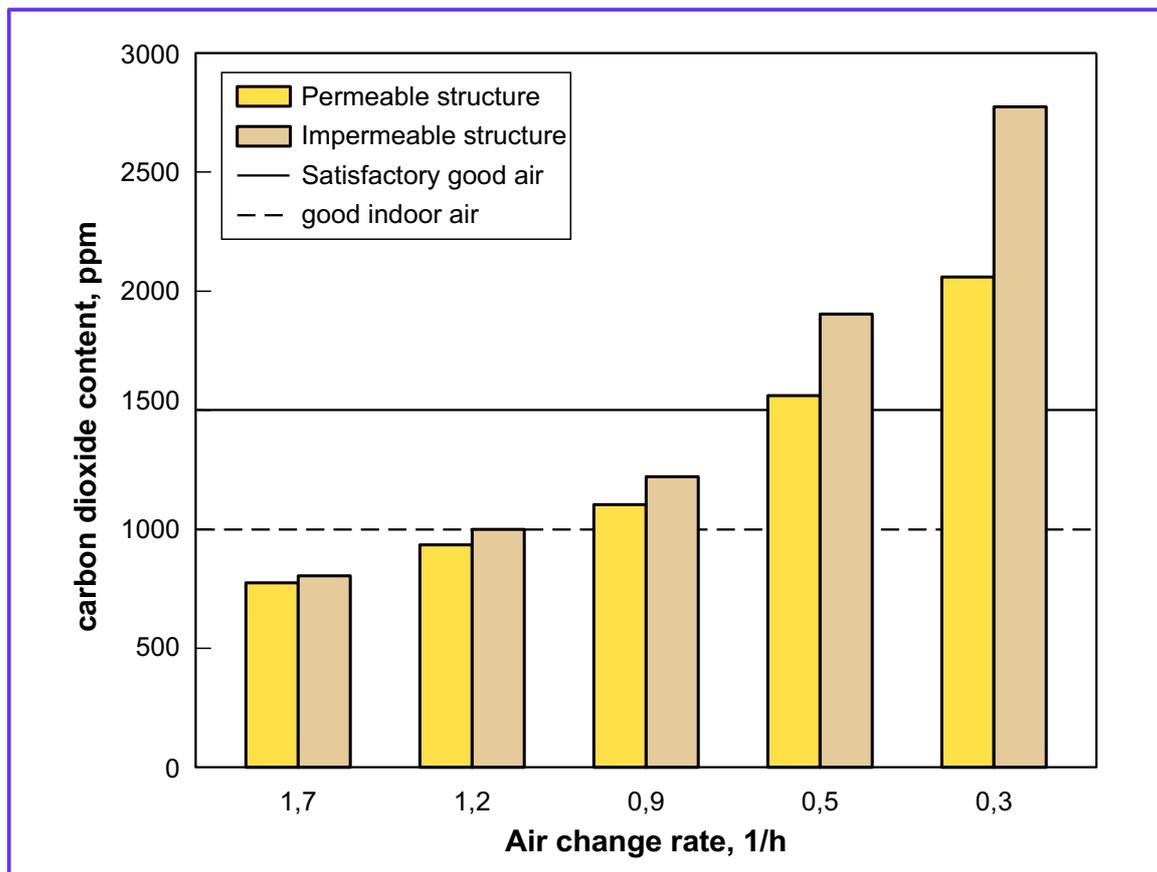


Timo Niemelä - Juha Vinha - Ralf Lindberg

## CARBON DIOXIDE PERMEABILITY OF CELLULOSE-INSULATED WALL STRUCTURES





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INSULATED WALL STRUCTURES**



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### **Abstract**

A study was conducted at Tampere University of Technology, Laboratory of Structural Engineering in 1995 where the diffusion of carbon dioxide through different building materials, finishes and entire external wall structures was examined. Test equipment consisting of a test chamber and different types of measuring apparatus was developed for the study. The tested material or structure was inserted in the opening of the chamber and sealed. Then a carbon dioxide content of 1 percent was created within the chamber for the test. Tests measured the reduction in the flow of carbon dioxide through the subject material or structure to indoor air over a certain period of time.

The results of measurements were used to determine the carbon dioxide permeabilities of materials and the carbon dioxide resistance of structures. Various surveys modelling the carbon dioxide balance of a building's indoor air were conducted using the measured values. The surveys took into consideration the diffusion of carbon dioxide through the wall structure.

Test results indicated that the carbon dioxide permeabilities of building materials correlate closely with the water vapour permeabilities and diffusion through air indicated by other studies. Thus, the more permeable a material is to carbon dioxide, the more permeable it is to water vapour.

Based on the modelling surveys, it can be stated that gas-permeable (breathable) wall structures lower the carbon dioxide content of indoor air, but do not reduce the need for ventilation. In a well-ventilated building permeable walls have no practical significance in improving indoor air quality. On the other hand, permeable structures can alleviate the detrimental effects of temporarily high carbon dioxide contents.

This study examined indoor air quality using carbon dioxide. Yet, the quality of indoor air is generally determined by other gases which people find unpleasant at much lower concentrations than carbon dioxide. The removal of these impurities through structures would call for even more permeable wall structures which is impracticable. This also emphasizes the significance of efficient and properly planned ventilation in buildings.

In order that external wall structures could have an impact on the carbon dioxide content of indoor air, the materials of the structures should be as permeable (allowing diffusion) as possible. Yet, this also allows more water vapour to pass through the structures which makes them more at-risk for condensation in autumn and winter. The risk of moulding also increases. Thus, use of structures that are too permeable on the inside is not recommended.

## Foreword

This research has determined the gas permeabilities of different materials and cellulose-insulated wall structures without a vapour barrier.

The research was conducted at Tampere University of Technology (TUT), Laboratory of Structural Engineering in 1995. The responsible director was Prof. Ralf Lindberg. The research work was done by engineering student Timo Niemelä under supervision of M.Sc. (Tech.) Juha Vinha.

The management group of the project consisted of:

|                           |   |
|---------------------------|---|
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| <i>Ralf Lindberg</i>      | Professor, TUT                                      |
| <i>Lasse Pöyhönen</i>     | M.Sc. (Tech.), TEKES                                |
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| <i>Reijo Louko</i>        | Managing Director, Ekovilla Oy                      |
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The research was financed by National Technology Agency of Finland, TEKES (about 80 %) and Ekovilla Oy, Termex-eriste Oy, Uudenmaan Puhalluseristevilla Oy and Schauman Wood Oy (about 5 % each).

Tampere, 12 February 1996

Timo Niemelä

Juha Vinha

Ralf Lindberg

## **Foreword to English version**

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Tampere, 28 July 2000

Timo Niemelä

Juha Vinha

Ralf Lindberg

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## List of symbols

|            |  |
|------------|--|
| $c$        | concentration of carbon dioxide in the air ( $\text{g}/\text{m}^3$ , $\text{mol}/\text{m}^3$ ) |
| $g$        | density of carbon dioxide flow ( $\text{g}/\text{m}^2\cdot\text{s}$ )                          |
| $D$        | diffusion coefficient based on gas content ( $\text{m}^2/\text{s}$ )                           |
| $\delta_v$ | carbon dioxide permeability based on carbon dioxide content ( $\text{m}^2/\text{s}$ )          |
| $d$        | thickness of homogeneous material layer (m)  |
| $Z_v$      | carbon dioxide resistance based on carbon dioxide content (s/m)                                |
| $p$        | air pressure (Pa)  |
| $t$        | time (s, min, h)   |
| $T$        | temperature (K, °C)  |
| $C$        | carbon dioxide content (ppm, %)  |
| $n_a$      | apparent air change rate (l/h)   |

### Subscripts:

|     |   |
|-----|---|
| $t$ | test piece                                |
| $v$ | calculated using concentration difference |
| $p$ | primary side                              |
| $s$ | secondary side                            |

## Concepts and definitions

|                                       |   |
|---------------------------------------|---|
| <b>Gas permeable structure</b>        | A "breathable" structure that allows diffusion of gases through it. Yet, no convection currents pass through the structure.   |
| <b>Structure impermeable to gases</b> | Structure that prevents diffusion of gases through it.  |
| <b>Apparent air change rate</b>       | Rate calculated on the basis of the speed of carbon dioxide diffusion. It indicates the rate of air change required to remove as much carbon dioxide from indoor air as is diffused through permeable structures. |
| <b>Primary side</b>                   | Space limited by the steel walls of the test equipment chamber and the examined test piece where carbon dioxide was fed.  |
| <b>Secondary side</b>                 | Space which received the carbon dioxide diffused through the test piece.  |
| <b>ppm</b>                            | Parts per million   |

# 1 Introduction

Plastic sheeting has been used as a vapour barrier in the walls of normal wood-framed detached and semi-detached houses to prevent transmission of moisture inside the wall structure and to make it airtight. However, increasing criticism against too airtight "bottle houses" has been voiced in recent years. This has led to a discussion of the "breathability" of wall structures and, consequently, the ability of "breathable" wall structures to improve the quality of indoor air.

The capacity of cellulose insulations for retaining and releasing moisture differs from that of mineral wool insulations. This capacity allows exclusion of the vapour barrier from a wall structure on certain conditions /1/, /8/, /12/ whereby gas molecules can penetrate the wall structure by diffusion.

The aim of this study was to determine both theoretically and empirically the transmission of indoor air carbon dioxide through different materials and wall structures by diffusion. In addition, the behaviour of water vapour in structures was examined theoretically and compared to that of carbon dioxide. At the same time, an effort was made to determine the impact of the different thermal, moisture and pressure conditions on opposite sides of a wall structure on the gas flows through the wall.

Test equipment was developed for the study, which was used to determine the diffusion of carbon dioxide through typical construction materials and some wall finishes. The test results were converted into carbon dioxide resistance values. The results from materials tests were used to build two wall structures of maximum carbon dioxide permeability. Then, their overall carbon dioxide resistance was determined as well as the apparent carbon dioxide permeability of the so-called primary side. The impact of moisture on carbon dioxide permeability was also examined using two test pieces.

Transmission of water vapour in materials and structures has been studied extensively. Water vapour transmission values have been determined for different materials and a simple manual calculation method based on them has been developed. The method allows calculating the amount of moisture transmitted through a structure by diffusion as well as the amount condensed in the structure. The method has been simplified significantly so that it does not, for instance, consider the moisture retaining capacity of building materials or other forms of moisture transmission. Yet, it usually provides the accuracy required in practical design work.

The test results were used as a basis of modeling the impact of diffusion on the carbon dioxide content of indoor air. The theoretical calculations were based on apparent air change rates derived from structural tests and the manual calculation method describing the transmission of water vapour.

## 2 Building climate

### 2.1 General

During the last 15 years increasing attention has been paid to building climate and its quality. Many studies have shown that people spend, on average, 70-90 percent of their time indoors. Certain groups of people, such as the elderly and the sick, stay indoors practically all the time.

The increased time spent indoors, and the construction of airtight houses as a result of the energy crisis of the 1970s, have affected the health of people. Symptoms such as irritation of mucous membranes and respiratory passages, skin symptoms, fatigue, stress and various aches and pains have become more commonplace. Different allergic symptoms and asthma have also increased significantly in recent years. The adverse effects on health have often been linked to substandard indoor air, deficient ventilation or various mould-related problems of buildings.

### 2.2 Impurities of indoor air

The sources of the impurities of indoor air are:

- man himself (carbon dioxide, moisture, odour)
- man's activities (laundry, hygiene, cooking, smoking)
- structures, surfacings, textiles, fittings (formaldehyde, dust)
- soil (radon)
- pets (dust, dandruff)
- outdoor air (pollen, industrial and motor vehicle emissions)

According to studies of the building climate project /2/, the most detrimental impurities of indoor air in Finland are **radon, formaldehyde and tobacco smoke**. The harmful effects of these factors can, however, often be eliminated by proper design and implementation, especially in new construction.

In indoor spaces where no one smokes and the primary polluter of air is man himself, air quality is usually determined by **the strength of the odour exuded by man** /3/. The body, clothing and exhaled air of man continuously give off gases that produce different smells such as ammonia, acetone, methanol, ethanol, methane and toluene. Yet, attempts to develop a reliable and easy-to-use method for measuring the strength of odours have failed. If one wishes to study the intensity of a smell, it must be done on the basis of the subjective perceptions of a panel of smellers /3/.

**Carbon dioxide** is the product of metabolic reactions released in exhalation. Quantitatively it is the most significant impurity produced by the human body, but is not normally a standard for indoor air quality. Odour and carbon dioxide content do, however, correlate closely with each other in spaces where smoking does not take place /4/. Carbon dioxide content has also been established as the most reliable indicator of indoor air quality where appropriate ventilation exists. Consequently, it is used almost without exception with controlled ventilation systems /4/.

Indoor air contains also many other impurities. Their contents are, however, small under normal conditions and do not determine the quality of indoor air. These impurities include particle-type impurities, allergens, spores of moulds and rot fungi, biological impurities, bacteria and viruses, as well as different organic compounds.

### 2.3 Carbon dioxide limits of indoor air

Many different sources have set different grading and maximum values for the carbon dioxide content of indoor air. This is due the fact that it is easier to measure carbon dioxide content than the intensity of the odour emitted by human beings which normally determines the quality of indoor air. Table 2.1 contains various limits for carbon dioxide presented in different indoor air classifications and guidelines.

**Table 2.1.** Various indoor air carbon dioxide limits.

| CO <sub>2</sub> content<br>ppm | Description   |
|--------------------------------|---|
| 350                            | Normal carbon dioxide content of outdoor air  |
| 800                            | Max. content in room air, if carbon dioxide content is used to control ventilation /5/  |
| 1,000                          | Class S1, good indoor air /6/<br>Good indoor air quality, content due to exhaled air /2/<br>At this carbon dioxide content odour is still assumed bearable /3/  |
| 1,250                          | Class S2 /6/  |
| 1,500                          | Class S3, satisfactory indoor air, (total content) /6/<br>Satisfactory indoor air. Nat'l Board of Health, Regulations governing condition and maintenance of dwellings, 1990<br>Satisfactory indoor air quality, content due to exhaled air /2/ |
| 2,500                          | Max. allowed content in indoor air /5/<br>(Max. content due to man 1,500 ppm)<br>Satisfactory indoor air quality, total content /2/   |
| 5,000                          | An 8-hour continuous stay at this content has been determined harmful. Nat'l Board of Labour Protection 1987  |
| approx. 150,000                | = 15 % Life-threatening content   |

Carbon dioxide is well suited for examining the "breathability" of wall structures in laboratory tests. Its advantages:

- availability of meters
- gas readily available
- large contents of carbon dioxide in indoor air compared to other impurities

### 3 Theoretical study

Gases can migrate in structures by four methods: diffusion, convection, thermodiffusion and effusion. The two latter ones, thermodiffusion and effusion, are considered insignificant from the viewpoint of practical building physical examinations and are omitted here.

#### 3.1 Diffusion

##### 3.1.1 Diffusion through air

The diffusion of gases has been studied extensively. Several calculation models have been developed for determining theoretically the amount of diffusion through air. The correlation based on experimentation suggested by Fuller /15/ is considered good:

$$D_{AB} = 0,0101 \times \frac{T^{1,75} \times (1/M_A + 1/M_B)^{1/2}}{p \times \left[ (\sum v_A)^{1/3} + (\sum v_B)^{1/3} \right]^2} \quad (3.1)$$

where

|                           |   |
|---------------------------|---|
| $D_{AB}$                  | diffusion coefficient of gas A through B ( $m^2/s$ )                      |
| T                         | temperature (K)   |
| p                         | total pressure (Pa)   |
| $M_A$ and $M_B$           | molecular masses of examined gases (g/mol)                                |
| $\sum v_A$ and $\sum v_B$ | so-called structural volumetric growths of some gases shown in Table 3.1. |

**Table 3.1.** Structural volumetric growth /15/ and molecular masses of some gases.

| Gas            | Chemical symbol  | Structural volumetric growth<br>$\Sigma v$ | Molecular mass<br>g/mol |
|----------------|------------------|--|-------------------------|
| water vapour   | H <sub>2</sub> O | 12.7                                       | 18                      |
| carbon dioxide | CO <sub>2</sub>  | 26.9                                       | 44                      |
| oxygen         | O <sub>2</sub>   | 16.6                                       | 32                      |
| ammonia        | NH <sub>3</sub>  | 14.9                                       | 17                      |
| air            | -                | 20.1                                       | 29                      |

### 3.1.2 Impact of temperature on diffusion

The movement of gas molecules is directly proportional to temperature. Thus, molecular movement and the rate of diffusion slow down as temperature drops. Table 3.2 presents diffusion coefficients for water vapour and carbon dioxide through air at various temperatures calculated with formula 3.1.

**Table 3.2.** Diffusion coefficients for carbon dioxide and water vapour through air at various temperatures.

|                | Diffusion coefficient through air<br>$\times 10^{-6} \text{ m}^2/\text{s}$ |      |       |
|----------------|--|------|-------|
|                | 20°C   | 0°C  | -20°C |
| carbon dioxide | 15.3   | 13.6 | 11.9  |
| water vapour   | 24.6   | 21.8 | 19.1  |

### 3.1.3 Diffusion through a structure

Diffusion of a certain gas through a structure is caused by the fact that the air on opposite sides of the structure contains different levels of that gas, and the levels seek an equilibrium. Thus, the gas flow caused by diffusion is the movement of molecules through a structure from a lower concentration to a higher one. The air pressure difference between opposite sides of a structure, or changes in it, do not affect the diffusion rate of gases. Neither does diffusion cause air currents.

The density of the diffusion current is based on Fick's law:

$$j_A = -D_{AB} \times \frac{\partial c_A}{\partial z} \quad (3.2)$$

|          |   |
|----------|---|
| $j_A$    | density of molar flow of component A ( $\text{mol}/\text{m}^2 \cdot \text{s}$ ) |
| $D_{AB}$ | diffusion coefficient of A through B ( $\text{m}^2/\text{s}$ )                  |
| $c_A$    | concentration of component A ( $\text{mol}/\text{m}^3$ )                        |
| $z$      | component parallel to flow (m)  |

### 3.1.4 Basic principles of general calculation model

Calculations regarding the transmission of water vapour through structures and materials have often been done as part of building physical studies - generally as unidimensional manual calculations.

This method of calculation can be applied as such also to other gases. Then, the amount of gas passing through a homogeneous material by diffusion can be calculated from the formula:

$$g = \delta_v \times \frac{\Delta c}{d} \quad (3.3)$$

where

|            |   |
|------------|---|
| $g$        | amount of passed gas ( $\text{g}/\text{m}^2 \cdot \text{s}$ )               |
| $\delta_v$ | gas permeability of material ( $\text{m}^2/\text{s}$ )                      |
| $\Delta c$ | concentration difference of gas over distance $d$ ( $\text{g}/\text{m}^3$ ) |
| $d$        | thickness of material layer (m)   |

The volume of the gas flow through a material consisting of several homogeneous material layers can be determined from the formula:

$$g = \frac{\Delta c}{\sum Z_v} \quad (3.4)$$

where

|                            |   |
|----------------------------|---|
| $Z_v = \frac{d}{\delta_v}$ | gas impermeability of various material layers (s/m) |
| $d$                        | thickness of homogeneous material layer (m)         |

### 3.1.5 Flaws of general calculation model

The results yielded by the described calculation model are inaccurate - especially as concerns moisture behaviour studies. The following flaws have been attributed to the model:

- It does not consider the moisture-carrying capacity of materials, i.e. the fact that different materials retain their characteristic amount of moisture under certain ambient conditions.
- Other forms of moisture transmission are ignored.
- Water vapour permeability is assumed to be constant, which it is not.
- Temperature distribution in a structure is assumed linear.
- Simultaneous transmission of heat and its effects are ignored.
- Gas flow is assumed independent of time and place.

The diffusion of carbon dioxide through materials is theoretically a simpler phenomenon than diffusion of water vapour. The application of the general calculation model to the diffusion of carbon dioxide eliminates at least the following problems compared to the diffusion of water vapour:

- Unlike water vapour, air does not have a temperature-dependent maximum capacity for carbon dioxide (carbon dioxide does not undergo phase transformations at normal temperatures).
- Regular construction materials (excluding concrete) do not bind carbon dioxide molecules - at least not to the extent that organic materials bind water vapour.

## 3.2 Convection

Convection can be divided into convection through a structure and within a structure.

### 3.2.1 Convection through a structure

In practice, there is almost always a pressure difference between indoor and outdoor air. The difference may be due to wind, differences in air density due to temperature differences, and different ventilation systems. Convection through a structure means that gases pass through a structure in a current caused by a difference in air pressure - either by seeping through a porous material or by flowing through gaps and holes. Convection is caused by the difference in air pressure on opposite sides of a structure.

The Fukthandbok /7/ presents a calculation method based on the airtightness of a building's shell structures (Formulas 3.5 and 3.6) which can be used to calculate the amount of gas carried out by a convection current.

$$G = c \times R_s \quad (3.5)$$

where

|                |   |
|----------------|---|
| G              | gas that exits with air current (g/s)                                     |
| c              | indoor air's gas concentration (g/m <sup>3</sup> )                        |
| R <sub>s</sub> | air flow through structures (m <sup>3</sup> /s), derived from Formula 3.6 |

$$R_s = R_{s0} \times \left( \frac{\Delta p}{50Pa} \right)^\beta \quad (3.6)$$

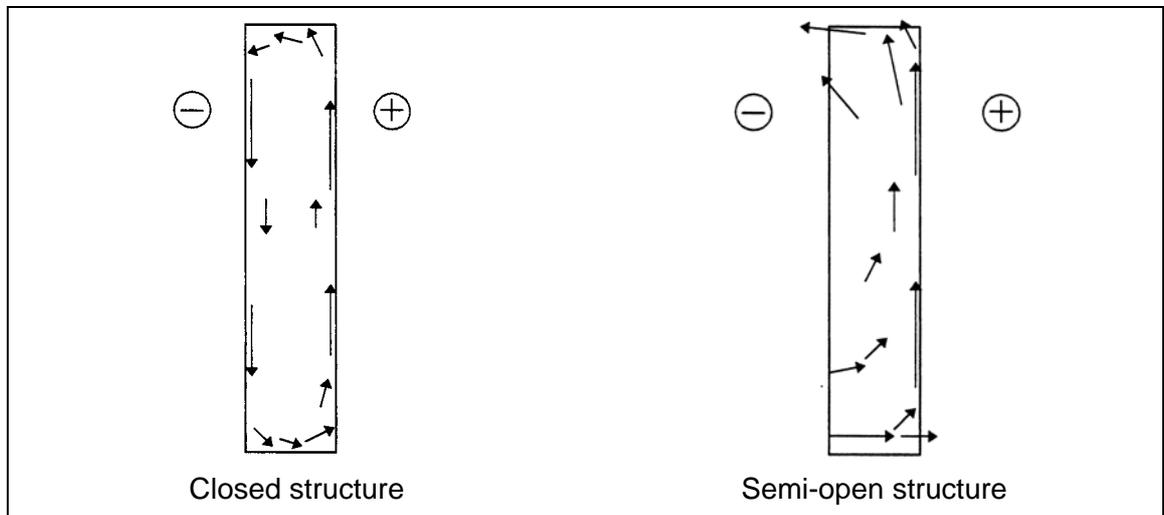
where

|            |  |
|------------|--|
| $R_{50}$   | volume of air flow ( $\text{m}^3/\text{s}$ ) determined by building's airtightness measurement at 50 Pa pressure |
| $\Delta p$ | air pressure difference through structure (Pa)   |
| $\beta$    | coefficient dependent on type of flow, $0.5 < \beta < 1$ ; $\beta = 0.67$ is an often used value                 |

### 3.2.2 Convection within structures

Convection also occurs within wall structures. It is a result of the temperature difference between the top and bottom sections of a wall and causes air circulation within it.

If the windshield of a wall is tight compared to the thermal insulation layer, the temperature difference causes air circulation within the structure (so-called closed structure). When regular windshield materials (permeability approx.  $10^{-12} \text{ m}^2$ ) are used, walls function like closed structures since the air flow through a windshield is small /14/. On the other hand, if the windshield is relatively permeable to air, air circulation occurs through the windshield (so-called semi-open structure). The basic air-flow fields in the two mentioned cases are presented in Figure 3.1.



**Figure 3.1.** Basic air-flow fields due to internal convection in the case of a closed and a semi-open wall structure.

### 3.2.3 Significance of convection currents

Determining the volume and direction of convection currents in real-life situations is difficult since the prevailing conditions are not stable and flows may vary between different structural elements. The direction of a convection current through a structure may be from inside out in some structural elements even with mechanical exhaust

ventilation, although indoor air pressure should be lower compared to outdoor air then /9/. The volumes of convection currents are affected at least by:

- the properties and number of layers of the wall structure
- how well the wall structure is built
- the size and shape of the wall structure and possible barriers to convection
- prevailing climatic conditions outside an in
- pressure conditions created by ventilation system
- location, surroundings, shape and orientation of building

The amount of moisture transmitted by convection currents may be manyfold compared to the amount transmitted by diffusion /8/. Internal convection also has a significant impact on the distribution of moisture in wall structures. Flows through a structure do, however, affect the thermal and moisture field of a structure more than convection within it /9/.

Convection through structures occurs whether they have a vapour barrier or not. It is dependent on the airtightness of a building's shell structures. No systematic difference has been detected between the airtightness values of buildings with or without vapour barriers /10/, /11/, /12/. Thus, according to the calculation method presented in section 3.2.1, the volume of the convection currents through a structure is not dependent on whether the structure has a vapour barrier or not.

It should also be noted that the nature of the convection is of crucial importance for the moisture behaviour of a structure. Convection may occur through holes and gaps or by seeping through porous material. The nature of the current does not, however, have any significance as regards the amount of carbon dioxide carried away by convection according to the presented calculation method.

Although the internal convection of a structure has a major impact on its moisture field, the transmission of moisture and carbon dioxide due to it cannot be directly compared. Generally, an increase in the carbon dioxide content of the indoor air of detached or semi-detached houses is dynamic - recurrent short-term loading following the 24-hour cycle. The moisture load on structures from indoor air, again, lasts significantly longer and is more even. The different molecular weights of gases are also likely to cause variation in the movement of water vapour and carbon dioxide molecules in the case of internal convection.

The relative importance of convection and diffusion in removing carbon dioxide from indoor air could not be determined experimentally as part of this study since the convection currents through a wall structure cannot be examined with equipment built to study carbon dioxide permeability.

## 4 Testing

### 4.1 Test equipment

The tests were conducted using test equipment built in TUT's laboratory. The equipment was used to determine the conditions prevailing during each test and the amount of carbon dioxide transmitted through test pieces by diffusion. Measurement and recording of data were computerized. The basic principle of the test equipment is shown in Appendix 1.

#### 4.1.1 Test chamber

The test chamber consisted of a box open on one side. It was made of 2-mm stainless steel sheet and its external dimensions were approx.  $600 \times 500 \times 400 \text{ mm}^3$ .

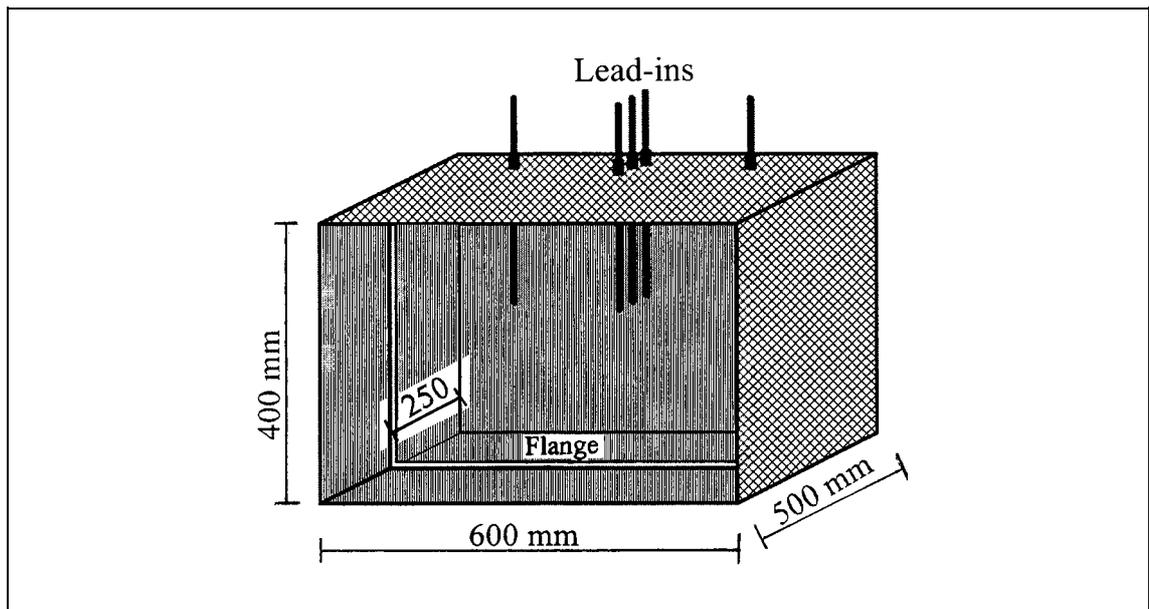


Figure 4.1. Test chamber.

A test piece was inserted in the open side and sealed against the flanges of the chamber. The flanges were positioned so that the primary side bordering on the chamber walls and the test material had a volume of  $0.0579 \text{ m}^3$  and the size of the clear opening was  $0.196 \text{ m}^2$ . The test piece was vertical during testing.

#### 4.1.2 Measurement of carbon dioxide

The carbon dioxide of the primary side was measured with the SERVOMEX 1400B4 gas analyzer. The analyzer was located outside the chamber, and the primary-side air

was circulated through the analyzer by a separate pump. The analyzer was calibrated during the test series at about one week intervals using two calibration gases (pure nitrogen and 4 % CO<sub>2</sub>).

CO<sub>2</sub> measurement on the secondary side was conducted with the HORIBA APBA-250E analyzer. The analyzer was positioned on the secondary side of the test piece so that the distance between the meter's air intake and the test piece was about 10 cm. The meter was calibrated under controlled carbon dioxide contents according to the values provided by the SERVOMEX analyzer.

#### **4.1.3 Pressure measurement**

Air pressure was measured in the primary and secondary sides with a relative pressure gauge. The difference between readings of the primary and secondary sides at a certain moment was compared to the difference at the start of the test. This reading then indicated whether the air pressure differential between the sides increased during the test. Pressure measurement results were not necessary during tests after a vent pipe was installed between the primary and secondary sides.

#### **4.1.4 Temperature measurement**

Temperature was measured with separate temperature sensors. The sensors were calibrated before the test series using water of two different temperatures and an officially calibrated thermometer.

The maximum temperature fluctuation between tests was 2°C. Thus, temperature did not have any practical meaning when comparing the volume of carbon dioxide that had passed through different test pieces.

#### **4.1.5 Humidity measurement**

The relative humidity of air was measured using two Vaisala HMI 31 moisture meters. Prevailing humidity conditions affected the pore structure of materials and thereby their gas permeability.

#### **4.1.6 Calibration of test equipment**

The test equipment was calibrated in July '95. The used test piece was a steel sheet and two requirements were set for the equipment:

- No pressure difference between the primary and secondary sides must occur
- During calibration the carbon dioxide concentration of the primary side must remain constant

Initially, calibration was done with the primary side completely isolated from the secondary side. This way, the CO<sub>2</sub> content of the primary side stayed constant, but pressure difference occurred between the primary and secondary sides in all measurements. Temperature fluctuations during calibration were one reason for the pressure differences. Consequently, the pressure of the primary side was regulated in tests by a pipe 2 mm in diameter.

Since the pipe was open, carbon dioxide exited the primary side through it. The amount of carbon dioxide passing through the pipe per unit of time was measured experimentally at different primary-side contents. The results were used to determine a correction factor dependent on time and content which was used to rectify the content of the primary side.

Due to the small diameter of the vent pipe, the correction of the primary side content remained small during testing compared to the overall content. After calibration measurements lasting a day, the correction was about 300 ppm. On the other hand, in tests on materials that were permeated the fastest by carbon dioxide, the impact of the correction factor was insignificant. Since the installation of the vent pipe, no pressure difference between the primary and secondary sides in calibration or actual tests could be detected.

#### **4.1.7 Running of tests**

A test was started by sealing a test piece against the flange and walls of the test chamber using silicone. After the silicone had dried, a plastic sheet was taped onto the secondary side of a test piece so that the fed carbon dioxide would have time to spread evenly throughout the primary side prior to actual permeability measurement.

Then, 100 % carbon dioxide was led into the primary side from a gas cylinder so that the CO<sub>2</sub> content exceeded 1.0 %, and the gas mixture was allowed to stabilize for at least an hour. During the feeding and stabilization of the gas, the pressure difference between the primary and secondary sides was eliminated by keeping open a hole 10 mm in diameter in addition to the vent pipe.

The moisture content of air was measured following the stabilization period, the pressure equalization hole was stopped, the measurement program was launched, and the plastic sheet was removed from the secondary side of the test piece. The measurement program monitored the carbon dioxide content of the primary side and

started recording data as it fell below 1.0 %. CO<sub>2</sub> contents, temperatures and changes in air pressure were measured at one minute intervals.

The test was continued until the carbon dioxide content of the primary side dropped below 0.15 %. Tests on highly impermeable materials were finished 24 hours after recording of results began.

Tests were repeated so that, at the end of the first one, a new dose of carbon dioxide was fed into the primary side and the measurement was repeated. The second measurement ensured the success of each test. No significant difference was observed between the results of the first and second measurements with regard to any test piece.

The test equipment was also used to test two wood-based test pieces to determine the impact of moisture on their carbon dioxide permeability. In the tests, the relative humidity of air in the primary side was increased while normal room humidity prevailed on the secondary side. Humidity of the primary side air was increased by pouring water onto the bottom of the test chamber. Conditions were allowed to stabilize for several days before the permeability tests. Otherwise moisture tests followed the pattern of other tests.

## **4.2 Test pieces**

Test pieces were made of generally used building materials. Here follows a brief description of them:

- External dimensions of test pieces were 390 x 590 mm ± 5 mm
- Gypsum boards 1 and 2 were by different manufacturers
- Porous fibreboards 2 and 3 were different trademarks
- Gypsum board 2 was used as backing in tests on wall finishes and as the wall board of structural tests
- Wallpapers were attached on gypsum board using regular wallpaper paste
- Paints were applied with a roller (2 coats)
- Paints were not thinned down
- Water-base, semigloss (4/RT class) interior acrylate latex paint was used as normal latex
- Water-base matt (6/RT class) PVA latex paint suitable for interiors was used as matt latex
- A building paper used in the products of a cellulose insulation manufacturer was used as building paper
- The timber slab was made by gluing together four pine boards and by planing it to a thickness of 13 mm.
- Interior paneling was of pine (STV 12 x 95).

- The timber slab and paneling were uncoated.
- Average measured densities of insulations:
  - mineral wool 17 kg/m<sup>3</sup>
  - mineral wool (windshield material) 80 kg/m<sup>3</sup>
  - cellulose insulation 45 kg/m<sup>3</sup>
- Test pieces of cellulose insulation were wet-blasted into frames made of wood or plywood. The inside dimensions of frames matched the clear opening of the test chamber. Thus, the area permeated by carbon dioxide was as large with cellulose-insulated test pieces as with the others.

#### 4.2.1 Tests on materials

Temperature or air humidity were not measured in the first tests on materials. The conditions of these tests did not, however, differ essentially from those of other tests. The run material tests and the average air humidities and temperatures during them are presented in Table 4.1.

**Table 4.1.** Tests on materials

| Date   | Material                           | Thickness<br>mm | RH<br>% | Temperature<br>°C |
|--------|------------------------------------|-----------------|---------|-------------------|
| 21.08. | gypsum board 1                     | 13              | -       | -                 |
| 22.08. | combi plywood                      | 12              | -       | -                 |
| 25.08. | construction plastic               | 0.2             | -       | -                 |
| 30.08. | timber slab                        | 13              | 45      | 21                |
| 04.09. | mineral wool (windshield material) | 30              | 44      | 21                |
| 21.09. | chipboard 1                        | 12              | 40      | 20                |
| 26.09. | porous fibreboard 1                | 25              | 47      | 21                |
| 27.09. | porous fibreboard 2                | 12              | 34      | 21                |
| 02.10. | fir plywood                        | 9               | 37      | 20                |
| 04.10. | chipboard 2                        | 11              | 41      | 21                |
| 10.10. | gypsum board 2                     | 13              | 37      | 21                |
| 17.10. | mineral wool                       | 150             | 41      | 22                |
| 23.10. | gypsum board (windshield material) | 9               | 40      | 21                |
| 28.10. | porous fibreboard 3                | 12              | 37      | 21                |
| 02.11. | cellulose insulation               | 150             | 25      | 20                |
| 01.12. | building paper                     | -               | 20      | 20                |
| 10.12. | interior paneling                  | 12              | 23      | 20                |

#### 4.2.2 Tests on wall finishes

The finishing materials of the tests are generally used products available at home furnishing stores. Run tests and the prevailing average relative humidities and temperatures are presented in Table 4.2.

**Table 4.2.** Tests on wall finishes

| Date   | Material           | RH<br>% | Temperature<br>°C |
|--------|--------------------|---------|-------------------|
| 05.10. | wallpaper          | 28      | 20                |
| 13.10. | matt latex paint   | 30      | 21                |
| 19.10. | normal latex paint | 38      | 22                |
| 21.10. | vinyl wallcovering | 30      | 21                |

#### 4.2.3 Tests on structures

Two tests on entire wall structures were conducted using the test equipment. The structures and the average relative humidities and temperatures during the tests are presented in Table 4.3.

**Table 4.3.** Tests on structures

| Date   | Structure   | RH<br>% | Temperature<br>°C |
|--------|---|---------|-------------------|
| 05.11. | Structure 1<br>wallpaper<br>gypsum board 2, 13 mm<br>cellulose insulation, 150 mm<br>porous fibreboard 2, 12 mm | 28      | 20                |
| 14.11. | Structure 2<br>building paper<br>cellulose insulation, 150 mm<br>porous fibreboard 2, 12 mm                     | 23      | 21                |

#### 4.2.4 Humidity tests

The test pieces used in humidity tests and the prevailing average temperatures and relative humidities are presented in Table 4.4.

**Table 4.4.** Humidity tests

| Test piece        | RH %         |                | Temperature<br>°C |
|-------------------|--------------|----------------|-------------------|
|                   | Primary side | Secondary side |                   |
| Interior paneling | 93           | 21             | 21                |
| Structure 2       | 89           | 20             | 21                |

### 4.3 Determination of factors

Carbon dioxide resistance of test pieces made of various materials and finished pieces was determined by two methods on the basis of conducted tests. Method 1 was based on the amount of carbon dioxide that had exited over a certain period of time while Method 2 relied on the apparent air change rate. Permeability of structures was described by apparent air change rates and carbon dioxide resistances.

#### 4.3.1 Determination of carbon dioxide resistance, Method 1

Method 1 involved dividing the test into short periods. The average concentration difference in the primary and secondary sides as well as the amount of carbon dioxide diffused through the test piece during each period were computed.

Carbon dioxide contents were converted into concentrations using the general gas law:

$$c = \frac{p \times C \times M}{R \times T} \times 10^{-6} \quad (4.1)$$

where

|   |  |
|---|--|
| c | carbon dioxide concentration (g/m <sup>3</sup> ) |
| p | overall pressure (Pa)                            |
| C | carbon dioxide content (ppm)                     |
| M | molar mass of carbon dioxide = 44.010 g/mol      |
| R | molar gas constant = 8.3143 J/(mol x K)          |
| T | temperature (K)                                  |

The average concentration difference ( $\Delta c_i$ ) during the measurement period (i) was derived from the formula:

$$\Delta c_i = \frac{c_{p,1} + c_{p,2}}{2} - \frac{c_{s,1} + c_{s,2}}{2} \quad (4.2)$$

where

|           |  |
|-----------|--|
| $c_{p,1}$ | primary side concentration at start of measurement period ( $\text{g/m}^3$ )   |
| $c_{p,2}$ | primary side concentration at end of measurement period ( $\text{g/m}^3$ )     |
| $c_{s,1}$ | secondary side concentration at start of measurement period ( $\text{g/m}^3$ ) |
| $c_{s,2}$ | secondary side concentration at end of measurement period ( $\text{g/m}^3$ )   |

The amount of carbon dioxide ( $g_{k,i}$ ) that passed through the test piece in the measurement period (i) was derived from the formula:

$$g_{k,i} = \frac{(c_{p,1} - c_{p,2}) \times V_p}{(t_2 - t_1) \times A_t} \quad (4.3)$$

where

|       |  |
|-------|--|
| $V_p$ | volume of primary side ( $\text{m}^3$ )                  |
| $A_t$ | area of test piece open to diffusion ( $\text{m}^2$ )    |
| $t_1$ | total test duration at start of measurement period i (s) |
| $t_2$ | total test duration at end of measurement period i (s)   |

The carbon dioxide resistance value ( $Z_{v,i}$ ) for the measurement period i was derived from the formula:

$$Z_{v,i} = \frac{\Delta c_i}{g_{k,i}} \quad (4.4)$$

The carbon dioxide resistance of the test piece was derived from the formula:

$$Z_v = \left( \sum_{i=1}^n Z_{v,i} \right) / n \quad (4.5)$$

where

n number of measurement periods

#### 4.3.2 Determination of carbon dioxide resistance, Method 2

Method 2 relied on the apparent air change rate ( $n_{a,p}$ ) on the primary side which was derived from the formula for computing the amount of carbon dioxide having exited the primary side:

$$n_{a,p} = -\frac{1}{t} \times \ln \left( \frac{C_\infty - C}{C_\infty - C_0} \right) \quad (4.6)$$

where

|            |   |
|------------|---|
| $C_0$      | initial content on primary side (ppm)                     |
| $C_\infty$ | average secondary side content (ppm) during test          |
| $C$        | content (ppm) after elapse of time (t) from start of test |
| $t$        | duration of test (h)                                      |

The derived factor was converted into a carbon dioxide resistance factor ( $Z_v$ ) by the formula:

$$Z_v = \frac{A_t}{n_{a,p} \times V_p} \times 3600 \quad (4.7)$$

where

|       |  |
|-------|--|
| $V_p$ | volume of primary side ( $m^3$ )               |
| $A_t$ | area of test piece open to diffusion ( $m^2$ ) |

#### 4.3.3 Determination of carbon dioxide resistance of wall finishes

The carbon dioxide resistance of wall finishes was determined by subtracting the carbon dioxide resistance of the backing of the finish from the total carbon dioxide resistance of the finished board according to Formula 4.8.

$$Z_{v,coat} = Z_{v,tot} - Z_{v,plate} \quad (4.8)$$

where

|               |  |
|---------------|--|
| $Z_{v,coat}$  | carbon dioxide resistance of used finish                                 |
| $Z_{v,tot}$   | carbon dioxide resistance of test piece consisting of backing and finish |
| $Z_{v,plate}$ | carbon dioxide resistance of backing                                     |

#### 4.3.4 Determination of carbon dioxide resistance of structures

The carbon dioxide resistances of structures were also determined by Methods 1 and 2. Moreover, total carbon dioxide resistances were also determined for structures based on the general calculation model by adding together the resistance values of various material layers.

#### 4.3.5 Determination of apparent air change rates of structures

The apparent air change rates produced by structures in the primary side were calculated on the basis of structural tests' results according to Formula 4.6.

#### 4.3.6 Determination of materials' carbon dioxide permeability

Carbon dioxide permeability of homogeneous test pieces was also determined by dividing the material's thickness by the calculated resistance value:

$$\delta_v = \frac{d}{Z_v} \quad (4.9)$$

where

$\delta_v$                       carbon dioxide permeability ( $m^2/s$ )  
 d                            thickness of material (m)

#### 4.3.7 Evaluation of determination of factors

The methods for determining factors were deficient in the sense that the primary side was not in a steady state during the tests with regard to carbon dioxide content. This applies especially to Method 1 of determining carbon dioxide factors. In Method 2, this flaw was partly eliminated since the apparent air change rate serving as the basis of calculations remained constant. There is a small systematic difference between the results of Methods 1 and 2 — Method 1 yields a slightly higher resistance value.

In the case of finishes, the principle of manual calculation was adhered to. Accordingly, the total resistance of a structure is the sum of the partial resistances of the homogeneous material layers that make it up. This may cause some error since gypsum board 2 that served as backing had higher resistance than the finishes (except for the normal latex paint).

The apparent air change rate is the most accurate quantity describing permeability of structures. The inaccuracy from the decreasing carbon dioxide content of the primary side is emphasized in the case of structures since the carbon dioxide permeability of the windshield on the outer surface of the insulation is lower than that of the insulation.

The results of the calculations are, however, of the correct magnitude. Development of the methods would probably provide insignificant benefits from the viewpoint of real-life situations. This is primarily due to the wide variation in materials within product groups and changing conditions.

## **5 Test results**

### **5.1 General**

If the primary-side carbon dioxide content for a test piece was still over 0.90 % 24 hours after a test, its carbon dioxide resistance and permeability were not determined. This was the case with:

- construction plastic
- combi plywood, 12 mm
- normal latex paint

The used test equipment was designed for permeable building materials and structures. Thus, the accuracy of measurements decreases if a material has low carbon dioxide permeability. Different type of equipment would be needed to determine the accurate carbon dioxide permeabilities of the above materials. On the other hand, these materials cannot be used in wall structures that should be highly permeable to gases. Therefore, more detailed testing was deemed unnecessary.

The secondary side carbon dioxide content was usually about  $400 \pm 30$  ppm during tests. In some tests it went higher but did not affect the calculated factors based on repeat measurements.

### **5.2 Decrease in carbon dioxide content of primary side**

The reductions in the primary-side carbon dioxide contents of various test pieces are presented in the appendices as follows:

- Primary-side decrement curves for material tests lasting over 24 hours in Appendix 2
- Primary-side decrement curves for short material tests (reached lower limit in less than 24 hours) in Appendices 3 and 4
- Primary-side decrement curves for finish tests in Appendix 5
- Primary-side decrement curves for structure tests in Appendix 6

The decrement curves of the appendices go to 300 minutes to render them mutually comparable.

### 5.3 Carbon dioxide resistance of test pieces

#### 5.3.1 Materials

Carbon dioxide resistances derived from tests are presented in Table 5.1.

**Table 5.1.** Average carbon dioxide resistances ( $Z_v$ ) for materials derived from the tests.

| Material                           | Thickness<br>mm | Carbon dioxide resistance, $Z_v$<br>$\times 10^3$ s/m |          |
|------------------------------------|-----------------|---|----------|
|                                    |                 | Method 1  | Method 2 |
| gypsum board 1                     | 13              | 5.8   | 5,7      |
| timber slab                        | 13              | 320   | 290      |
| mineral wool (windshield material) | 30              | 3.2   | 3.2      |
| chipboard 1                        | 12              | 74  | 73       |
| porous fibreboard 1                | 25              | 7.9   | 7.7      |
| porous fibreboard 2                | 12              | 4.3   | 4.1      |
| fir plywood                        | 9               | 1950  | 1850     |
| chipboard 2                        | 11              | 35  | 33       |
| gypsum board 2                     | 13              | 7.2   | 6.9      |
| mineral wool                       | 150             | 11  | 10       |
| gypsum board (windshield material) | 9               | 5.7   | 5.5      |
| porous fibreboard 3                | 12              | 5.3   | 5.2      |
| cellulose insulation               | 150             | 15  | 15       |
| building paper                     | -               | 3.4   | 3.3      |
| interior paneling                  | 12              | 380   | 345      |

#### 5.3.2 Wall finishes

The carbon dioxide resistances ( $Z_v$ ) determined by tests are shown in Table 5.2.

**Table 5.2.** Average carbon dioxide resistances ( $Z_v$ ) of wall finishes.

| Finish             | Carbon dioxide resistance, $Z_v$<br>$\times 10^3$ s/m |          |
|--------------------|---|----------|
|                    | Method 1  | Method 2 |
| wallpaper          | 1.5   | 1.3      |
| matt latex paint   | 4.0   | 4.1      |
| vinyl wallcovering | 3.0   | 3.2      |

### 5.3.3 Structures

The carbon dioxide resistance values of tested structures are presented in Table 5.3. A comparison of the values indicates that the used method of summing up the resistance values of various layers gives a total carbon dioxide resistance value of the correct magnitude.

**Table 5.3.** Comparison of carbon dioxide resistance values derived by different methods from structural tests.

|             | Carbon dioxide resistance, $Z_v$ ,<br>derived from structural tests<br>$\times 10^3$ s/m |          | Sum of carbon dioxide resistances,<br>$\Sigma Z_v$ , derived from material tests<br>$\times 10^3$ s/m |          |
|-------------|--|----------|---|----------|
|             | Method 1   | Method 2 | Method 1  | Method 2 |
| structure 1 | 27   | 25       | 28  | 27       |
| structure 2 | 19   | 19       | 23  | 22       |

## 5.4 Apparent air change rates derived from structural tests

The primary-side apparent air change rates derived from the results of structural tests are presented in Table 5.4

**Table 5.4.** Primary-side apparent air change rates of test equipment based on structural tests.

| Structure   | Apparent primary-side air change rate, $n_{a,p}$<br>l/h |
|-------------|---|
| structure 1 | approx. 0.50  |
| structure 2 | approx. 0.65  |

## 5.5 Results of humidity tests

The results of humidity tests indicate that as humidity increases, the diffusion of carbon dioxide in wood slows down noticeably. In the case of the other piece tested for humidity, i.e. structure 2, no noticeable difference in carbon dioxide permeability due to humidity was detected. The quantities describing permeability calculated from the primary-side decrement curves are shown in Table 5.5.

**Table 5.5.** The quantities describing permeability derived from humidity tests in comparison to corresponding values based on normal tests.

|                       | <b>Interior paneling<br/>carbon dioxide resistance, Method 2<br/><math>\times 10^3</math> s/m</b> | <b>Structure 2<br/>apparent air change rate<br/>l/h</b> |
|-----------------------|---|---|
| primary side, "dry"   | approx. 345   | approx. 0.65  |
| primary side, "humid" | approx. 620   | approx. 0.65  |

The primary-side carbon dioxide decrement curves derived from the conducted humidity tests are presented in Appendix 7 as regards the interior paneling and in Appendix 8 as regards structure 2.

## 5.6 Carbon dioxide permeability of materials

The carbon dioxide permeabilities derived from the carbon-dioxide resistance figures for test pieces are presented in Table 5.6. The table shows certain ranges of permeability values since absolute permeability values are ambiguous. This is primarily due to three factors:

- Many different products may be called by the same "material name" and may, yet, have widely different properties.
- Changes in conditions alter permeability.
- There is no widely used, standardized research method for examining carbon dioxide permeability of structures. For instance, the orientation of the test piece in the test equipment may affect the results of measurements.

**Table 5.6.** Carbon dioxide permeabilities of construction materials based on test results.

| <b>Material</b>      | <b>Carbon dioxide permeability, <math>\delta_v</math><br/><math>\times 10^{-6}</math> m<sup>2</sup>/s</b> |
|----------------------|---|
| porous fibreboard    | 2.0 - 3.5   |
| gypsum board         | 1.5 - 2.5   |
| chipboard            | 0.13 - 0.38   |
| wood                 | 0.04 - 0.05   |
| mineral wool         | 14 - 15   |
| cellulose insulation | 9 - 11  |

## 6 Modeling of the results

An attempt was made to model the impact of the results of the experimental part of the study on the real-life situation through theoretical calculations. Results were modeled in two ways:

- The apparent air change rate produced by the permeable wall structures of different spaces was determined.
- The overall carbon dioxide balance of the bedroom of a normal detached or semi-detached house was calculated.

### 6.1 Apparent air change rate of different spaces

In the modeling of apparent air change, the used wall structures were ones tested in the test equipment (see Table 4.3). The apparent air change rates determined by tests are shown in Table 5.4. The rates can be converted into apparent air change rates of a space of the desired size by the following formula:

$$n_a = n_{a,p} \times \frac{A}{A_t} \times \frac{V_p}{V} \quad (6.1)$$

where

|                |   |
|----------------|---|
| A              | Area of gas permeable walls of target space (m <sup>2</sup> ) |
| A <sub>t</sub> | Area of test piece open to diffusion (m <sup>2</sup> )        |
| V              | Volume of target space (m <sup>3</sup> )                      |
| V <sub>p</sub> | Volume of test chamber's primary side (m <sup>3</sup> )       |

Apparent air change rates were calculated for four different spaces. The ceiling and floor of each space were impermeable to gases.

#### **Room 1:**

- size: 3 m x 4 m x 2.7 m
- the walls had no openings and were gas permeable throughout

#### **Room 2:**

- size: 3 m x 4 m x 2.7 m
- two walls were gas permeable; the permeable area was reduced by a window (2.7 m<sup>2</sup>)

#### **Building 1:**

- size: 10 m x 12 m x 2.7 m
- the walls had no openings and were gas permeable throughout

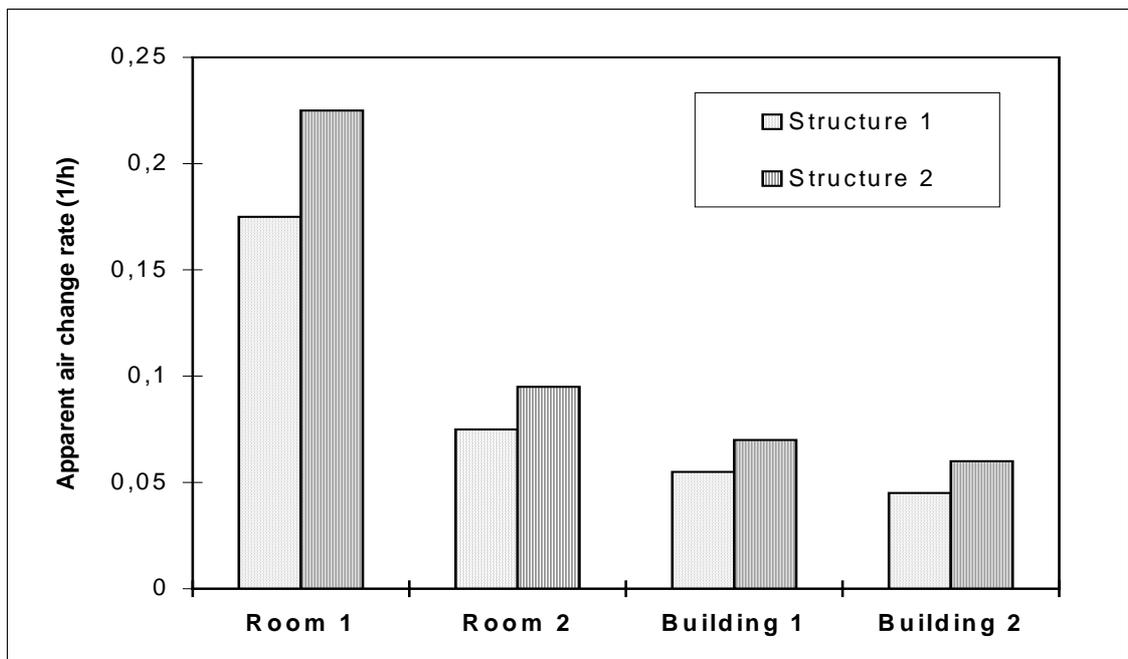
#### **Buildings 2:**

- size: 10 m x 12 m x 2.7 m
- 15 % of external wall area consisted of openings

The apparent air change rate of Room 1 was approx. 0.17-0.23 l/h depending on the wall structure. The figure can be considered significant with respect to indoor air quality. However, a space like Room 1 never actually exists. The apparent air change rates calculated for other spaces were clearly lower than that for Room 1. The true rate may, however, differ from the calculated one. The apparent air change rates are shown in Table 6.1 and Figure 6.1.

**Table 6.1.** Apparent air change rate produced by wall structures 1 and 2 in different spaces.

|            | Apparent air change rate, l/h |              |
|------------|-------------------------------|--------------|
|            | Structure 1                   | Structure 2  |
| Room 1     | 0.17-0.18                     | 0.22-0.23    |
| Room 2     | 0.07-0.08                     | 0.09-0.10    |
| Building 1 | 0.05-0.06                     | approx. 0.07 |
| Building 2 | 0.04-0.05                     | approx. 0.06 |



**Figure 6.1.** Average apparent air change rates produced by permeable wall structures in different spaces.

## 6.2 Carbon dioxide balance of bedroom

According to numerous building climate studies, the conditions determining the quality of the indoor air of detached and semi-detached houses often occur in bedrooms at night when the occupants sleep and the communicating door is closed. For this reason, an effort was made to build a mathematical model of the carbon dioxide balance of a normal detached or semi-detached house. The calculation was done by the manual

method which describes the transmission of water vapour and takes into account the impact of diffusion through external and partition walls and the ceiling. The standard of reference were gas impermeable structures.

The corner room of a one-storey detached or semi-detached house, whose walls consisted of two external walls and two partitions, was selected for modeling. The materials were chosen so that the structures would be as permeable to carbon dioxide as possible. Their resistance values were ones determined by Method 2. The structures are presented in Table 6.2.

**Table 6.2.** Structures used in calculation and their carbon dioxide resistance values.

| Structure     | Material                     | Carbon dioxide resistance<br>$\times 10^3 \text{ s/m}$ |
|---------------|------------------------------|--|
| External wall | wallpaper                    | 1.3  |
|               | gypsum board 2, 13 mm        | 6.9  |
|               | building paper               | 3.3  |
|               | cellulose insulation, 150 mm | 15.1   |
|               | porous fibreboard 2, 12 mm   | 4.1  |
|               | total                        | 30.7   |
| Partition     | wallpaper                    | 1.3  |
|               | gypsum board 2, 13 mm        | 6.9  |
|               | cellulose insulation, 100 mm | 9.9  |
|               | gypsum board 2, 13 mm        | 6.9  |
|               | wallpaper                    | 1.3  |
|               | total                        | 26.3   |
| Ceiling       | dull latex paint             | 4.1  |
|               | gypsum board 2, 13 mm        | 6.9  |
|               | building paper               | 3.3  |
|               | cellulose insulation, 300 mm | 30.2   |
|               | total                        | 44.5   |

The following initial values were used:

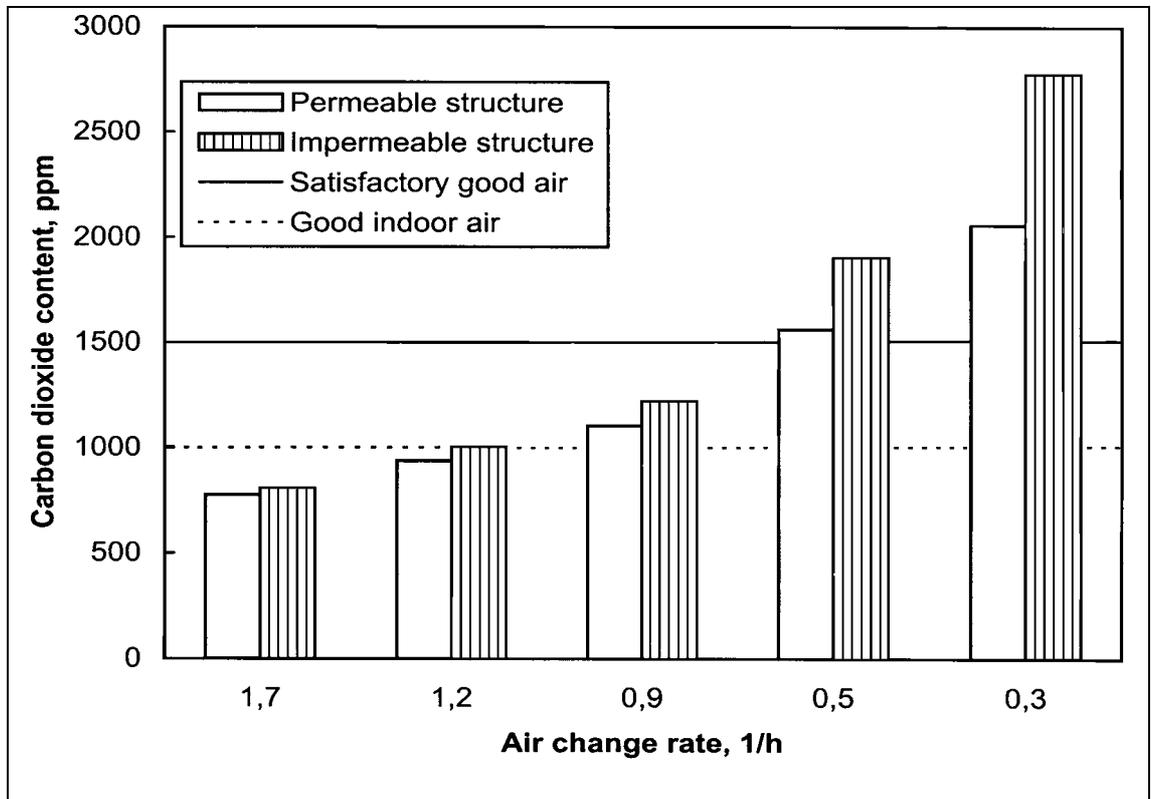
- the measurement period was 8 hours
- bedroom size: 3 m x 4 m x 2.7 m
- 2 persons sleeping in the room produced 215 ml/min/person of carbon dioxide (man's resting production /13/)
- external wall had a window (2.0 m<sup>2</sup>), and partition had a door (1.6 m<sup>2</sup>) — both were closed
- carbon dioxide content of outdoor air was 350 ppm
- CO<sub>2</sub> content of rest of indoor spaces was 600 ppm throughout the night
- the partitions of the gas impermeable bedroom were also impermeable

- indoor and outdoor temperature was +20 °C and RH 30 % (average conditions of permeability tests on materials used in structures)

The room's air change rate was used as the variable which was changed to produce different values of final carbon dioxide content. The results are shown in Table 6.3 and Figure 6.2.

**Table 6.3.** Final content values at different air change rates produced in modeling of bedroom.

| AC factor | Permeable structures<br>ppm CO <sub>2</sub> | Impermeable structures<br>ppm CO <sub>2</sub> | Comments  |
|-----------|---|---|---|
| 0.3       | 2060  | 2775  | typical bedroom with poor ventilation                                 |
| 0.5       | 1562  | 1905  | Min. air change rate of Building Code D2 for rooms of normal height   |
| 0.9       | 1104  | 1221  | Min. air change rate of Building Code D2 based on number of occupants |
| 1.2       | 935   | 1000  | ideal level of carbon dioxide 1,000 ppm (good quality indoor air /6/) |
| 1.7       | 775   | 805   | ideal level of carbon dioxide 800 ppm                                 |



**Figure 6.2.** Final carbon dioxide content values at different air change rates and carbon dioxide contents of satisfactory and good indoor air produced in modeling of bedroom /6/.

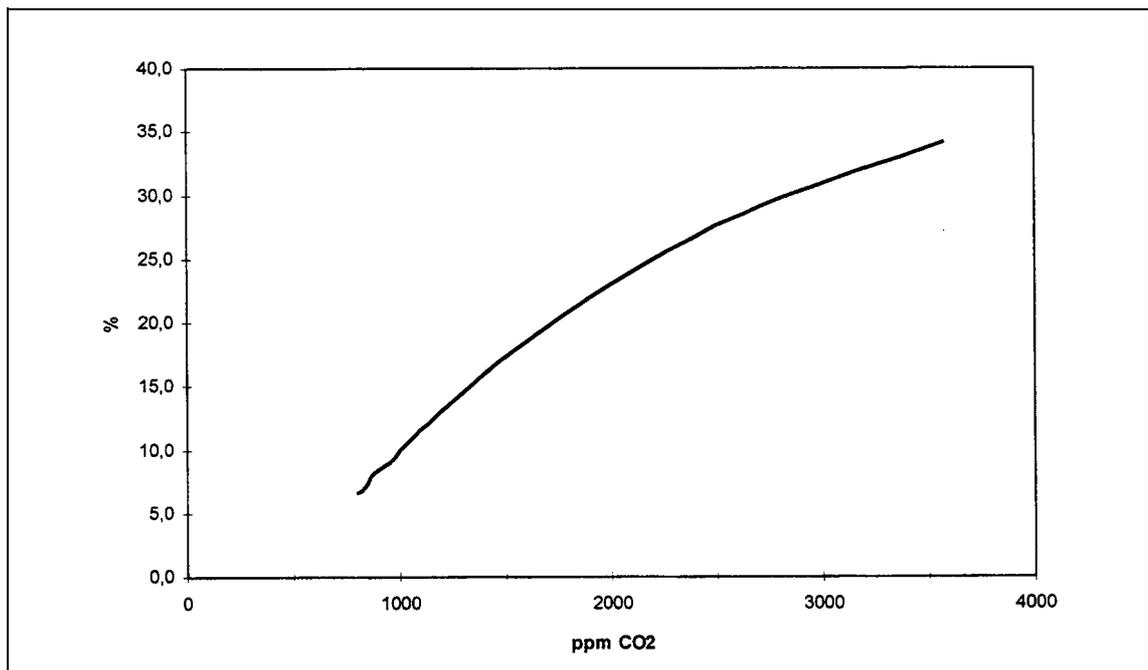
The results were used to calculate the percent decrease ( $\rho$ ) in the carbon dioxide increase of indoor air due to gas permeable structures compared to gas impermeable structures using Formula 6.2:

$$\rho = \frac{C_i^- - C_i^+}{C_i^- - C_{out}} \times 100\% \quad (6.2)$$

where

$C_i^-$                     final content with impermeable structures  
 $C_i^+$                     final content with gas permeable structures  
 $C_{out}$                    outdoor air carbon dioxide content (350 ppm)

The percent change increases strongly as the content of the bedroom rises. The decrease at carbon dioxide contents corresponding to good indoor air (< 1,000 ppm) is small, but at "problem bedroom" contents (approx. 3,000 ppm) the reduction is about 30 percent. The results are shown in Figure 6.3.



**Figure 6.3.** Percent decrease in indoor air carbon dioxide regain due to permeable walls compared to impermeable walls indicated by modeling.

The results of the modeling of the bedroom were also used to determine the apparent air change rate produced by gas permeable wall structures. The value was about 0.11-0.13 l/h which is greater than the values for Room 2 in Table 6.1. This is primarily due the different assumptions incorporated in starting values (e.g. "breathable" ceiling and partition) and different calculation method.

### 6.3 Evaluation of modelings

The modeling calculations must be viewed critically since they involve many assumptions. In a real-life situation, there are many other factors affecting the carbon dioxide balance of indoor air besides diffusion — such as convection. The calculations also ignored the following factors affecting the carbon dioxide balance:

- The manual calculation method does not consider the amount of carbon dioxide that the pore air of structures may contain. Thus, it underestimates the reduction in carbon dioxide in indoor spaces, at least at the beginning of the observation period. If the CO<sub>2</sub> content of pore air is low at the start of the loading period, the carbon dioxide flow is resisted only by the wall board and finish.
- Due to its heavier molecular weight compared to air, carbon dioxide tends to sink to the lower sections of a building's air space. Thus, diffusion of carbon dioxide through the ceiling is apparently slower than through a wall. The calculations overestimate the reduction in carbon dioxide to some extent since the resistance coefficients used for the ceiling are ones derived from vertical test pieces.
- Changes in outdoor and indoor temperatures. As temperature drops, diffusion slows down.
- Moisture contents of materials. Diffusion through certain materials slows down as the materials' moisture content increases.
- The general mistakes related to manual calculation.

## 7 Comparison of carbon dioxide and water vapour

### 7.1 Comparison of carbon dioxide and water vapour permeabilities

Water vapour permeability is generally studied by a standardized research method, the so-called cup method (standards DIN 52 615 and ASTM E96-95). This study did not include water vapour permeability tests — the presented permeability and resistance values were derived from literature.

Table 7.1 shows the water vapour and carbon dioxide permeabilities of some building materials and air. There is significant correlation between the factors. Thus, a certain material's permeability for a certain gas depends on the diffusion factor of that gas through air.

**Table 7.1.** Water vapour and carbon dioxide permeabilities for some building materials and through air at 20°C.

| Material             | Water vapour permeability /7/<br>$\times 10^{-6} \text{ m}^2/\text{s}$ | Carbon dioxide permeability<br>$\times 10^{-6} \text{ m}^2/\text{s}$ |
|----------------------|--|--|
| air                  | 24.6   | 15.3   |
| cellulose insulation | 13.5 /8/   | 9 – 11   |
| mineral wool         | 15 – 24  | 14 – 15  |
| porous fibreboard    | 3.8-4.6  | 2.0 – 3.5  |
| gypsum board, 13 mm  | approx. 2.3  | 1.5 – 2.5  |
| chipboard            | 0.1-0.5  | 0.13 – 0.38  |
| wood                 | 0.2 – 3.5  | 0.04 – 0.05  |

In the comparison of the carbon dioxide resistances of examined wall finishes (Table 7.2) the correlation was considerably lower.

**Table 7.2.** Comparison of water vapour and carbon dioxide resistances of finishes.

| Finish             | Water vapour resistance<br>$\times 10^3 \text{ s/m}$ | Carbon dioxide resistance<br>$\times 10^3 \text{ s/m}$ |
|--------------------|--|--|
| matt latex paint   | 0.7 /17/   | 4.3  |
| normal latex paint | 6.6 /17/   | not determined   |
| wallpaper          | 1 /7/  | 1.5  |
| vinyl wallcovering | 10 /7/   | 3.2  |

The difference between the paints is probably due to the thickness of the coat. The water vapour permeability of latex paints depends highly on coat thickness /16/. In the tests where water vapour permeability of paints was studied, the coat was sprayed onto paper. On the other hand, in carbon dioxide permeability tests, two coats of unthinned paint were applied by roller onto a gypsum board. The same brands of paint were used

in determining both resistance values. When using latex paints, it must also be taken into account that the smoothness of the surface to be painted affects significantly the uniformity of the coat.

The correlation between the permeabilities of wallpapers and wallcoverings was not as high as with building materials, either. One reason is that carbon dioxide and water vapour resistance factors were not determined on the basis of the same brands.

## 7.2 Diffusion of water vapour through a wall structure

According to the manual calculation method, the transmission of water vapour through a wall structure due to diffusion is the greater, the lower the structure's water vapour resistance. Since the water vapour and carbon dioxide resistance values of materials depend primarily on each other, improvement of the carbon dioxide permeability of a structure also increases the amount of water vapour passing through said structure.

Wood is a material that both retains and releases moisture. Therefore, the manual calculation method does not give an absolutely correct picture of the moisture behaviour of wooden walls and structures incorporating wood-based materials. The equilibrium moisture content of wood, as of all hygroscopic materials, depends on ambient air temperature and relative humidity. Figure 7.1 shows the interdependence of the equilibrium moisture content of wood and the water content of air ( $\text{g/m}^3$ ) and temperature.

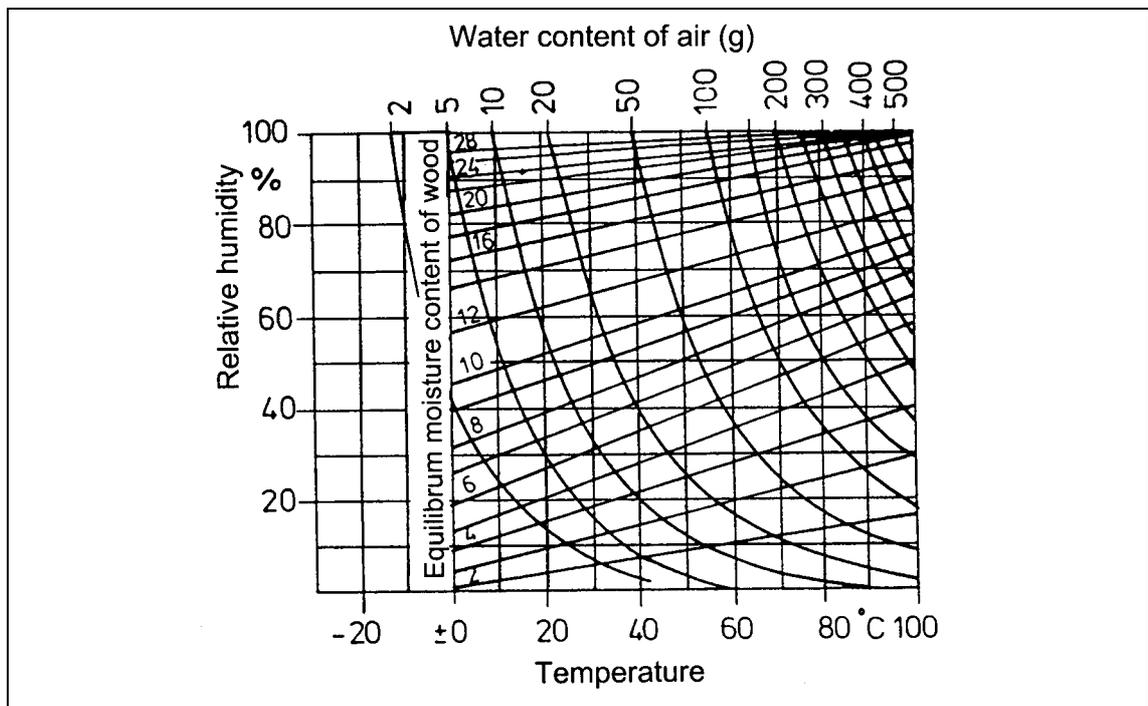


Figure 7.1. Impact of water content of air and temperature on equilibrium moisture content of wood.

One of the following states exists always between a hygroscopic material and its surroundings:

- The material absorbs moisture from its surroundings. The phenomenon is called absorption.
- The material releases moisture into its surroundings. The phenomenon is called desorption.
- The moisture content of the material is in equilibrium with that of its surroundings.

The equilibrium moisture content of a material is also affected by whether the material has reached equilibrium by absorbing or releasing moisture. This difference between the equilibrium moisture contents of materials resulting from moistening and drying under different conditions of humidity is called hysteresis.

Since cellulose insulation can retain and release moisture like wood, its moisture behaviour can be compared to that of old sawdust-insulated and log walls. These structures can store the moisture entering them in winter thanks to the moisture-retaining properties of wood - in summer they dry again. The moisture behaviour of these structure is determined by the sufficiency of their moisture-retaining capacity.

Although the manual calculation model has some shortcomings (Ch. 3.1.5), it has nevertheless been used in the modeling calculations of Chapter 6 to determine the moisture behaviour of a wall structure in winter conditions.

The used moisture difference between outdoor and indoor spaces is  $3.5 \text{ g/m}^3$  and the water vapour resistances of structural layers are presented in Table 7.3.

**Table 7.3.** Water vapour resistance values of materials used in calculations.

| Material             | Thickness<br>mm | Water vapour resistance<br>$\times 10^3 \text{ s/m} / \text{I}$ |
|----------------------|-----------------|---|
| Wallpaper            | -               | 1   |
| Gypsum board         | 13              | 6   |
| Building paper       | -               | 5 <sup>°°</sup>   |
| Cellulose insulation | 150             | 10 <sup>°°°</sup>   |
| Porous fibreboard    | 12              | 3   |

<sup>°°</sup> The water vapour resistance value was derived from the value for carbon dioxide by multiplying the latter with the ratio of the air permeabilities of carbon dioxide and water vapour.

<sup>°°°</sup> The resistance value of sawdust has been used as the value for water vapour.

At the used initial values, no area of the external wall structure reaches dew point - the RH of the external surface of the insulation space is 82 %, and moisture is transmitted through the structure at a rate of  $80 \text{ g/m}^2 \times \text{week}$  by diffusion. The amount of moisture passing through has no significance since no condensation occurs in the insulation space. Appendix 9 consists of the worksheet.

## 8 Conclusions

The study examined the transmission of carbon dioxide and water vapour through structures that allow diffusion of gases.

Test equipment was developed for the study which allowed looking into the diffusion of carbon dioxide through various building materials, wall finishes and structures. The carbon dioxide resistance values determined with the test equipment correlate closely with the water vapour transmission values presented in other studies.

Moisture seems to clearly lower the carbon dioxide permeability of wood. The test results do not allow determining how moisture affects the carbon dioxide flow through a structure composed of other materials. Theoretically, lower temperature slows down the diffusion of carbon dioxide.

Test results were also used to build various models of indoor-air carbon dioxide balance which took into account the diffusion of carbon dioxide through the wall structure. Models never give a fully accurate result of real-life carbon dioxide contents, but the results of calculations do, however, allow drawing some conclusions.

"Breathable" structures do lower the carbon dioxide content of indoor air. If the ventilation of a building is in compliance with the Finnish Building Code D2, or if the goal is to have high quality indoor air, "breathable" wall structures do not significantly affect the increase in the carbon dioxide. The impact is emphasized if the indoor carbon dioxide content becomes high.

To sum up the modelings, it may be said that the need of ventilation is not reduced by the use of gas permeable structures, but their use can alleviate the harmful effects of temporarily raised carbon dioxide contents.

Materials must be selected carefully in order to build wall structures that are highly permeable to carbon dioxide. Tests revealed, for example, that the use of paneling without background ventilation and normal interior latex paint as internal lining does not provide the desired result. The exterior cladding of the structure must also allow sufficient free convection. Moreover, it should be seen to that the wall structures remain gas permeable throughout the building's service life.

If the interior wall board of a wall structure has background ventilation, the structure's permeability to carbon dioxide improves, which also makes possible free selection of the wall board material and finish. When using wall board with background ventilation, sufficient air circulation must be ensured. Internal lining that allows free convection subjects the rest of the structure to a higher moisture load since, then, the wall finish and

board do not resist the diffusion of water vapour. Consequently, a structure with internal lining that allows free convection must be equipped with a sufficient water vapour barrier.

When considering the overall quality of indoor air, one must keep in mind that carbon dioxide is only an indicator of quality. Other impurities, especially those determining quality in normal situations, must be considered before we can speak of the beneficial impact of "breathable" structures on indoor air quality.

The impact of permeable wall structures on the total carbon dioxide balance is, all in all, a highly complicated mass transfer event. The simple manual calculation method used for modeling in this study provides only a rough estimate of the total content. Further study involving more accurate models is necessary especially as concerns momentary dynamic loading. Also, the study did not determine experimentally the impact of temperature on diffusion rate, and the examination of the impact of moisture was also limited. The question of the impact of the thermal current and different convection currents occurring in a structure in winter also remains unanswered.

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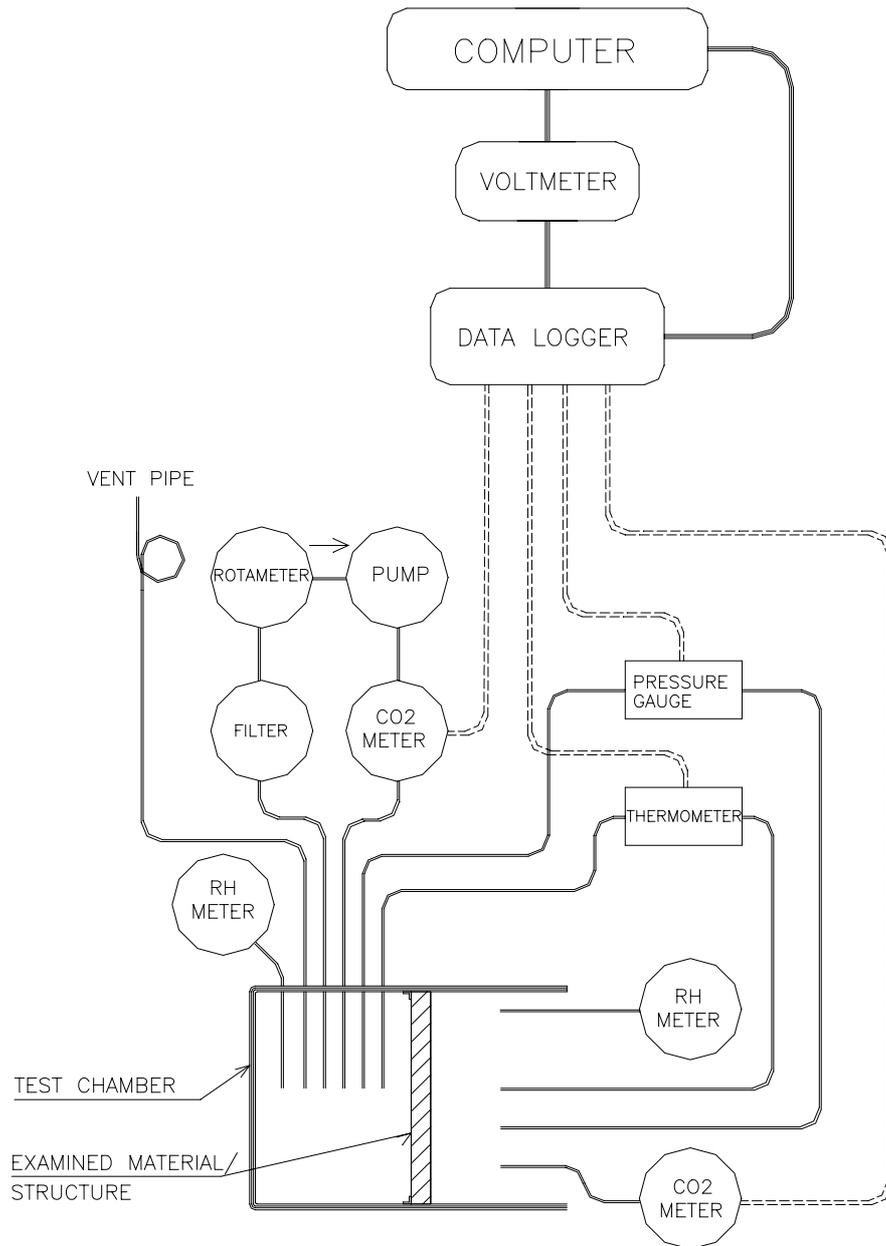
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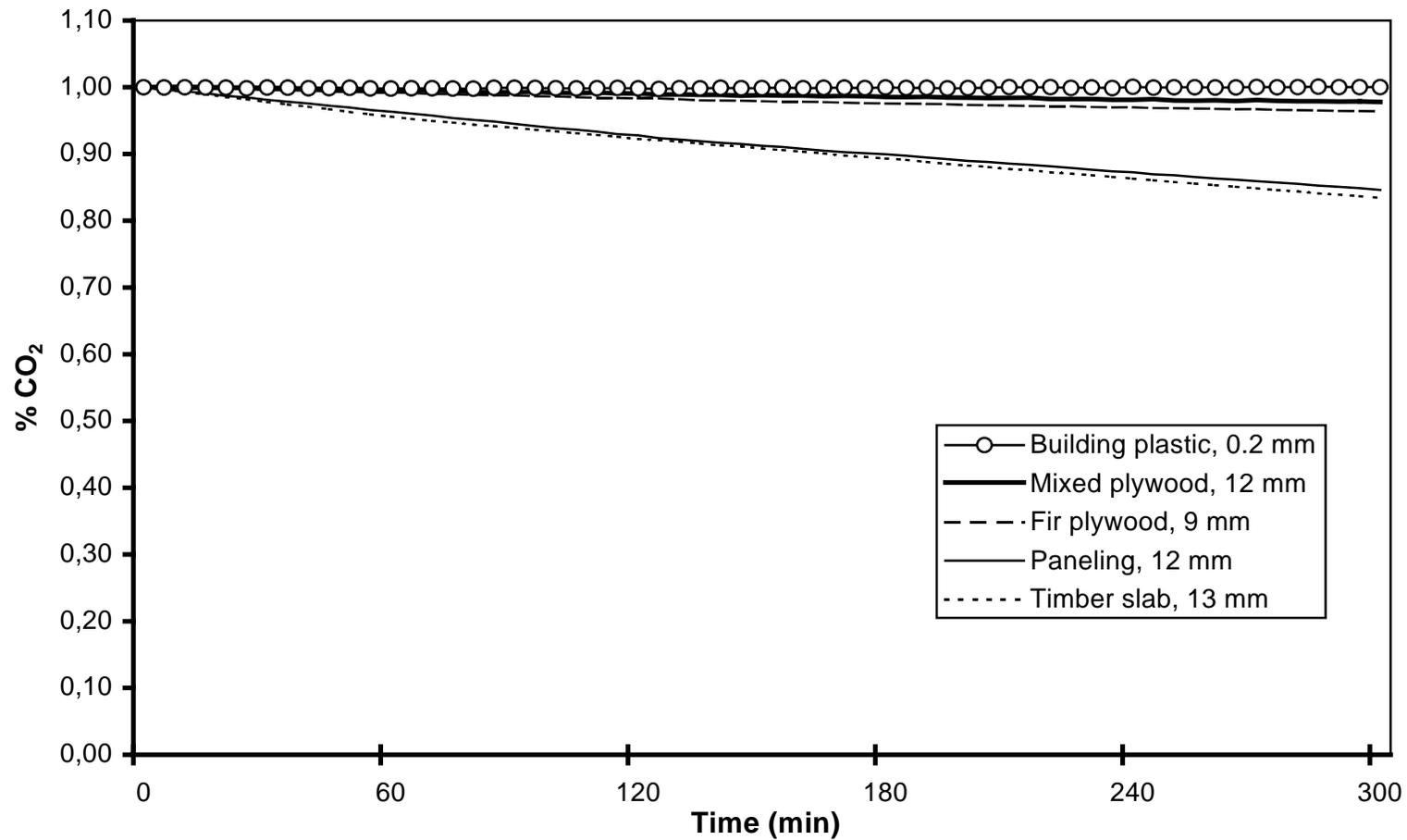
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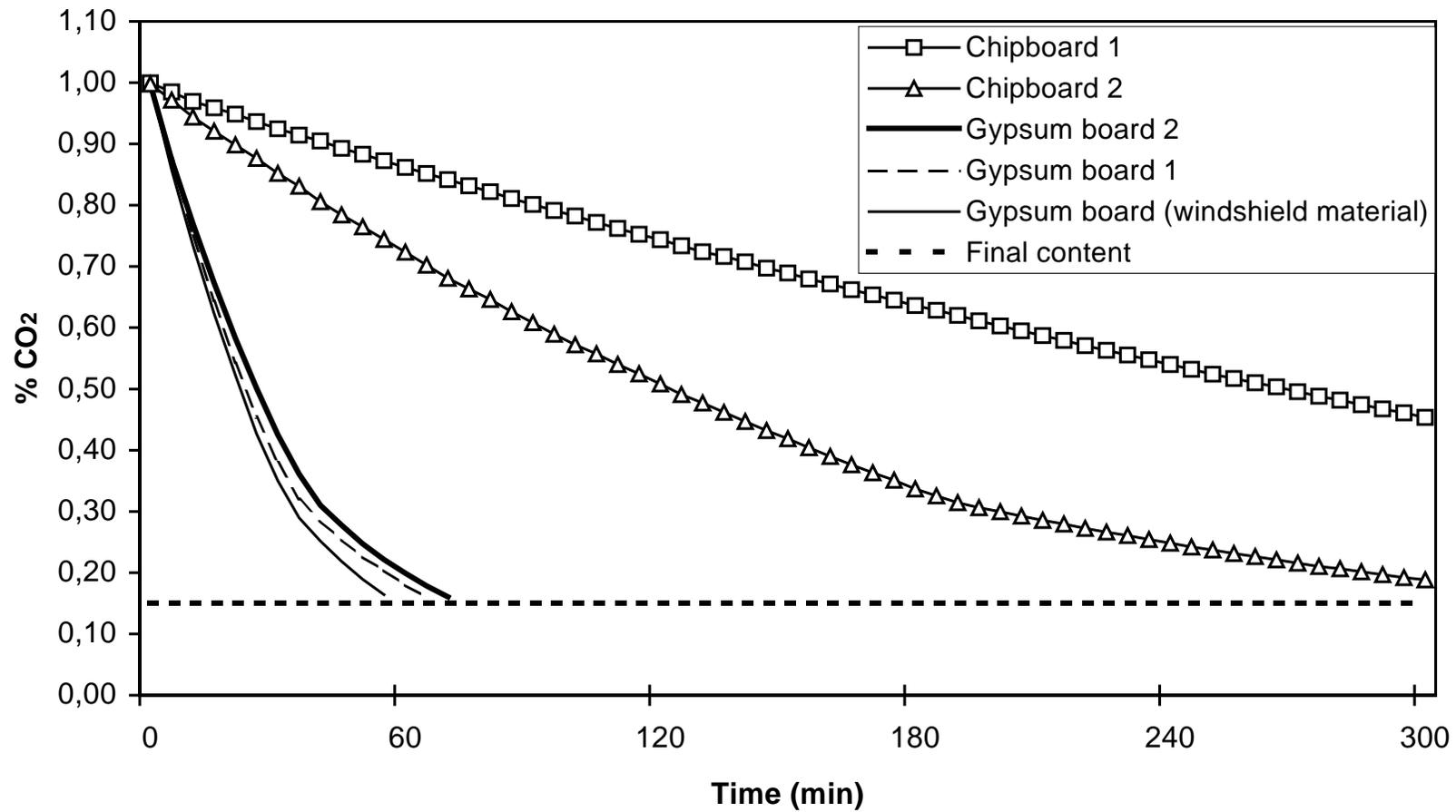
EQUIPMENT FOR TESTING  
CARBON DIOXIDE PERMEABILITY



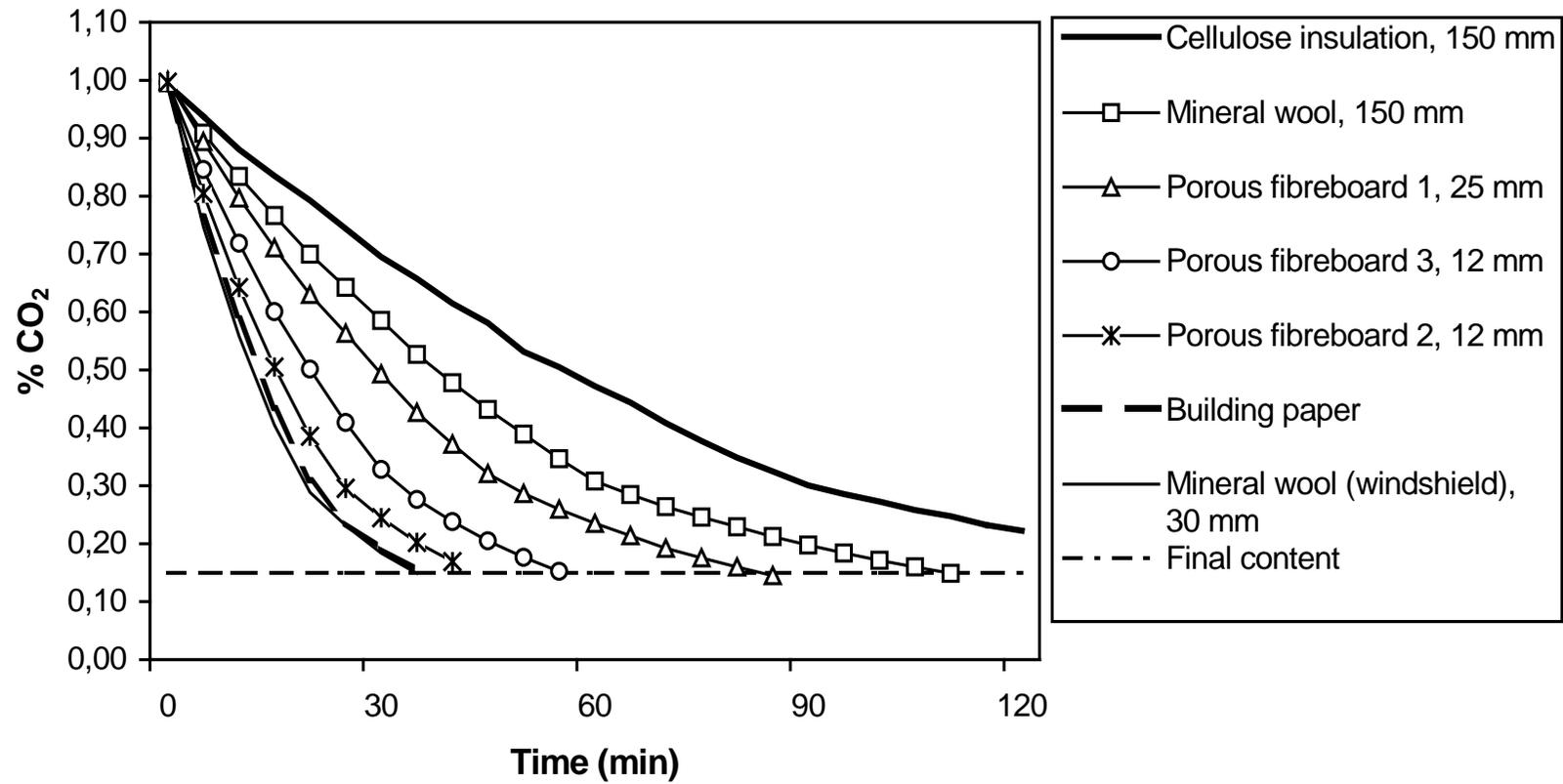
### Reduction in carbon dioxide content on primary side, materials of low permeability



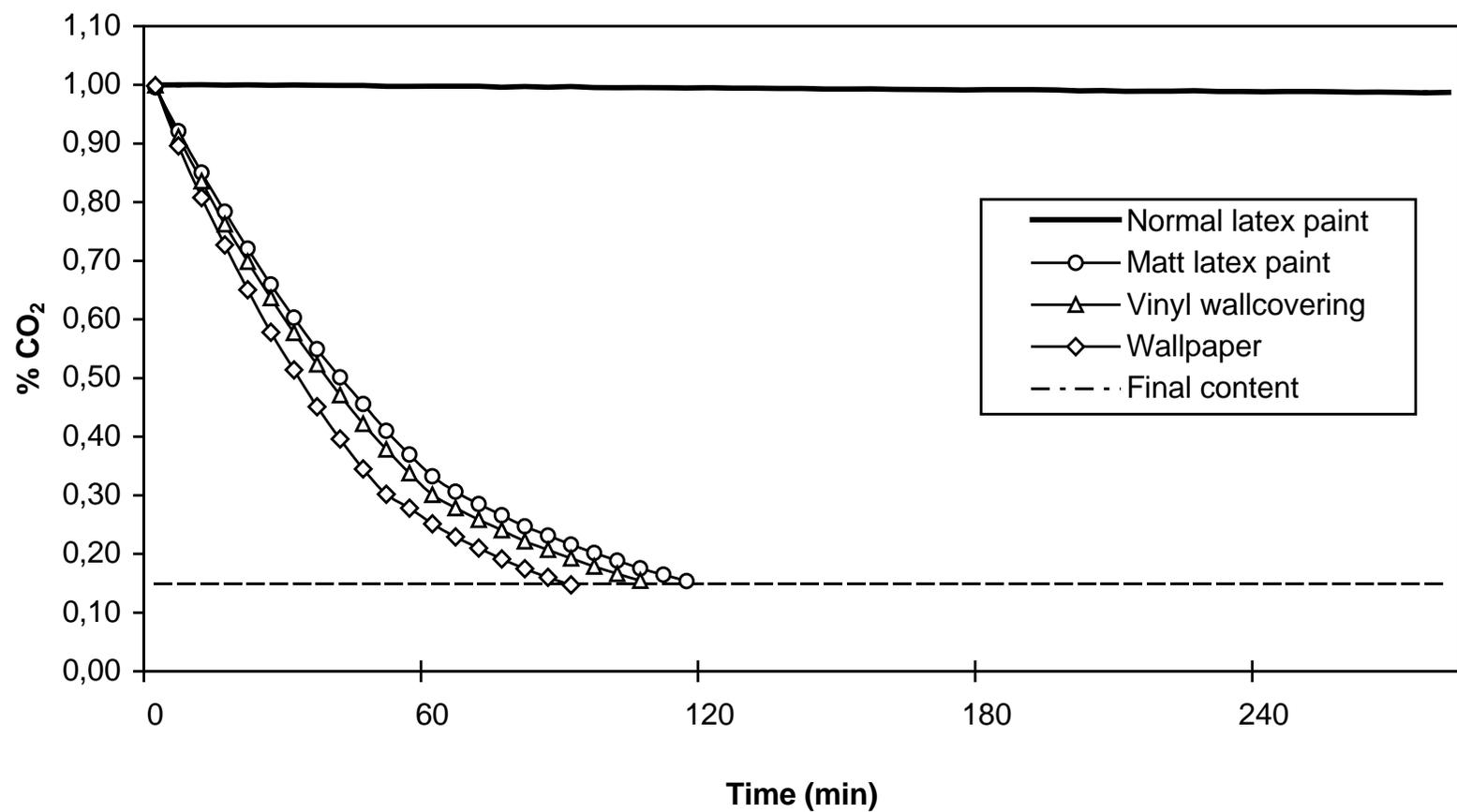
### Reduction in carbon dioxide content on primary side, chipboards and gypsum boards



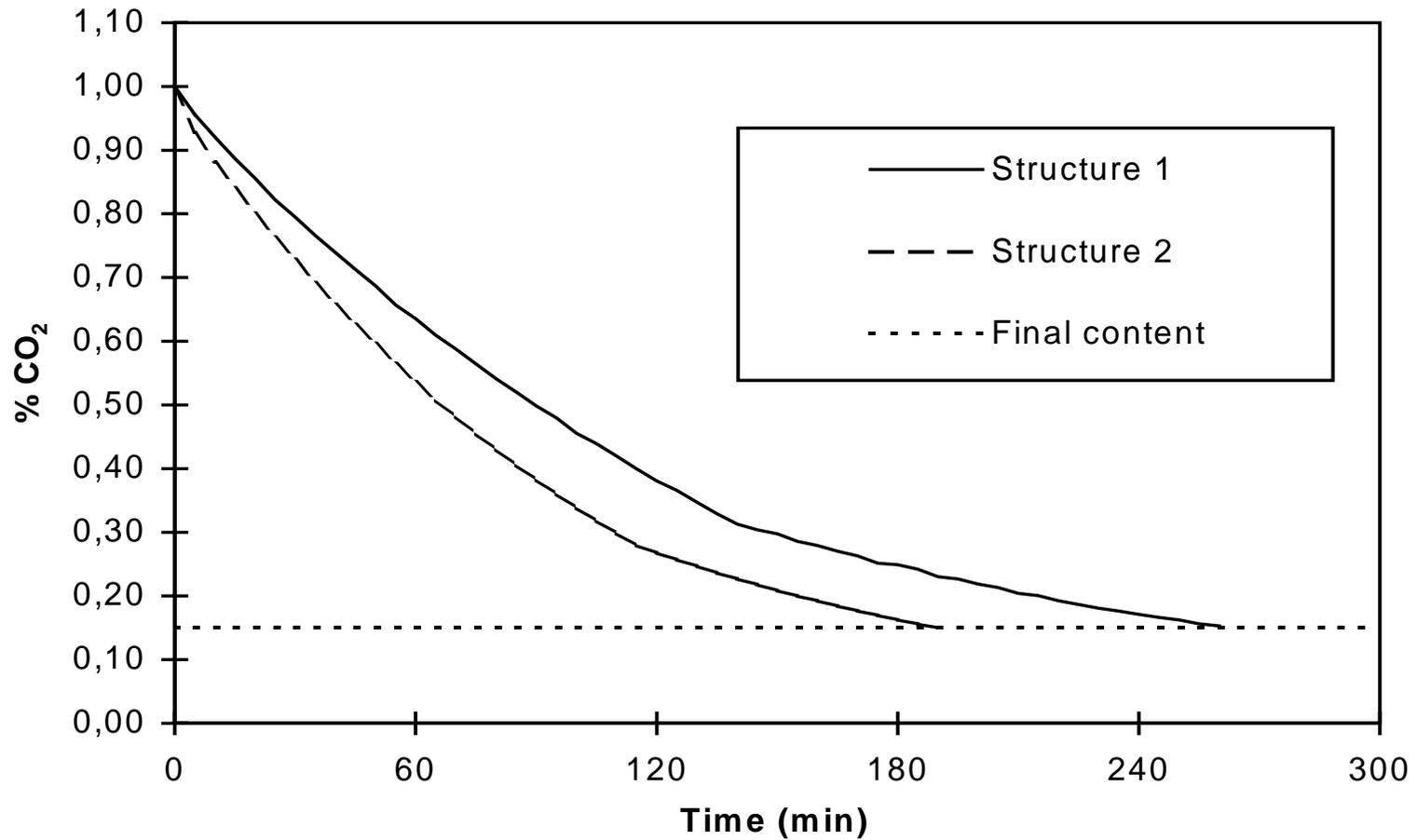
## Reduction in carbon dioxide content on primary side, materials



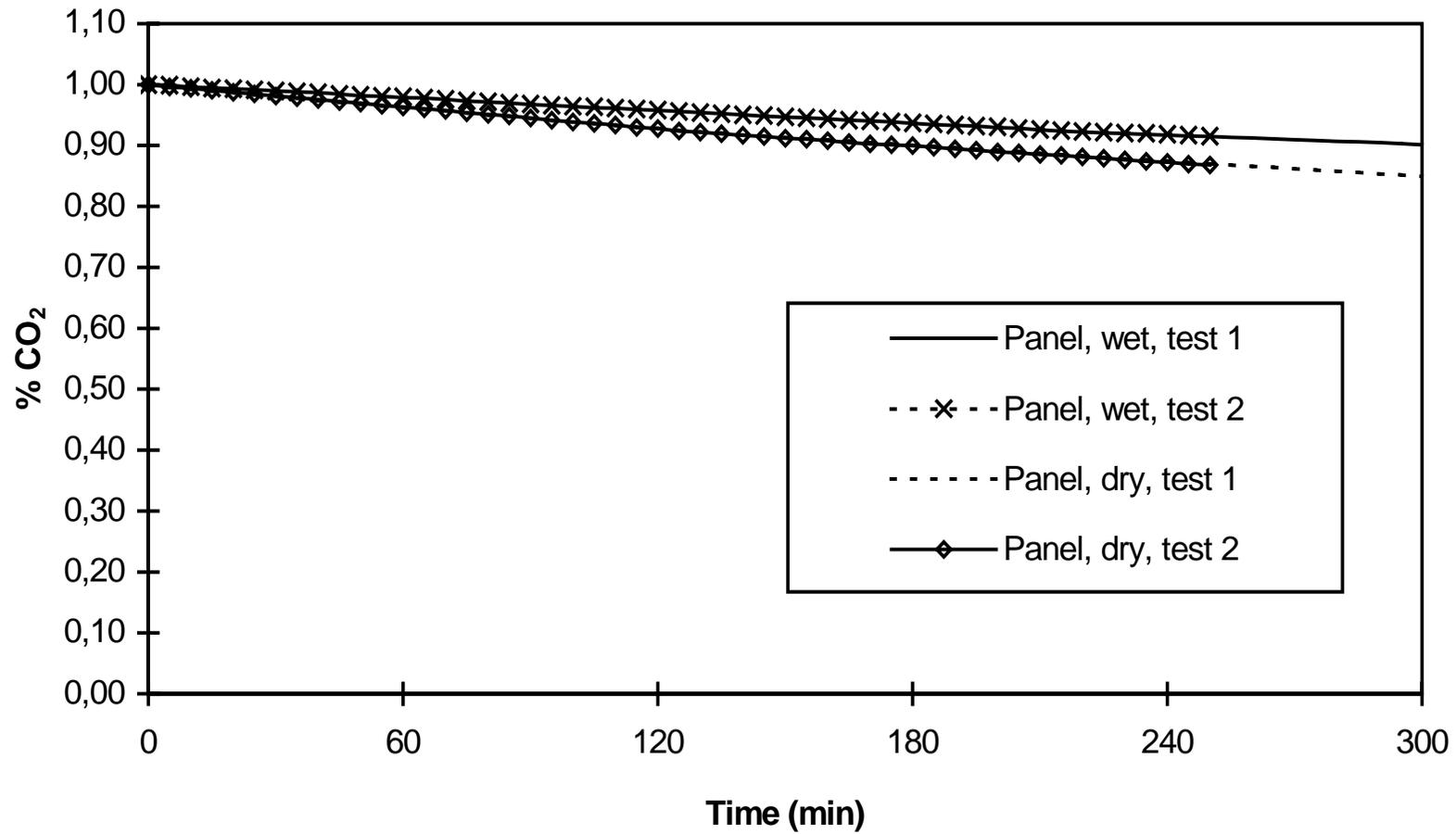
### Reduction in carbon dioxide content on primary side, wall finish tests



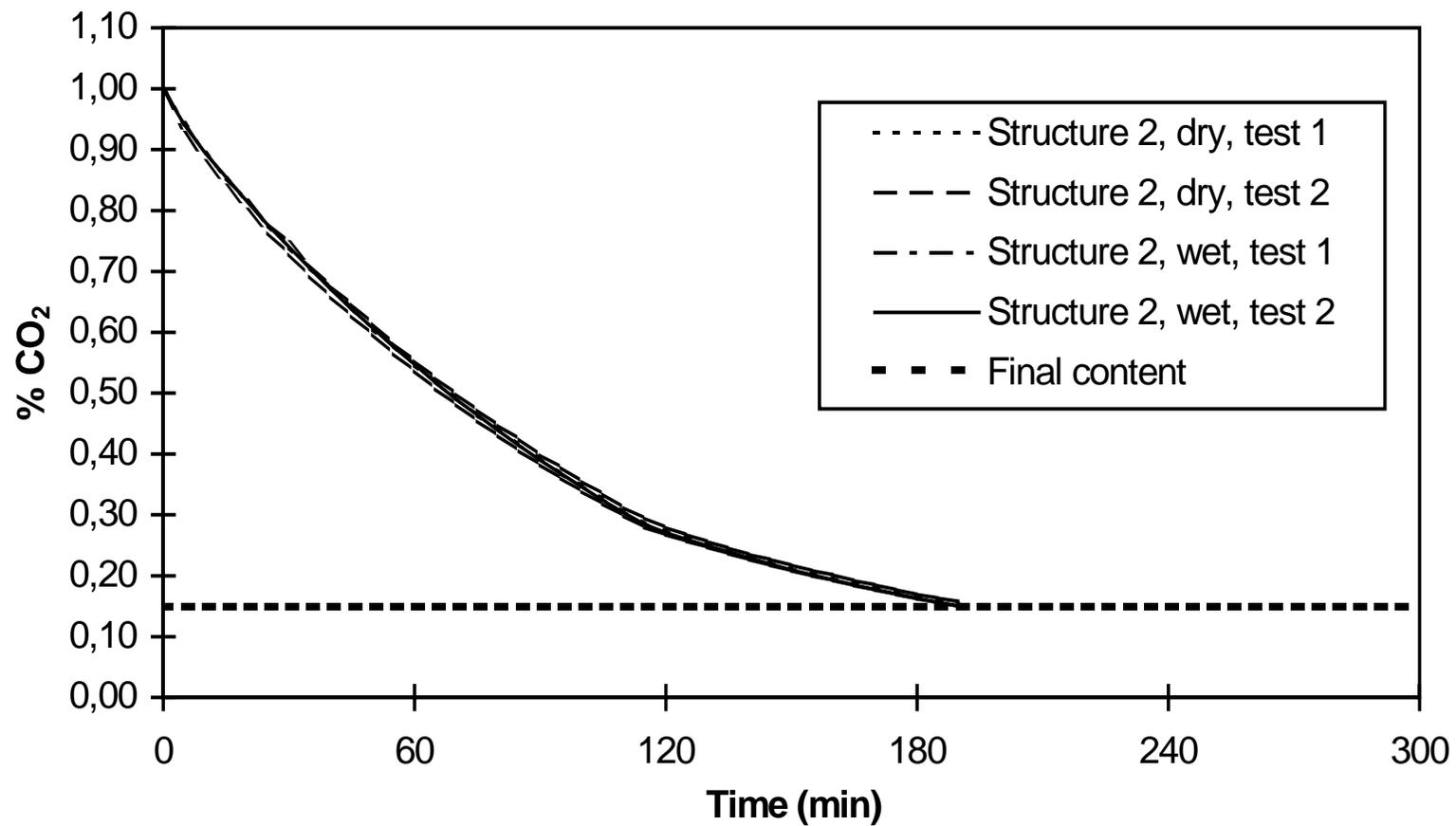
### Reduction in carbon dioxide content on primary side, wall finish tests



### Reduction in carbon dioxide content on primary side, moisture tests, interior paneling



### Reduction in carbon dioxide content on primary side, moisture tests, structure 2



|  |           | Modeling structure   |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
|--|-----------|----------------------|---|----------------------|---------|----------------------|---------------------------|----------------------------------|-----------|-----------------------|-----------------------|----------------------|
| Outdoor air  | t=        | -6 °C                |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
|  | RH        | 82 %                 |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
| Indoor air   | t=        | 20 °C                |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
|  | RH        | 35 %                 |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
|  | Thickness | Thermal conductivity | m   | Share                | Temp.   | Satur. humidity      | Water vapour permeability | Z                                | Share     | Water vapour content  | Ext. surface of layer | Condensing moisture  |
|  | mm        | W / m°C              | m <sup>2</sup> °C / W                       | %                    | °C      | g / m <sup>3</sup>   | 10E-6 m <sup>2</sup> /s   | 10 <sup>3</sup> s/m              | %         | g / m <sup>3</sup>    | RH %                  | g/m <sup>2</sup> vko |
| Indoor air   | -         | -                    | -   | -                    | 20,0    | 17,28                | -                         | -                                | -         | 6,05                  | 35 %                  | -                    |
| Internal surface   | -         | -                    | 0,13  | 3,4 %                | 19,1    | 16,41                | -                         | -                                | -         | -                     | -                     | -                    |
| Wallpaper  | 0         | 0                    | 0,00  | 3,4 %                | 19,1    | 16,41                | -                         | 3                                | 11,3 %    | 5,65                  | 34 %                  | -                    |
| Gypsum board   | 13        | 0,23                 | 0,06  | 4,9 %                | 18,7    | 16,04                | 2,3                       | 6                                | 32,5 %    | 4,90                  | 31 %                  | -                    |
| Building paper   | 0         | 0                    | 0,00  | 4,9 %                | 18,7    | 16,04                | -                         | 5                                | 51,2 %    | 4,24                  | 26 %                  | -                    |
| Cellulose insulation   | 150       | 0,045                | 3,33  | 92,6 %               | -4,1    | 3,58                 | 15                        | 10                               | 88,7 %    | 2,92                  | 82 %                  | 0,00                 |
| Porous fibreboard  | 12        | 0,05                 | 0,24  | 98,9 %               | -5,7    | 3,15                 | 4                         | 3                                | 100,0 %   | 2,52                  | 80 %                  | -                    |
| External surface   | -         | -                    | 0,04  | 100,0 %              | -6,0    | 3,08                 | -                         | -                                | -         | -                     | -                     | -                    |
| Outdoor air  | -         | -                    | -   | -                    | -6,0    | 3,08                 | -                         | -                                | -         | 2,52                  | 82 %                  | -                    |
| Total  |           |                      | 3,80  |                      |         |                      |                           | 27                               |           |                       |                       |                      |
|  |           |                      |   | delta t =            | 26,0 °C |                      |                           |                                  | delta v = | 3,52 g/m <sup>3</sup> |                       |                      |
|  |           |                      | k=  | 0,26                 |         |                      |                           |                                  |           |                       |                       |                      |
| Building volume V=   | 300       | m <sup>3</sup>       |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
| Shell area A=  | 350       | m <sup>2</sup>       | Average volume of air carried by convection |                      |         |                      |                           |                                  |           |                       |                       |                      |
| Air change rate n 50 =   | 2         | 1/h                  |   |                      |         | R=                   | 0,12                      | m <sup>3</sup> /m <sup>2</sup> h |           |                       |                       |                      |
| Pressure difference delta p=   | 1         | Pa                   |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
| Amount of moisture passing through structure, if structure has not reached dew point |           |                      |   |                      |         |                      |                           |                                  |           |                       |                       |                      |
| Convection   |           | g=                   | 1,22E-04                                    | g/m <sup>2</sup> s = | 0,44    | g/m <sup>2</sup> h = | 74                        | g/m <sup>2</sup> week            |           |                       |                       |                      |
| Diffusion  |           | g=                   | 1,32E-04                                    | g/m <sup>2</sup> s = | 0,48    | g/m <sup>2</sup> h = | 80                        | g/m <sup>2</sup> week            |           |                       |                       |                      |
| Total  |           | g =                  | 2,54E-04                                    | g/m <sup>2</sup> s = | 0,92    | g/m <sup>2</sup> h = | 154                       | g/m <sup>2</sup> week            |           |                       |                       |                      |

## **CARBON DIOXIDE PERMEABILITY OF CELLULOSE-INSULATED WALL STRUCTURES**

This publication examines the impact of carbon dioxide-permeable cellulose-insulated wall structures on the carbon dioxide content of indoor air and the need for providing ventilation in the building in question.

Equipment for testing carbon dioxide permeability was built in a laboratory and was used to determine the diffusion of carbon dioxide through various construction materials, finishes and entire external wall structures. The test results were used to calculate carbon dioxide permeability and resistance values which were also compared to the water vapour permeability values for the same materials. Test results were also used to build models for examining the carbon dioxide balance of indoor air where the diffusion of carbon dioxide through the wall structures were considered. The reference structures had vapour barriers impermeable to carbon dioxide.

A Finnish-language version of the study was published in 1996.

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