%	90,0	93,9	94,7
Relative humidity at point E (RH)	ϕ_{strE}	%	70,5	74,4	77,3
Relative humidity at point F (RH)	ϕ_{strF}	%	51,8	53,3	54,5
Relative humidity at point G (RH)	ϕ_{strG}	%	67,5	74,7	79,8
Humidity by volume of ventilation gap	v_{vg}	g/m³	1,87	1,96	2,04
Humidity by volume at point A	v_{strA}	g/m³	2,84	3,11	3,24
Humidity by volume at point B	v_{strB}	g/m³	4,64	5,05	5,33
Humidity by volume at point C	v_{strC}	g/m³	6,80	7,09	7,29
Humidity by volume at point D	v_{strD}	g/m³	2,82	3,03	3,12
Humidity by volume at point E	v_{strE}	g/m³	4,28	4,60	4,78
Humidity by volume at point F	v_{strF}	g/m³	6,64	6,90	7,04
Humidity by volume at point G	v_{strG}	g/m³	2,24	2,49	2,63

MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES

Moisture content of pieces of wood (top of structure)	u_{wd}	%	18,3	24,9	26,0
Moisture content of pieces of wood (bottom of structure)	u_{wd}	%	17,2	21,8	29,0
Moisture content of windshield before test	u_{ws}	%	8,0		
Moisture content of mineral wool insulation on outside (top)	u_{ins}	%	1,0		-
(bottom)	u_{ins}	%			
Moisture content of windshield (top of structure)	u_{ws}	%	12,7	15,4	19,5
Moisture content of windshied (bottom of structure)	u_{ws}	%			
					-
Moisture content of bracing	u_{br}	%			-
Moisture retained by thermal insulation	m_{ins}	g			-
Water retained by frame	m_f	g			-
Moisture retained by windshield	m_{ws}	g			-

*) Value calculated on the basis of windshield moisture contents

Visual observations

The inner surface of the windshield was damp to the touch already after the underpressure period and got dampe

TEST RESULTS (Test Wall 8)

The measurement results are averages of the five last hours of each measurement period.
Cumulative values are based on the period between the first and last values.
Structure samples were taken at the end of each measurement period.

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Test time (hours)	t	h	**297,3**	**256,8**	**231,8**
Indoor air temperature	T_i	°C	19,99	20,00	20,00
Outdoor air temperature	T_o	°C	-10,00	-9,99	-10,01
Indoor air relative humidity (RH)	ϕ_i	%	50,0	50,0	50,0
Outdoor air relative humidity (RH)	ϕ_o	%	90,0	89,8	88,1
Pressure difference across structure	Δp_{str}	Pa	-9,9	-0,9	10,0
Temp. on inner surface of structure	T_{ip}	°C	18,97	19,00	19,13
Temp. on outer surface of windshield	T_{ws}	°C	-8,59	-8,15	-7,67
Temp. on inner baffle	T_{ib}	°C	19,30	19,30	19,33
Temp. on outer baffle	T_{ob}	°C	-10,39	-10,64	-10,64
Environmental inside temperature	T_{ei}	°C	19,80	19,81	19,84
Environmental outside temperature	T_{eo}	°C	-10,15	-10,34	-10,44
Cold room temperature	T_{cr}	°C	-12,76	-14,50	-14,71
Cold room relative humidity (RH)	ϕ_{cr}	%	-	-	-
Indoor air humidity by volume	ν_i	g/m³	8,64	8,64	8,64
Outdoor air humidity by volume	ν_o	g/m³	1,98	1,97	1,93
Cold room humidity by volume	ν_{cr}	g/m³	-	-	-
Heat flow rate from outside in	Φ_{tot}	W	52,7	52,7	52,6
Velocity of air flow at inner surface (from bottom up)	r_i	m/s	<0,05	<0,05	<0,05
Velocity of air flow at outer surface (from top down)	r_o	m/s	0,04	0,06	0,04
Velocity of air flow in ventilation gap (from top down)	r_{vg}	m/s	0,18	0,11	0,12
Air flow rate through structure	R_{str}	l/min	-5,84	0	6,77
Density of air flow rate through structure	r_{str}	l/min•m²	-4,41	0	5,12
Velocity of air flow through structure	r_{vel}	m/s	-7,35E-05	0	8,53E-05
Volume of air transmitted through structure	V_{str}	l	-105733	0	98775
Moisture flow rate to structure	G_{str}	g/day	36,6	58,8	126,7
Moisture flow rate to structure by convection	G_{con}	g/day	-16,3	0	84,2
Moisture flow rate to structure by diffusion	G_{dif}	g/day	52,9	58,8	42,4
Density of moisture flow rate to structure	g_{str}	g/day•m²	27,7	44,5	95,8
Density of moisture flow rate to structure by convection	g_{con}	g/day•m²	-12,3	0	63,7
Density of moisture flow rate to structure by diffusion	g_{dif}	g/day•m²	40,0	44,5	32,1
Moisture transmitted to structure	m_{str}	g	453	629	1223
Air permeance of structure (*	K_{str}	m/s•Pa	7,40E-06	0	8,52E-06
Water vapour permeance of structure (**	$W_{v,str}$	m/s	6,95E-05	7,10E-05	5,53E-05

Variable	Symbol	Unit	Underpres.	Δp = 0	Overpres.
Temperature in ventilation gap	T_{vg}	°C	-9,38	-9,09	-9,28
Temperature at point A	T_{strA}	°C	16,25	17,85	19,19
Temperature at point B	T_{strB}	°C	-7,35	-5,67	-2,98
Temperature at point C	T_{strC}	°C	17,18	17,37	17,82
Temperature at point D	T_{strD}	°C	-6,96	-6,21	-5,21
Temperature at point E	T_{strE}	°C	17,21	17,40	17,58
Temperature at point F	T_{strF}	°C	-6,75	-6,32	-5,62
Temperature at point G	T_{strG}	°C	16,59	16,84	17,16
Temperature at point H	T_{strH}	°C	-7,50	-6,72	-6,21
Relative humidity in ventilation gap (RH)	ϕ_{vg}	%	83,5	83,4	79,9
Relative humidity at point A (RH)	ϕ_{strA}	%	39,7	44,7	49,1
Relative humidity at point B (RH)	ϕ_{strB}	%	78,4	88,7	91,3
Relative humidity at point C (RH)	ϕ_{strC}	%	42,5	44,2	45,8
Relative humidity at point D (RH)	ϕ_{strD}	%	85,8	88,4	88,6
Relative humidity at point E (RH)	ϕ_{strE}	%	46,9	47,7	48,8
Relative humidity at point F (RH)	ϕ_{strF}	%	89,5	87,6	87,1
Relative humidity at point G (RH)	ϕ_{strG}	%	45,3	46,7	47,8
Relative humidity at point H (RH)	ϕ_{strH}	%	81,8	83,9	84,3
Humidity by volume of ventilation gap	ν_{vg}	g/m³	1,93	1,98	1,87
Humidity by volume at point A	ν_{strA}	g/m³	5,50	6,81	8,10
Humidity by volume at point B	ν_{strB}	g/m³	2,16	2,80	3,56
Humidity by volume at point C	ν_{strC}	g/m³	6,22	6,54	6,96
Humidity by volume at point D	ν_{strD}	g/m³	2,44	2,67	2,90
Humidity by volume at point E	ν_{strE}	g/m³	6,88	7,08	7,32
Humidity by volume at point F	ν_{strF}	g/m³	2,59	2,63	2,76
Humidity by volume at point G	ν_{strG}	g/m³	6,41	6,70	7,00
Humidity by volume at point H	ν_{strH}	g/m³	2,23	2,44	2,55
MOISTURE CONTENTS MEASURED FROM STRUCTURAL SAMPLES					
Moisture content of pieces of wood (top of structure, holes through internal surface)	u_{wd}	%	16,1	22,5	30,4
Moisture content of pieces of wood (bottom of structure, no holes)	u_{wd}	%	21,0	25,2	25,1
Moisture content of cellulose insulation before test	u_{ins}	%	12,0		
Moisture content of windshield before of test	u_{ws}	%	9,0		
Moisture content of cellulose insulation on outside (holes through internal surface)	u_{ins}	%	18,5	31,6	32,3
Moisture content of cellulose insulation on outside (no holes)	u_{ins}	%	21,2	41,4	28,7
Moisture content of windshield (holes through internal surface)	u_{ws}	%	15,2	18,9	18,1
Moisture content of windshied (no holes)	u_{ws}	%	14,9	21,7	19,8
Moisture content of bracing (10.0 % at start of test)	u_{br}	%			outside >24 inside~12
Moisture retained by thermal insulation	m_{ins}	g	-	-	-
Water retained by frame	m_f	g	-	-	-
Moisture retained by windshield	m_{ws}	g	-	-	-

*) Measurement result reflects effect of holes

**) The moisture contents of the structure were not at equilibrium

Visual observations

Condensation and icing could be detected on inner surface of windshield during period of no pressure difference and during overpressure period. Materials could not be weighed after the test since the insulation froze to the windshield.

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WATER VAPOUR TRANSMISSION IN WALL STRUCTURES DUE TO DIFFUSION AND CONVECTION

This publication looks into the moisture behaviour of different timber-framed wall structures under winter conditions. Wall structures have been studied under laboratory conditions using new test equipment built in connection with the study. The test equipment can control indoor and outdoor conditions (temperature, relative humidity and pressure difference) as desired. The behaviour of structures can be monitored during tests under controlled conditions without disturbances.

The study has examined, for instance, the need for a vapour barrier in wall structures, and the impact of the difference in air pressure between the inside and outside of a building on the behaviour of structures. Especially the cellulose-insulated wall structure with no vapour barrier and the mineral wool-insulated one with a vapour barrier have been compared.

The study began in 1996 and was conclude in 1998. The design, building and testing of the new test equipment took about two years of that period; the final year was used to study wall structures. The study is part of the building physics studies conducted as part of the Wood in Construction technology programme of the National Technology Agency (TEKES).

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