Heated Air Gaps

A Possibility to dry out Dampness from Building Constructions

Tord af Klintberg

Licentiate Thesis

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KTH-The Royal Institute of Technology
School of Architecture and the Built Environment
Div. of Building Technology

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Förord

Angående ideer, forskning och stöd

Det finns ibland en vulgäruppfattning att det tar lång tid för nya idéer att få stöd och fotfäste i Sverige. Mitt projekt bekräftar inte den tesen och jag har fått hjälp av en stor mängd människor under vägens gång, så jag har många att tacka.

Först och främst vill jag tacka min fru Tove och min familj, det är ju faktiskt de som fått leva med det här projektet på skinnet och det är också de som skulle kunnat bli direkt lidande av ett misslyckande. Tove är också den som i grunden har fått mig att tänka om när det gäller konsten att skriva.

Sedan vill jag tacka hela min referensgrupp på över 100 personer. Denna grupp täcker in minst ett dussin sektorer i byggbranschen från arkitekter till utbildningsföretag och jag har haft hundratals möten där jag kunnat inhämta mycken kunskap under vägens gång. Speciellt de möten där jag har grillats timmavis av ytterligt skeptiska personer har verkligen fört projektet framåt.

Vidare vill jag tacka alla de institutioner och bolag som har ställt upp med finansieringen till detta projekt, jag tänker då på Almi, Connect, Folksam, Formas, Formas/BIC, Innovationsbron, Länsförsäkringar, NCC Teknik och SBUF. Jag har också fått en omfattande sponsring av Blücher, Byggmax, Danogips, Ebeco, KGC, Lagerstedt & Kranz, Munthers, Paroc och Sigvard Spångberg. Nu ska man veta att det är inte bara pengar och resurser som jag har fått från dessa parter utan även ett stort personligt engagemang från dessa organisationers tjänstemän och kvinna (Nina Davidovic/Formas).

Så vill jag också tacka hela den Byggvetenskapliga institutionen på KTH, jag upplever att det finns här en höjd i tak och en nyfikenhet på nya idéer som jag inte har upplevt sedan jag arbetade med teater på Fria Pro under 1980 talet. Den samlade kunskapen som finns på institutionen är gigantisk och här finns dessutom en vänlighet och trygghet som skapar en mycket kreativ stämning,

Till sist vill jag så tacka allra djupast de personer som bjöd in mig att få genomföra denna forskning, nämligen Gudni Johannesson och Folke Björk. Jag anser att det vittnar om ett mod gränsande till dumdristighet att bjuda in en gammal teatertekniker för att genomföra detta projekt och utan Folkes ledning hade det definitivt inte gått.

Stockholm September *Tosse af Klintberg*

Sammanfattning

Spaltmetoden är en modifiering av det reguljära sättet av att bygga innerväggar och bjälklag. Syftet med metoden är att skapa en byggnadskonstruktion som är mindre skör med avseende på fuktskador. Detta görs med spalter där fukt kan avlägsnas genom ett termiskt drivet luftflöde som orsakas av en värmekabel. Denna avhandling innehåller ett antal experimentella studier på metoden. Spaltmetoden har studerats med avseende på 1. Samband mellan temperatur och luftflöde, 2. Uttorkning och RF nivåer i golvkonstruktioner samt 3. Översvämning av ett mellanbjälklag

1. Samband mellan temperatur och luftflöde

Temperatur och konvektivt luftflöde har studerats i en vertikal spalt och resultatet visar att luftflödet ökar med ökad effekt hos värmekabeln. Luftflödet i en vägg med en meters bredd varierade mellan 50 kubikmeter/dag (13 luftväxlingar per timme) och 140 kubikmeter/dag (36 luftväxlingar per timme). Det lägre flödet orsakades av en temperaturskillnad på 0,2-0,3 °C mellan luftspalt och rum. När värmekabeln var avstängd så registrerades inget luftflöde.

2. Uttorkning och RF nivåer i golvkonstruktioner ovan betongplatta

Detta experiment visade att fukt har transporterats från spalten i golvet genom spalten i väggen ut i rumsluften. I spaltkonstruktion var RF inuti golvkonstruktionen lägre (och understeg 75 % RF), jämfört med den konventionella konstruktionen, (mögel växer inte under 75 % RF). Det har också registrerats att betongplattan som hörde till spaltmetoden torkade ut snabbare än betongplattan som var inbyggd i ett gängse rum.

3. Översvämning av ett mellanbjälklag

I studien där ett mellanbjälklag blev översvämmat noterades att spaltmetoden förkortade torktiden från 21 dagar till 13 vid den fuktigaste mätpunkten. Mögelväxt noterades endast då värmekabeln hade varit frånslagen.

Abstract

The air gap method is a modification of the common way of building indoor walls and floors. The aim of the method is to make a construction, less fragile to water damage, with air gaps where moisture can be removed with a thermally driven air flow, caused by a heating cable. The thesis includes a number of experimental studies of this method.

Temperature and convective air flow in a vertical air gap was studied and it was noted how air flow increased with raised power of the heating cable. The air flow for one meter of wall varied between 50 m^3/day (13 air changes per hour) and 140 m^3/day (36 air changes per hour). The lower value was caused by a temperature difference in the range 0.2-0.3 ^oC. Without heating no air flow was found.

In studies of moisture and RH in wet “slab on ground” constructions, it was noted how the slab in the room with the air gap method dried to a much higher extent than the slab in the room built in an ordinary way. It was also noted that moisture was transported from the air gap in the floor and up through the air gap in the wall. In the room with the air gap construction, the RH values beneath the floor was at a lower level (and below 75 % RH) than the RH values beneath the floor of conventional construction. Mould does not grow below 75 % RH.

In the study of a flooded intermediate floor it was noted how the thermally driven convective air flow evidently speeded up drying of the construction. Mould growth was only noted in the case where the heating cables were turned off.

Keywords: Water damage, convection, air gap, building, construction

List of enclosed Papers

This Licentiate thesis is based on the following research papers:

I. af Klintberg T., Johannesson G. and Björk F. 2008 Air gaps in building construction avoiding dampness and mould *Structural Survay Volume 26 Number 3, pp 242-255*

II. af Klintberg T. and Björk F. 2008 Air Gap Method: measurements of airflow inside air gaps in walls *Structural Survay Volume 26 Number 4, pp 343-363*

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Heated Air Gaps

A Possibility to dry out Dampness from Building Constructions

By

Tord af Klintberg

1. Introduction

1.1 Water damages

Swedish building constructions are generally more sensitive to water damage, compared to corresponding constructions in southern Europe. The constructions in the latter countries are nowadays generally built by concrete and this material is more robust against such damages. Bathrooms are also supplied with a floor drain in Sweden and such a drain is seldom installed within southern Europe, (Arfvidsson et al 2005). Poorly mounted floor drains are considered to be a risk construction in Sweden, (Andersson & Kling 2000).

Water damage and mould

Water damage could cause mould growth if the damage results in a high *RH* within the construction. In an exterior wall of a bathroom, even a small amount of water, passing through a damp-proof membrane and trapped by the vapour barrier, may cause mould growth on gypsum boards in the construction, (Jansson 2005). Mould needs satisfactory temperature, enough time and at least 75 % *RH* to grow and when the humidity rises, the growth of the mould will become more rapid, (Sedlbauer 2001, Viitanen 2002). The level of 75% RH is also considered to be the critical moisture limit according to BBR (Boverkets Byggregler 2006).

In Sweden, 0.7 % of all buildings are harmed by water damages yearly (Länsförsäkringar Bengt G. Johansson, personal communication) and small water damage can be hard to detect. Building construction is often rather tightly built and there are situations when mould growth is not noted, many mould toxins are also odourless. (University of Lund Lennart Larsson, personal communication).

Costs of water damages

Vattenskadecentrum, a Swedish organisation, run by insurance companies and building trade associations, that survey water damages, estimated that water damages cost more than 5 billions SEK in the year of 2005. (Ström et al 2005).

This sum includes:

1. Actual costs for the insurance companies
2. Estimated costs regarding private deductibles
3. Estimated costs for water damages in the big public real-estate companies

This sum does not include:

1. Water damage costs for buildings owned by the public, as hospitals, schools and other official buildings (Ström et al 2005)
2. Water damages that the insurance companies does not assure, as from outside coming water and condense damages (Villahemförsäkring VH 07)

3. Health costs caused by water damage as allergy and asthma. Investigations performed by Emenius (2003) and Hägerhed Engman (2006) show that there are a clear correlation between water damages and asthma/allergy.
4. Costs caused during the building process and paid by the building enterprises. This cost is also difficult to estimate and there are no estimations yet found, calculated by the building enterprises, although many builders are committed to solve the problem (Tutti 2008).

1.2 Robust constructions of today

The author of this thesis claims that a majority of Swedish dwellings are fragile concerning water damages because moisture may become trapped within the building constructions. There are though some good examples to show, the Vaska concept, which is a regular building concept and also a number of ventilated constructions for floors and bathrooms.

Vaska concept

The Vaska concept was developed by the county authority of Västerbotten and Länsförsäkringar/Västerbotten during the eighties. This method implies systematization of water protection and specially a secure installation of pipes (Länsförsäkringar/Vaska 2006) The building costs increase in price by 1 %, but the water damages caused by broken pipes and floods in kitchens are reduced to a minimum (Andersson & Kling 2000).

The ventilating plastic membrane

This kind of membrane is purchased by different manufacturer, (see www.floordry.se and www.isola-platon.se). The membrane creates an air gap of about 5 mm above the water damaged floor and gives the physical preconditions for construction air ventilation, which should be executed by mechanical appliances. The ventilation rate in this type of system was investigated scientifically by Hagentoft and Holmberg (2005).

The ventilated prefabricated bathroom

This method is used to build prefabricated bathrooms, which are installed inside an old bathroom, also with possible water damage (www.inwall.nu, www.rumirum.se,). The method is constructed with an air-gap between the old and the new bathroom, where ventilating air can circulate. Construction damp could dry after the prefabricated bathroom is installed. The time for this drying could, according to experience, be at about 6 to 9 months.

The floor on joists, (Nivell floor)

The floor is built on joists attached to the structural slabs of the building and creates an air-gap below the insulation, (www.nivellsystem.se). The floor system gives the physical preconditions for construction air ventilation, which also could be executed by mechanical appliances. The manufacturer estimates that the air flow should be between 0.15-0.20 $l/m^2 \cdot s$.

1.3 Air gap method

The air gap method is hereby introduced as a modification of the common way of building indoor walls and floors. The method is a building construction design of walls and floors, with an air gap and a heating cable. The air gap method opens for convective airflows that can remove dampness that has entered the construction in case of water damage.

Close research fields

The air gap method uses slow air movements to obtain a dry out effect. The author have not yet found any reports from scientific studies that deal with the dry out effect of a heated air gap. There are however at least five other research fields where slow air movements are of interest:

1. Air flows inside air gaps inside a building envelope. These air gaps systems play an important role of drying exterior walls. This has been shown both by experiments and mathematically (Davidovic et al 2006, Gudum 2003) and is also the topic in ground level education material, (Johannesson 2006). The geometry of this type of air gap resembles the studied air gap of this thesis, but the air gap of the exterior wall has no heating cable. The temperature in these air gaps differ from the outdoor temperature because of solar radiation on the wall etc and this difference in temperature causes an air flow as well as wind pressure does.
2. Laminar convection in heated vertical channels is of interest in electronic cooling applications, (Burch et al 1985, Campo et al 2005 and Androzzi et al 2002). These articles treat wall conduction, wall and air gap temperatures and air velocity, but the geometry of the gap and the amount of power added differ much from what is used in the air gap method.
3. Natural convections occurring in a heated column of air, is described by the stack equation (Skistad 1995, Ashrae 1989) and this is further investigated in paper 2. Foster (1987) has compiled a number of different expressions that describes this effect.

4. Convective air flow is the reason for thermal plumes around persons and electrical devices in dwellings. This flow has been measured (Mierzwinski 1981, Popiolek 1981) as well as calculated (Mundt 1996, Mundt in Skistad 2002). These works are also interesting as they relate the flow with an estimated power from a line source.
5. The air flow in ventilated floors caused by fans has also been investigated. The generated air flow in these systems was found to be 5.5 m^3 per hour for a floor that measured 99 $m^{2,}$ which is the same as 0.015 litres of ventilating air per m^2 and second (Hagentoft & Holmberg 2005).

Studies in this thesis

This licentiate thesis contains two accepted articles, paper 1: "Air Gaps in Building Construction avoiding Dampness and Mould" by af Klintberg, Björk and Johannesson and paper 2:"Air Gap Method: Measurements of Air Flow inside Air Gaps of walls" ", by af Klintberg and Björk. Paper 1 describes that the air gap manage to drain and dry out a flooded intermediate floor in 13 days and also that the method prevents all mould growth provided that the indoor *RH* is not too high. Paper 2 quantifies the air flow inside a wall built by the air gap method and shows that it is a relation between the power of the heating cable, the increased temperature in the wall and the air flow.

The work of paper 1 is a full scale study of a flooding in an intermediate floor, which is not easy to control and make fully reproducible. The amount of water removed by drying from the ceiling board is not quite known, neither how much that was drained out, nor how much water actually was transported away by the air gap method. Paper 2 treats only with a ventilated wall; although a combined floor and wall construction would be a more interesting case.

Hence there are two more parts to investigate in this context:

1. Is it really established an air flow in a combined wall and floor construction in this air gap system?
2. If so, can the dry out effect from such a flow be quantified?

To answer the questions above and to complement the results of paper 1 and 2, this thesis also includes results from more controlled experiments relating to a "slab on ground" construction with thermal insulation placed on top of the slab. This is a type of small house construction that was built during the seventies and eighties, but is nowadays considered being a risk construction (Harderup 1991).

There is an obstacle in this context relating to the air flow measurements. In the second paper in this thesis it was found difficult to register really slow air movements and such movements in a combined wall and floor construction might be hard to detect.

General hypothesis

The general hypothesis for this thesis is that the air gap method makes it possible to drain and evaporate dampness after water damage without demolishing the construction, while keeping RH at a safe level, less than 75 %, during this process.

Limitations

This work deals only with small detached houses, built with a wooden frame. How the air gap method work in an apartment building will be investigated in coming articles.

2. Nomenclature

Latin

Abbreviation	Explanation	Denomination
a	Constant in saturation moisture content equation	-
b	Constant in saturation moisture content equation	-
C	Thermal capacity	J/K
I	Current of heating cable	A
l	Length of heating cable	m
M	Mean value of molecular weight of air	kg/kmol
m_{OD}	Owen dry mass	kg
m_{W}	Mass of water in moist material	kg
n	Constant in saturation moisture content equation	-
Nr	Experiment number	
p	Number of heating cables	-
p_s	Air pressure at saturation point	Pa
Q	Air flow	m^3/s
Q_{D}	Total air flow per meter wall during 24 hours	$m^3/24$ h
q	Power from the heating cable, calculated by equation (1)	W/m
q_{HC}	Power of heating cable, stated by manufacturer	W/m
R	General gas constant	J/kmol·K
RH	Relative humidity of air	%
T	Temperature	^{o}C
T_{AG}	Average temperature in air gap	^{o}C
T_{R}	Average temperature in room	^{o}C
ΔT	Temperature difference between T_{AG} and T_{R}	^{o}C

Greek

ρ	Air density	kg/m^3
v_{A}	Moisture content at air inlet, point A	kg/m^3
v_s	Vapour concentration at saturation point	kg/m^3
v_{x}	Actual vapour concentration at each measurement point A to M	kg/m^3
Δv_{x}	Moisture addition v_{x}-v_{A}	kg/m^3

3. Experimental studies

3.1 General

In order to evaluate the performance of the air gap method, measurements were made in a full scale construction in a laboratory hall close to Stockholm, during summertime conditions, which implies a comparably high *RH*. This section will present the experimental set up for several aspects of drying and air flow inside a construction built by an air gap system. Thus this section is divided into seven parts:

- Construction of the air gap system
- Heating cables
- Calibration of moisture ratio meter
- Drying of a flooded intermediate floor
- Investigation of mould growth
- Temperature and air flow in a vertical air gap
- *RH* studies in a “slab on ground” construction

3.2 Construction of the air gap system

This section of the thesis describes the common way of building a wooden detached house modified with the air gap system. The air gap system is built with inlets, air gaps, slits and outlets, shown in Figures 1 to 3 and 5 to 7. Some of the air gaps are already parts of a general construction method while others are provided by a simple modification of common methods.

It may be observed that all the figures showing construction parts are drafts without dimensioning and they are not suitable as basis for building. The air gap method is furthermore patented.

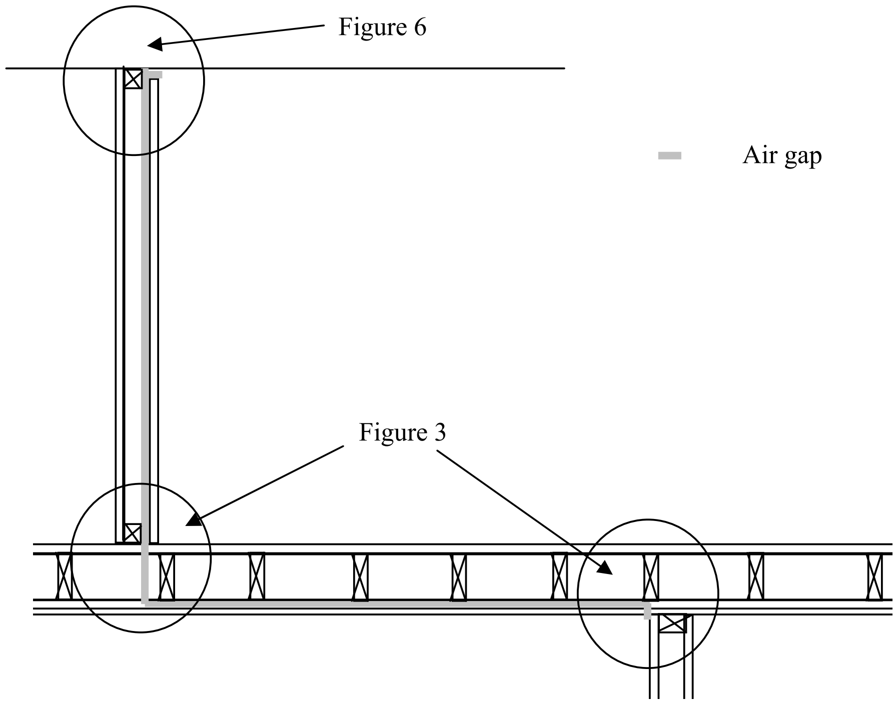
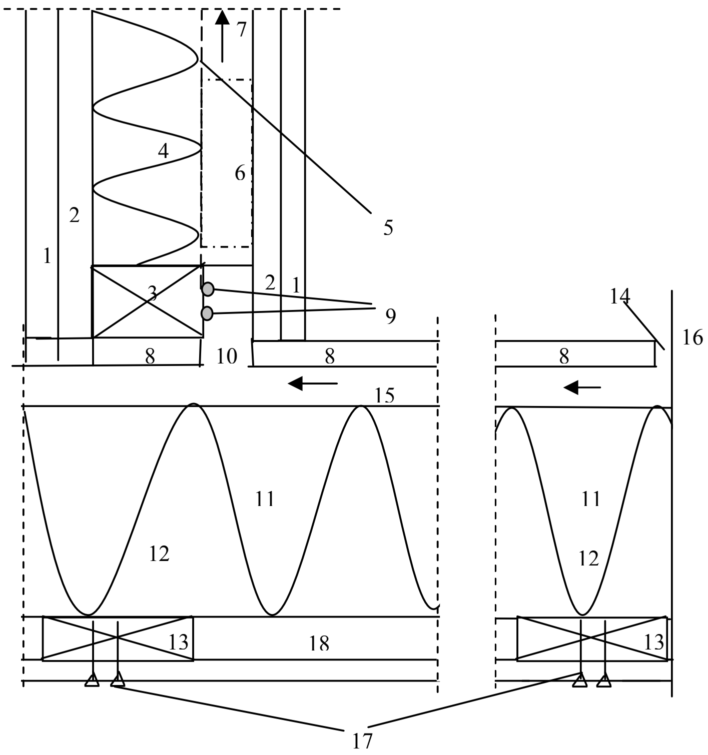


Figure 1 Schematic cross-section of an air gap system in a small detached wooden house, used in paper 1. The circles display three different applications found in Figures 3 and 6.

The general idea is that air gaps in floor construction and walls are connected with each other and have air inlets and outlets at connections between floor and wall and at connections between ceiling and wall. The ventilating air is interior air, which goes through the building construction driven by thermals caused by an electrical heating cable inside the vertical gap. The ventilation direction is shown as arrows in Figures 2 to 3 and 5 to 7 and is described more in detail in papers 1 and 2.

Intermediate floor construction

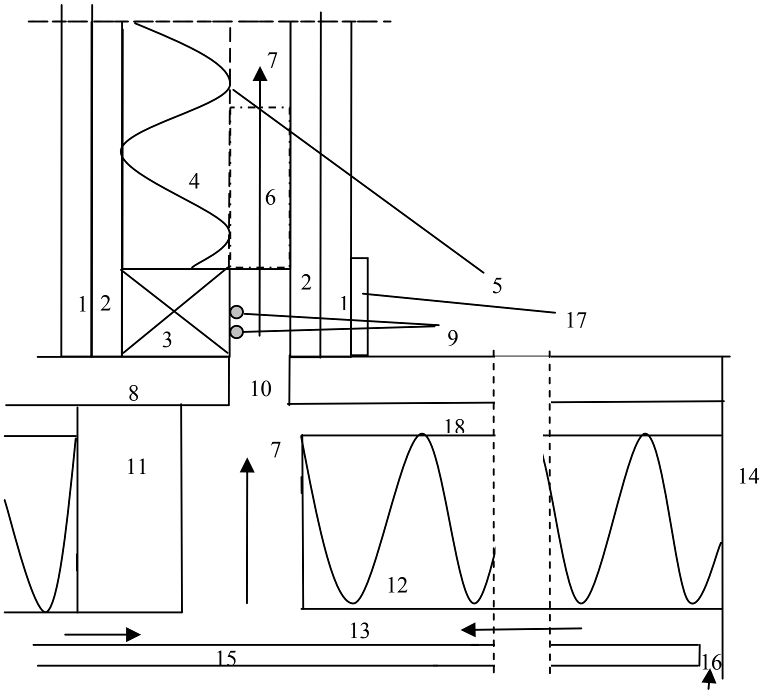
The type of floor used in this study, has wooden joists as the main load bearing part. Battings of mineral wool (for acoustic insulation) lie between the joists. There is an air gap, see Figure 2 point 15 and Figure 3 point 18, between floor chipboard and the mineral wool insulation, since this insulation is not as thick as the height of the floor joists. This air gap is parallel to the joists.



1. Gypsum wallboard 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/95 mm
4. Stud 45/120mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap in wall
8. Chipboard
9. Heating cable G-15
10. Slit in floor
11. Floor joist
12. Mineral wool in floor
13. Spaced boarding
14. Air inlet by slit at outer wall
15. Air-gap above mineral wool
16. Outer wall
17. Measurement point (a pair of screws)
18. Air-gap in spaced boarding

Figure 2 Cross-section of a spine-wall and floor used in paper 1. Arrows show the direction of ventilating air

The insulation rests upon secondary spaced boarding and there is also an air gap, see Figure 2 point 18 and Figure 3 point 13, between the battens of the spaced boarding. This air gap is perpendicular to the floor joists. This intermediate floor construction is combined with slits where the ventilating air may enter, see Figure 2 point 14, Figure 3 point 16 and it is used in the full scale studies of paper 1.

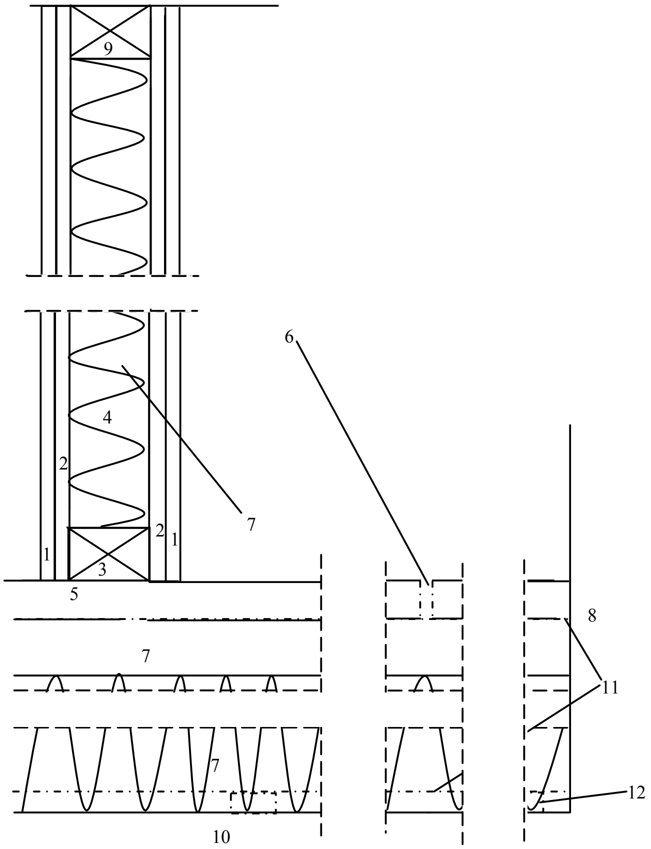


1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/45 mm
4. Stud 45/70mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap
8. Chipboard
9. Heating cables G-15
10. Slit in chipboard
11. Floor joist
12. Mineral wool insulation
13. Air-gap in spaced boarding
14. Outer wall
15. Ceiling board
16. Inlet of air
17. Skirting
18. Air-gap above mineral wool

Figure 3 Cross-section of an interior wall and intermediate floor, used in paper 1. Arrows show the direction of ventilating air.

Constructions with slab on ground

This floor is constructed with a “slab on ground” foundation and with mineral wool insulation placed on top of the slab. Two floors were constructed for comparison. The first floor was built in the ordinary way of building, the second by application of the air gap system and connected to an air gap system wall, see Figure 5. The first ordinary room lacks all the applications of the air gap method; the air gap in the wall, as well, the air inlet, slit in the chipboard and the outlet, see Figure 4. In this ordinary construction the bottom and the top plate have also the same width as the standing studs.

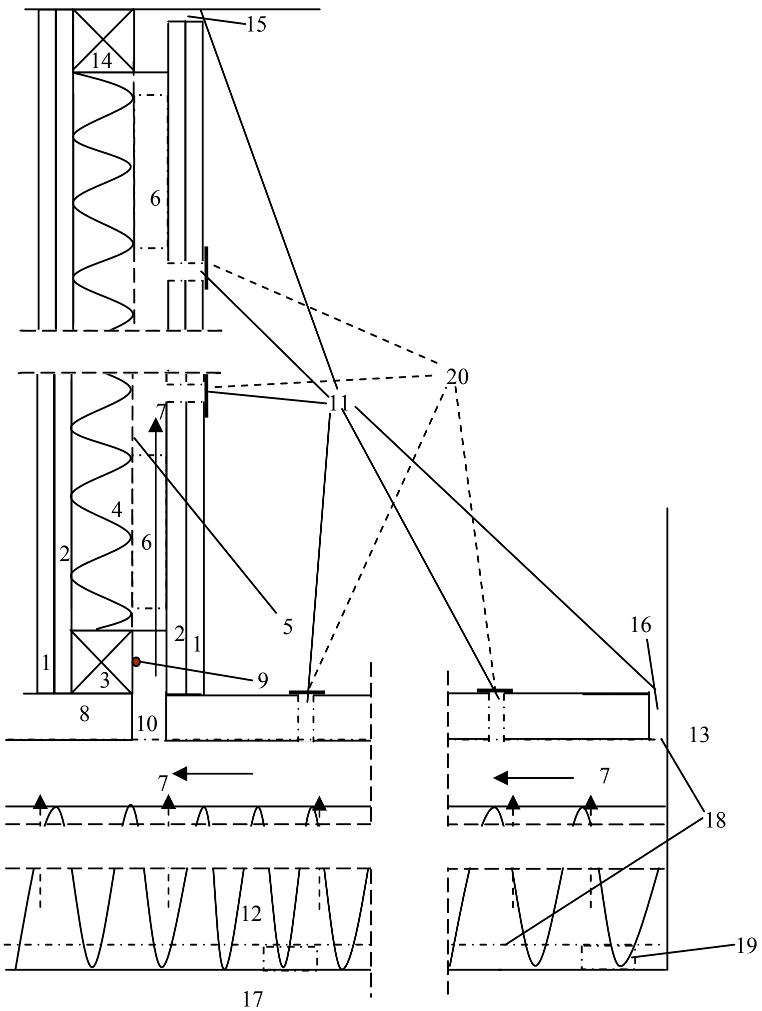


1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/45 mm
4. Stud 45/70mm
5. Chipboard
6. Point of T and RH measurements
7. Mineral wool board insulation
8. Exterior wall
9. Top plate
10. Concrete slab
11. Up and down sides of floor joist
12. Support of floor joist

Figure 4 Cross-section of wall and bottom floor by an ordinary construction of slab on ground with thermal insulation above the slab.

The second floor has a construction that is similar to Figure 2, the air gap is situated above the mineral wool board insulation and the inlet is in the connection between floor and wall. The only difference is that the insulation lies upon the concrete slab in this case.

These two building constructions were used in the *RH* studies of a “slab on ground” construction that are not covered by paper 1 and 2.



1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/45 mm
4. Stud 45/70mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air gap
8. Chipboard
9. Heating cable T-18
10. Gap in chipboard
11. Points of T and RH measurements
12. Mineral wool board insulation
13. Exterior wall
14. Top plate
15. Air outlet
16. Air inlet
17. Concrete slab
18. Up and down sides of floor joist
19. Support of floor joist
20. Poly ethylene tape

Figure 5 Cross-section of wall and bottom floor construction by the air gap method of the "slab on ground" construction with thermal insulation above the slab. Arrows show the direction of ventilating air and moisture transport.

Wall construction

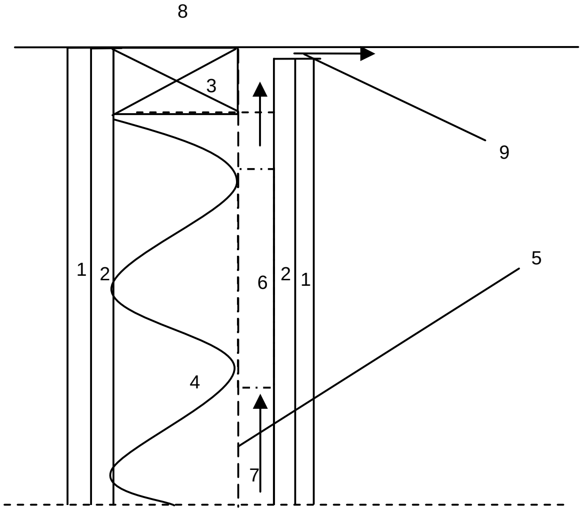
Ordinary wall

There are two types of walls in a wooden detached house, the exterior wall and the interior wall. The interior wall might be a load bearing spine wall or a common light wall. The inner part of the exterior wall could be supplied with an air gap, but this construction is not investigated in this thesis and therefore not described here. The spine wall and the light wall are built in the same way, but differ often in thickness as the spine wall is load bearing. Interior walls are built with bottom sill, top plate, standing studs and mineral wool for acoustic insulation between the studs.

Air gap wall

Unlike the intermediate floor described above, a common interior wall has no air gap. The mineral wool insulation usually fills all the space between the studs, the bottom sill, top plate and the covering boards and this construction part is rather tight. Thus it is necessary to construct an air gap in the wall that permits an air flow.

The wall of the air gap system is constructed with bottom sill, top plate and mineral wool wall boards that are not as thick as the width of the standing studs in order to create an air gap inside the wall. The mineral boards (for acoustic insulation) are hindered from falling back into the air gap by a number of cellular plastic-bars 100x25x30 mm and a heating cable is attached to the bottom sill. To vary the experimental conditions, two heating cables are used in the tests of this thesis. The outlet of air is situated in the connection of the wall and the ceiling, as shown in Figure 6 point 9.

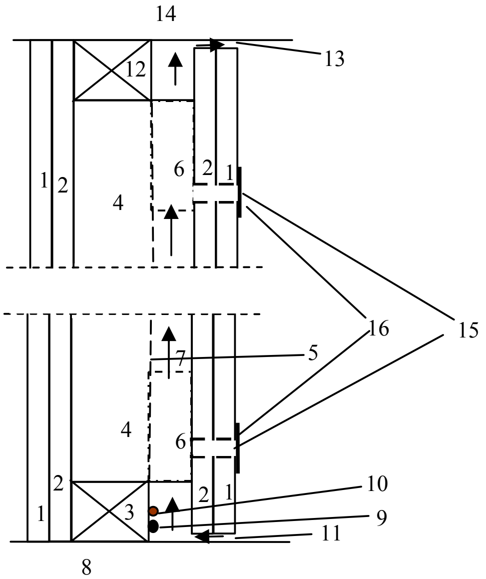


1. Gypsum wallboard 13 mm
2. Oriented strand board 13 mm
3. Top plate 45/95 mm
4. Stud 45/120 mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap, between studs
8. Ceiling
9. Outlet of air

Figure 6 Cross-section of an interior wall at the ceiling wall connection, built by the air gap method. Arrows show the direction of the ventilating air.

This type of wall is used as a spine wall, see Figure 2 and as a common light wall, see Figure 3. It is used in combination with the floor in paper 1 and in combination with the air gap in the “slab on ground” construction of this thesis.

A wall built by the air gap system can also be built with no air gap connection into the floor. In this case there are connections to the room air at bottom and top of the wall see Figure 7 points 11 and 13. This type of wall is used in paper 2.



1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/70 mm
4. Stud 45/95mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap
8. Floor
9. T-18 heating cable
10. G-15 heating cable
11. Air inlet
12. Top plate 45/70 mm
13. Air outlet
14. Ceiling
15. Measure hole for thermistors
16. Poly ethylene tape

Figure 7 Cross-section of air gap wall used in paper 2. The arrows indicate the direction of the ventilating air.

3.3 Heating cables

The heating cables, named T-18 and G-15 are manufactured by Ebeco AB. The intended use for T-18 is to melt ice inside drain pipes and the intended use for G-15 is to perform floor heating. The cables are made of two electrical conductors embedded in a semiconductor material which resistivity increase with temperature, so the maximum temperature lies in the range of 28-40 ^{o}C.

The cables are supposed to give different levels of power because of the temperature of the surrounding air “If this air is colder it takes more power to reach the maximum temperature of the cable”, (Ebeco AB, Kent Svensson, personal communication).

The manufacturer also states that T-18 gives a power of 15 W/m ± 3 W/m and G-15 a power of 8 W/m ± 2 W/m at room temperature. Each batch (around 3000 meter length of the cable) gives different levels of power, because of minor variations in the properties of the semiconductor material. The G-15 cable was used in paper 1, both cables were used in paper 2 and only the T-18 was used in the *RH* studies in a “slab on ground” construction.

3.4 Calibration of moisture ratio meter (Paper 1)

Measure point and device

A measure point in paper 1 of this study is literally a "pair of screws", which are screwed through the gypsum board ceiling and into the battens of the spaced boarding, see point 17 in Figure 2 and point 4 in Figure 8. The screws are 41 mm long and the distance between them is 25 mm. This measure point is chosen because it will be in contact with the presumably dampest spot in the experiment; the layer between the gypsum board of the ceiling and the spaced boarding. Any flooding into the floor construction will reach this layer and this water will remain last.

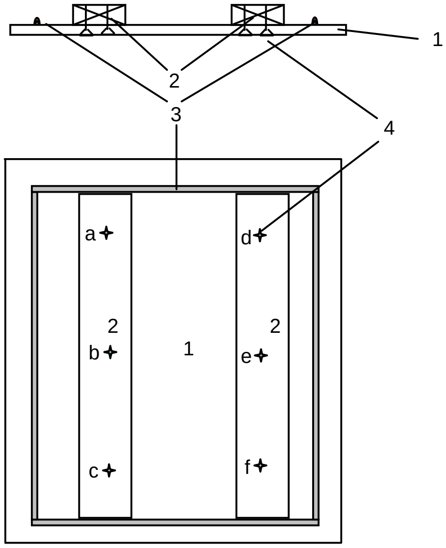
The moisture ratio of a measure point was measured by a moisture meter, "Surveymaster SM" from Protimeter pic. England. This moisture meter uses electrical conductance principles to measure the moisture level of the material between two electrodes and has an instrument scale, which grades moisture ratio from 0 to 100 %. Tests are performed by putting the two pin electrodes from the instrument in contact with the measure point. A value is shown on the display of the instrument after about 10 seconds.

Experiment

It is interesting to investigate which relation a certain reading of the instrument scale has to actual water content. Below the fibre saturation point, at 30 %, the readings indicate the ratio of m_W/m_{OD}, where m_W is the mass of water in the material and m_{OD} is the mass of the oven dry weight of the same material. However there is an uncertainty regarding how readings above 30 % in this equipment should be understood. Above this number, the wooden cells are saturated of water (Ashrae 2005) and it is not known what actually is measured in instrument scale between 30-100%. This experiment was set up at ordinary indoor temperature and *RH*.

In order to investigate this calibration task, a small part of a gypsum board ceiling was constructed, see Figure 8. The board was provided with six measuring points (a-f), which are "pair of screws" described above.

The area inside the water bank measured 0.125 m^2 and the amount of water, 157.8 grams, was chosen so it didn't spill over the water-bank, see point 3 in Figure 8. The following evaporation of the water was measured both by weighing the board in a lapse of time and by "measurements of the moisture meter" in the following called MMM.



1. Gypsum board
2. Spaced boarding
3. Water-bank
4. Measure point (a pair of screws)

Figure 8 Air Gap Method. Draft of cross-section and plan of ceiling part for calibration of moisture meter, together with six measure points (a-f).

3.5 Drying of a flooded intermediate floor (Paper 1)

Laboratory apartment

The laboratory apartment for paper 1 was built on 1.2 meter high posts and has a total area of 24 m^2. Thanks to the posts, the ceiling beneath the floor is available from a crawl space beneath, see the arrow in Figure 9

Figure 9 Photograph of the laboratory apartment, the arrow points into the crawl space beneath the ceiling.

The apartment is divided into two rooms, “bedroom” 18 m^2, and “bathroom”, 6 m^2. The walls are 2.5 m high. Intermediate floor, spine wall and interior wall are constructed by the air gap system described above. The spine wall and the interior wall are provided with two heating cables (G-15) each. As part of the experiment, two holes were drilled into the floor, to be inlets for flooding water. See ground plan Figure 10.

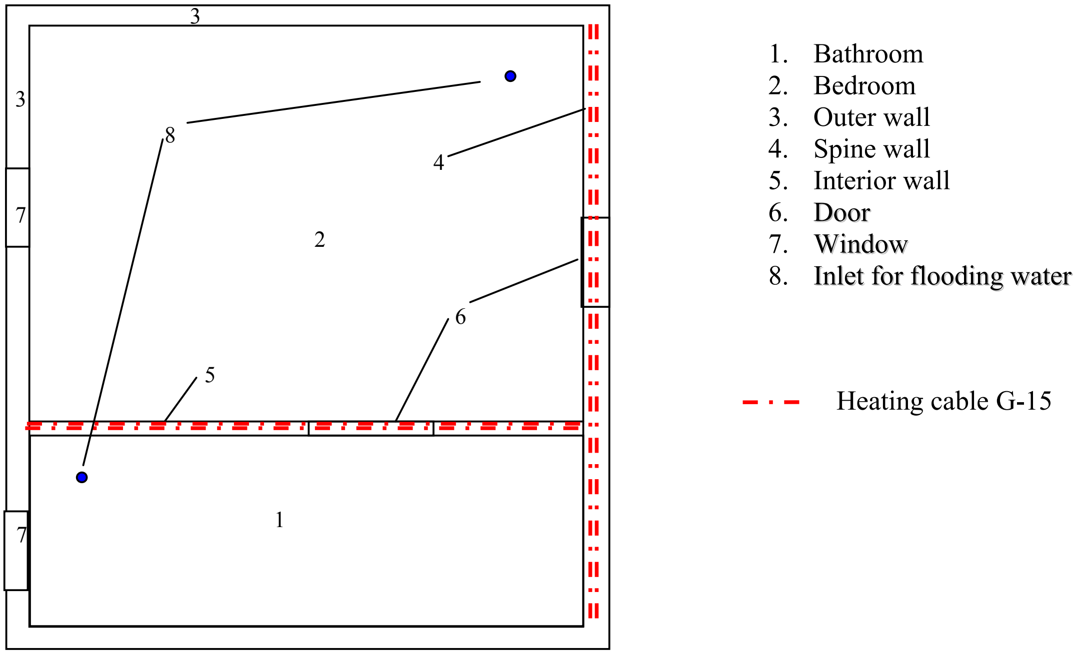


Figure 10 Ground plan of laboratory apartment. Showing places for heating cables and flooding inlets.

Measure points

The floor construction was provided with 98 measurement points, see Figure 11, attached to the spaced boarding from beneath, through the ceiling board. These are pairs of screws as shown in Figure 2, point 17 and Figure 8 point 4.

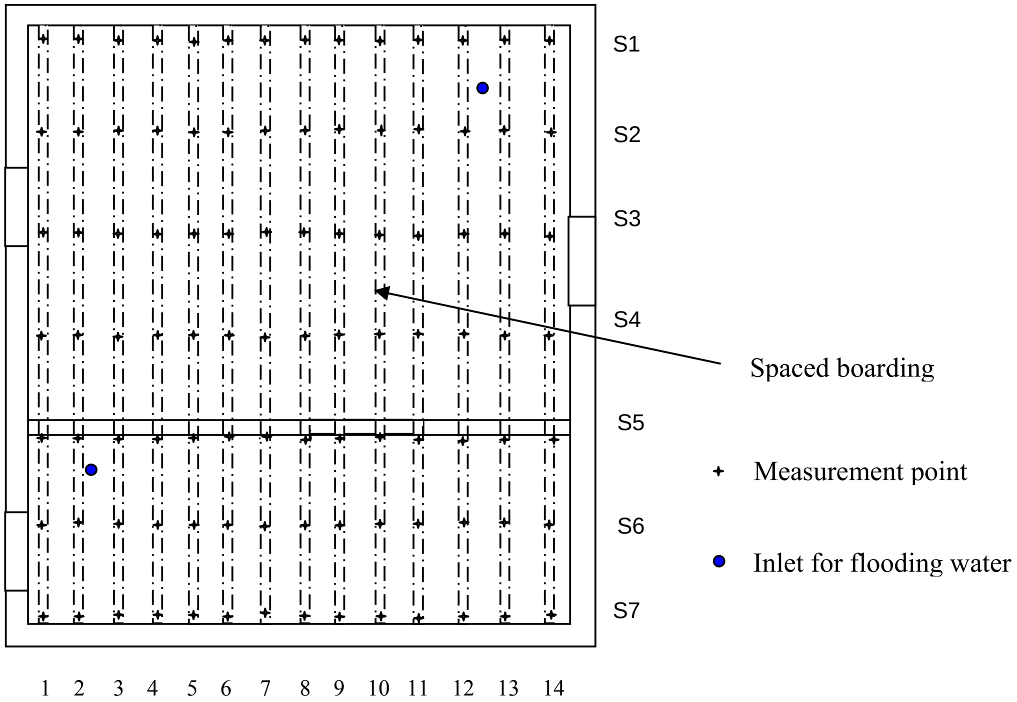


Figure 11 Ground plan of the intermediate floor. Placing of spaced boarding, positions of flooding inlets and measure points.

Experiments

Four experiments, named A1 to A4, were performed in the laboratory apartment. In each experiment 120 litres of domestic wastewater was poured into the construction i.e. 60 litres into each "Inlet for flooding water", see Figure 10. The "measurements of the moisture meter", MMM, were intermittently taken during each experimental period.

The conditions in the laboratory apartment are described below in Table 1. The *RH* and temperature were continuously measured by a thermo hygrograph from Thies Göttingen.

Table 1 Preconditions for experiments A1-A4, p stands for numbers of heating cables

Experiment	A1	A2	A3	A4
Heating cables	2p→16 (W/m)	1p→8 (W/m)	1p→8 (W/m)	0p→0 (W/m)
Temperature Average	19,7 (^{o}C)	21,2 (^{o}C)	19.8 (^{o}C)	19.9 (^{o}C)
Temperature Max/Min	22/17 (^{o}C)	23/19 (^{o}C)	23/18 (^{o}C)	22/18 (^{o}C)
Average max. *RH* during 5 days	43.6 (%)	53.4 (%)	65.2 (%)	74.4 (%)
RH Max/Min	48/40 (%)	65/47 (%)	74/50 (%)	77/63 (%)

3.6 Investigation of mould growth (Paper 1)

Experiments

After each experiment, A1 to A4, see above, the floor was opened from above and also from beneath. Clear tape samples for microscopic investigations of mould and bacteria, (Gutarowska & Piotrowska 2007) were taken from the battens of the spaced boardings and from the upper side of the ceilings gypsum board beside the measure points, point 17, see Figure 2. Samples were examined concerning mould species and quantity by a well-reputed mould laboratory (Aimex AB).

3.7 Temperature and air flow in a vertical air gap

(Paper 2)

The purpose of this part is to find a connection between raised temperature in an air gap wall and air flow. The experimental set up is presented in Figure 7 above; this wall was provided with two heating cables T-18 and G-15, also presented above. The experimental work was done during two occasions which are referred to as Day 1 and Day 2. Measurements of temperature and air velocity were performed simultaneously during stable conditions, when the heating cable had been switched on for at least 60 minutes.

Temperature and air velocity studies

When a heating cable warms the air inside the air gap, it will result in a temperature difference between the average air gap temperature and the average room temperature, hereby called ΔT. A positive value of ΔT gives a lower air density inside the air gap compared to room air. This lower density makes a pressure gradient that will create an upward air flow inside the air gap and this temperature rise is measured in this study, as well as the air velocity.

For the purpose of the experiments, eight holes were drilled at suitable heights in the panelling for insertion of temperature sensors. The room temperatures were measured simultaneously at three heights, with sensors placed 0.01 m from the surface of the wall.

A weighted mean value of the temperature in the air gap was calculated and, in a similar way, a mean value for the room temperature. The temperature difference, ΔT, turns out to be the mean value of the air gap temperature minus the mean value of the room temperature.

Air flow

The air flow, calculated from the air velocity, is supposed to be the important agent of the air gap method, both resulting in a dry out effect and in a low relative humidity (*RH*) inside a building construction. The air velocity was measured by the air inlet; see point 11 in Figure 7, at three measure points side by side with 10 cm in between, right below the line of temperature measure points. The air velocity measurements were made by a hot wire anemometer from TSI, USA, simultaneously with the temperature measurements. The lower detection limit of this anemometer is 5 cm/s. The measurements were performed for; no cable, T-18 cable, G-15 cable and both cables at Day 1 and 2 respectively and the air flows per meter wall were calculated from the measured air velocities.

Power of the heating cable, Δ*T* and air flow

The investigation of ΔT and its relation to the air flow was one of the main tasks of paper 2 and this relation is shown in the results. There is also a relation between the power coming from the heating cable, q, temperature difference, ΔT and the air flow, Q, shown in the energy equation:

$$q \cdot l = \rho \cdot Q \cdot C \cdot \Delta T \qquad (1)$$

where:

$l = 1$ m
$\rho = 1.2$ kg/m^3
$C = 1000$ J/K

The value q in equation (1) is actually the part of the total power that causes the temperature rise and the air flow. Yet the energy losses are not shown in this equation, therefore the power calculated here should be lower than the stated electrical power of the heating cable.

3.8 *RH* studies in a “slab on ground” construction

One consequence of the full scale study described in paper 1 is that the main part of the injected water disappears by drainage and evaporation through the ceiling of the “room” below. Therefore it was difficult to estimate the amount of water that was actually ventilated away by the air gap system. One goal of the studies of the “slab on ground” construction is to do such estimation. Another aim is to compare the *RH* values in a floor construction built with air gaps with an ordinary ground floor system.

Experimental rooms for “slab on ground” studies

Two rooms are constructed with chipboard floor and insulation on the slab, the first is built in the ordinary way of building, see Figures 4 and 12, the second by application of the air gap system; see Figures 5 and 13. Both rooms measure 2.75 times 2.25 meters (6 m^2) and the concrete (quality C 32/40-K40) slab is 0.1 m thick, giving a volume of each slab of approximately 0.6 m^3. The volume of the space between the rear side of the floor and the slab is 1.5 m^3 as the floor beams are 0.25 m high. This space was filled with mineral wool board insulation up to a height of 0.20 m.

Before casting the slabs the forms were covered with two layers of Polyethylene film (0.20 mm) in order to avoid moisture transport between the slab and the ground. The floors were covered too, for experimental reasons, with Polyethylene film, to prevent moisture transport through the chipboard. Thus all moisture transport out from the constructions goes through intended or unintended gaps in the constructions.

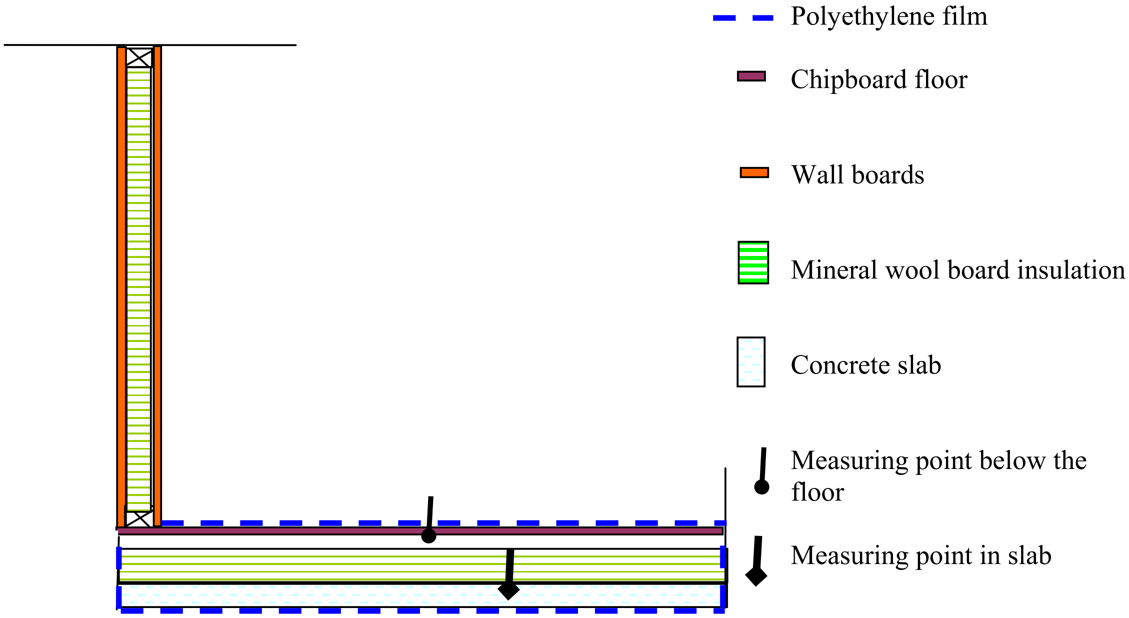


Figure 12 Schematic cross-section of an ordinary of wall and bottom floor construction used in the extra *RH* studies, supplied with measurement points for *RH* and *T* in concrete slab and in floor.

For the purpose of this study, five holes were drilled in the panelling and five holes in the chipboard of the floor, for insertion of measurement devices. The holes in the floor chipboard were situated along a line 25, 75, 125, 175, and 225 cm from the air inlet, see points A to F, Figure 13, and the holes in the wall were situated along a line 20, 70, 120, 170 and 220 cm height from the floor, see measuring points G to L in Figure 13. The holes were covered with vapour barrier tape to hinder moisture to escape and the holes were only open for short intervals when measurements were done.

The hypothesis concerning the air flow is that the air enters the air gap, at point A, in the opposite wall/floor connection, goes subsequently above the mineral wool insulation, through the slit of the floor, and up through the inside of the interior wall. The construction air outlet is in the interior wall/ceiling angel, at point L.

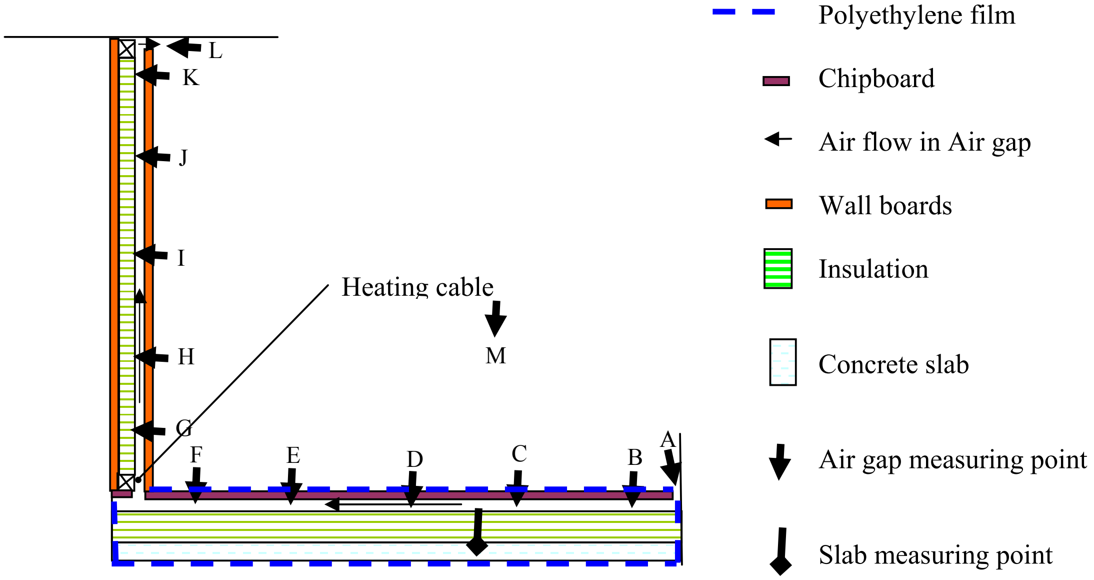


Figure 13 Schematic cross-section of wall and bottom floor construction by the air gap system, supplied with measurement points for *RH* and *T* in air gaps and concrete slab.

Experiments

The function of the air gap system in walls and floors can be tested by comparing the two dry out processes performed in the two rooms described above. If the method works, the wet concrete slab of the air gap room should dry faster than the slab of the ordinary room. It should also be possible to detect increased moisture concentrations in the total air gap shown in Figure 13.

This experiment was thus divided into two major studies. The first examined the water reduction in the concrete slabs. This was done directly after the concrete slab had been casted. The second investigated the development of *RH* and vapour concentration in the construction air. This second investigation was done later and the slabs were watered again in advance of this test.

RH decrease in the slabs

A few days after the concrete slabs were cast, one detector for *RH* and *T*, Vaisala Intercap Humidity and Temperature Probe HMP5 was installed at the depth of 50 mm into each slab. Location of the sensors is indicated in Figures 12 and 13.

The concrete slabs were saturated by water, as they were newly cast and the humidity decrease was followed during 56 days, by measuring the *RH* values. The investigation was performed at the same time for both experimental rooms, during summer time at ordinary indoor conditions. The heating cable in the air gap system room was turned on when the experiment started.

RH and vapour concentration in construction air

In this study the “slab on ground” constructions needed to be moist. Therefore the constructions were flooded in advance in order to provide the necessary dampness. As the slabs had dried out unequally in the “slab” study above, 26 litres of water were added to the air gap slab and 12 litres were added to the ordinary slab. This study was followed in a time lapse of 54 days.

This second study is divided in two parts, a: “*RH* levels in the air gap construction compared to ordinary” and b: “Distribution of *RH* and vapour concentration in the air gap system”.

RH levels between floor and concrete slab

A high *RH* level is an important factor for mould growth. If the air gap system manages to lower *RH* inside a building construction, it would lead to a less fragile construction, concerning mould growth. This study registered the difference in *RH* levels between the inside of an air gap construction, compared to the ordinary floor construction. *RH* measurements were performed, by the combined *RH* and temperature meter Vaisala HM 70, at the “Air gap measurement points”, see Figures 12 and 13/point D, below the chipboard floors.

Distribution of vapour concentration in the air gap system

It is of interest whether a higher vapour concentration is distributed in both floor and wall construction of the air gap system. This should indicate that the system actually transports the vapour away. If the heating cable manages to create an air flow through the air gap system, it would result in increasing values of vapour concentration also in the air gap wall.

In this study, *RH* and temperature values were intermittently registered, by the combined *RH* and temperature meter Vaisala HM 70. The measurements were taken at the "*RH* and *T* measuring points" A to M, see Figure 13, below the floor, inside the wall and also in room, during the experimental period. The hypothesis is that it should be possible to detect higher moisture content compared to the room air, inside the total air gap.

The moisture vapour concentration at saturation point, v_s, the actual vapour concentration, v_x and the moisture addition, Δv_x are calculated by the equations 2 to 5 (Nevander and Elmarsson 1994) and presented in the results.

$$v_s=p_s\cdot M/[R\cdot(273.15+T)] \qquad (2)$$

where:

$$p_\mathrm{s}=a\cdot(b+T/100)^n \qquad (3)$$

$$v_x=v_s\cdot RH/100 \qquad (4)$$

$$\Delta v_\mathrm{x} = v_\mathrm{x}-v_\mathrm{A} \qquad (5)$$

Where:

$a = 288.68$
$b = 1.098$ °C
$M = 18.02$ kg/kmol
$n = 8.02$
$R = 8\,314{,}3$ J/kmol·K
v_A = moisture content at air inlet

Air velocity in air gap

Air velocity measurements were also performed in the "Air gap measuring point H, see Figure 13, by a hot wire anemometer from TSI, USA

4. Results

4.1 Calibration of moisture meter (Paper 1)

The percentage decrease of weight and of the MMM is presented versus time at Figure 14. In this figure the evaporation is shown as the remaining part of the originally added amount of water in percent. For example 50 % means that 78.9 grams of the originally added 157.8 grams of water still remains. The readings from the moisture meter (MMM) are shown with the highest (from point a) and lowest value (from point f) together with mean values of the six points measured.

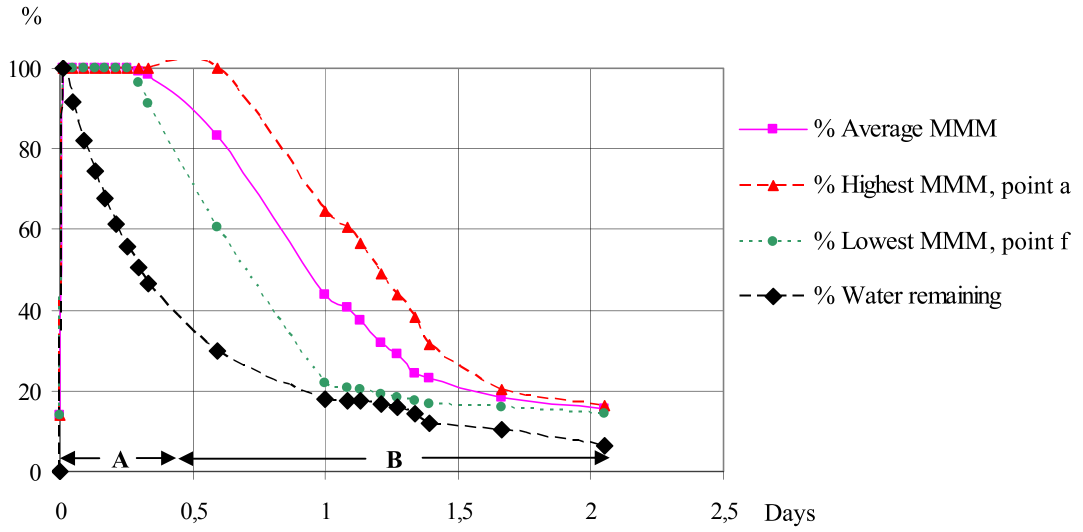


Figure 14 Air Gap Method. % Measurements of the moisture meter (MMM) and % Water remaining versus days

In this diagram two ranges can be noted:

"**Range A**", see A in Figure 14:

1. The water evaporates at a rate of little less than 10 %/hour and this decrease in weight is due to that water dries both upwards and downwards from the gypsum board. The whole area of the test set up is wet, during this "time range".

2. The curves for MMM remain on a 100 % plateau and this relates to the very high electrical conductance between the screws, because a water film is formed between the gypsum board and the battens of the spaced boarding and there is consequently free water between the screws.

“**Range B”,** see B in Figure 14:

1. The amount of remaining water has become smaller and the rate of drying is decreased to a lower level. More than 90 % of the added water has evaporated after two days.

2. In this part, the water that was stored between the gypsum board and the spaced boardings is dried out or taken up into the material. The readings from the MMM now goes quite rapidly down under the levels around the fibre saturation point (30 %).

This test show that the evaporation proceeds continuously, but the MMM values stays at level 100 for a quarter of a day before it starts to decrease. It can also be seen that half of the added water has evaporated before the value of the MMM becomes lower than 100%.

In spite of the different shapes of the % Water remaining curve and the %MMM curves, the conclusion of this part is that the “Surveymaster SM” is useful in this context because:

1. When the readings from the moisture meter have gone down to 20 %, more than 80 % of the water has evaporated.
2. When the readings from the instrument is higher than 30 %, a decreasing trend in the readings still reflects a decrease in moisture content in the construction.

The result of this calibration is the reason why the “measurements of the moisture meter” MMM were used to detect humidity decrease in the intermediate floor studied in paper 1. A number of measure points (98) were screwed into the spaced boarding in the intermediate floor of the laboratory apartment, see Figure 11 and Figure 2, point 17.

4.2 Drying of a flooded intermediate floor (Paper 1)

The flooded floor

The flooding was 120 litres and the floor area is 24 m^2, which gives 5 litres per square meter, giving the possibility of covering the whole area with a 5 mm deep layer of water if there were no drainage.

Drainage

Between 90 and 105 litres of the 120 litres of the water added, drained out immediately by the “inlet of air”, see point 16 in Figure 3. In Figure 15 below, this air inlet is situated at the S7 line in the lowest part of the diagram. Most of the drainage took place at this place, but some water also dripped slowly from some joints between the gypsum boards. This drainage was noted quite early in the process, already when less than 10 litres were poured into the floor.

Iso-humidity map

The water damage is shown as raised MMM values in parts of the floor map, see Figure 15 below. In this figure, shown as an example, there are measurement points in each cross of the screen, to be compared with Figure 11 above.

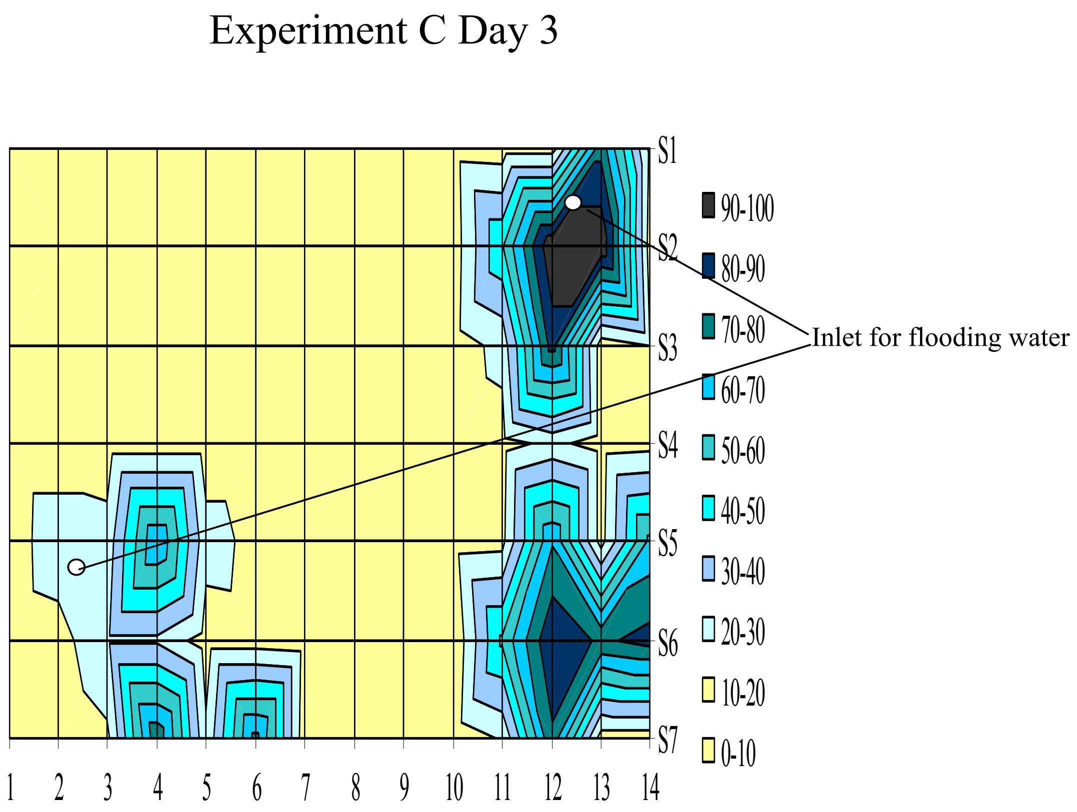


Figure 15 Schematic map of ground plan, showing the iso-humidity lines three days after flooding. The disposition of the MMM scale humidity is shown at the right side of the map.

This iso-humidity map confirms that a major part of the water has drained out from the construction and that most of the measurement points are unaffected by water. It is also clear that the remaining water seems to be in pools, for instance around the S6/12 cross and the S2/12 cross. The dampest point turned also out to be this cross at S2/12, for all the experimental series.

Results for dampest point; "cross at S2/12"

The results are shown in Figure 16, where the MMM readings for the S2/12 point for each test, are plotted versus time. It is shown that the flooding water evacuates faster when heating cables are switched on. This is displayed both by the time needed to reach down to the level of 20 % and also by the slope of the curves. The drying rate was fastest in experiment A1 (with two heating cables switched on), compared to experiment A2 and A3 (with one heating cable switched on).

It took 8 days for the construction to dry with two cables operating, compared to 12 and 13 days while one cable was switched on and 21 days with no cable working. So it is a significant difference in actual drying time and drying velocity between the first three experiments A1, A2 and A3 with heating cables operating, and the experiment A4, when the heating cable was switched off. The drying velocity can be understood as the gradient of the curves in Figure 16, the steeper inclination, the higher drying velocity.

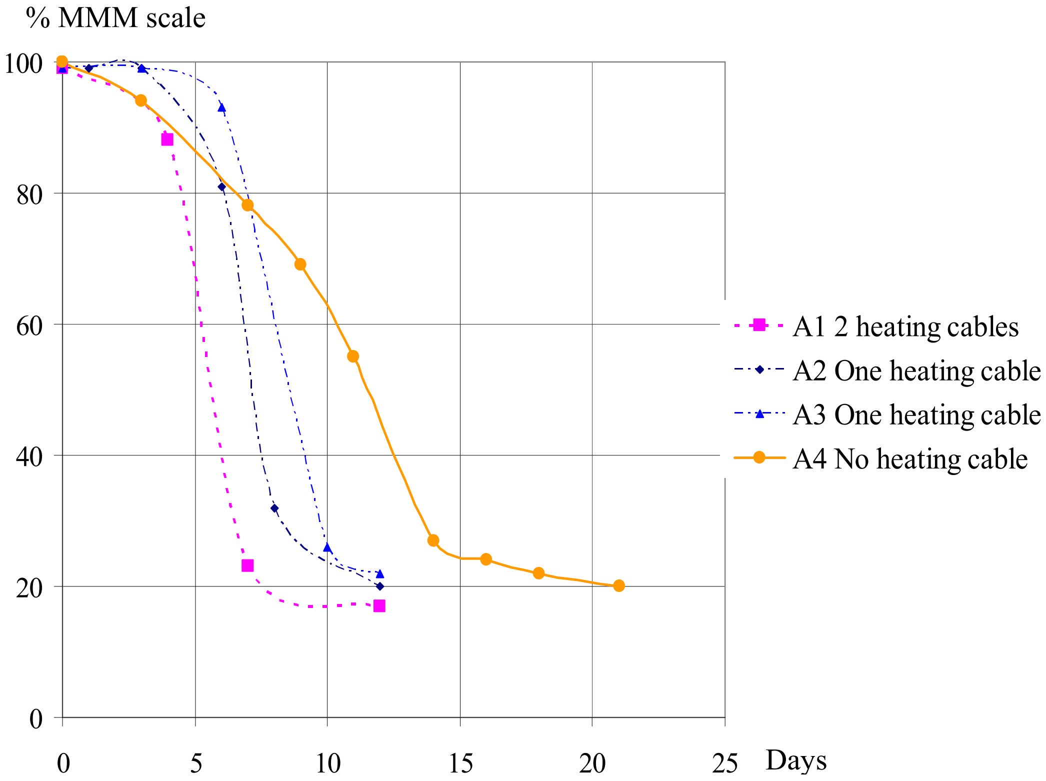


Figure 16 Decrease of moisture meter measurements (MMM) as a function of time. % MMM scale versus days.

4.3 Investigation of mould growth (Paper 1)

Results

The mould was investigated concerning species, growth and occurrence of mould by Aimex AB.

Table 2 Occurrence and fouling or bacteria and mould inside intermediate floor.

Experiment	A	B	C	D
Growth	No	No	No	Yes
Occurrence of spores and hyphas	Yes	Yes	Yes	Yes
Species mould	No	No	No	Acremonium sp Cladosporium sp

No mould growth was found after experiments A1, A2 or A3, based on visual examination and microscopic observation. After experiment A4, when the heating cables had been turned off, there were an abundant growth of active Acremonium sp and Cladosporium sp seen in microscope upon an area close to the S2/12 point.

4.4 Temperature and air flow in a vertical air gap

(Paper 2)

The temperature and air velocity measurements were performed during two days, named Day 1 and Day 2. The mean room temperature was 15.9 ^{o}C during Day 1 and 17.6 ^{o}C during Day 2, which, according to the manufacturer, should imply that the emitted power from heating cables ought to be somewhat higher during the colder Day 1.

Temperature

A typical result from the temperature measurements are displayed in the histogram in Figure 17 below, showing the air gap temperature for each measuring point in grey bars and the room temperature inside the dashed quadrangles. The difference in temperature, Δ*T*, could visually be described as the areas of the grey bars minus the area of the dash-lined quadrangles. The calculations are displayed in paper 2 in this thesis.

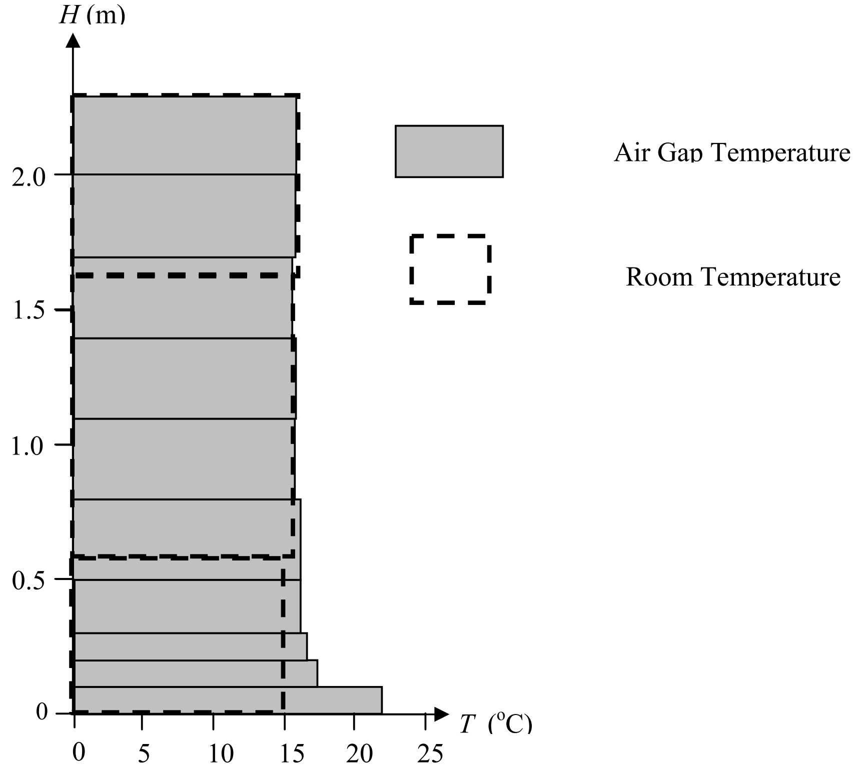


Figure 17 Histogram of temperature in air gap (grey bars) and in room (inside dashed lines), Day 1, Nr1. The raised temperature in the lower part of the histogram is caused by the T-18 cable.

Temperature difference Δ*T*

The heating cable causes a rise of temperature in the air gap and the values of Δ*T* are shown in Table 3. The values show a rather big disparity in the measure series for the same set of cable, with ratios up to 1.76 between highest and lowest values in the same sequence. There is also a big disparity between the different days, giving higher values for Day 1 compared to Day 2.

Table 3 Values of ΔT for each series, "No C." stands for no cable switched on, and "Bo. C" stands for cables "G-15 and T-18" switched on together. D 1 and D 2 stands for Day 1 and Day 2 respectively. Ratio H/L stands for ratio between the highest and the lowest value.

Nr	No C. D1	No C. D2	G-15 D1	G-15 D2	T-18 D1	T-18 D2	Bo. C. D 1	Bo C. D 2
1	0.18	-0.08	0.48	0.17	0.54	0.44	1.13	0.61
2	0.12	-0.03	0.40	0.24	0.59	0.36	1.20	0.64
3	0.09	-0.03	0.37	0.24	0.63	0.38	1.21	0.68
4	-0.04	-0.05	0.40	0.23	0.67	0.34	1.13	0.64
5	-0.01	-0.04	0.39	0.21	0.58	0.45	1.10	0.85
6	0.09	-0.03	0.54	0.30	0.60	0.39	1.13	0.69
7	-0.04	-0.11	0.40	0.27	0.69	0.39	1.15	0.70
8	-0.04	-0.11	0.34	0.31	0.64	0.41	1.15	0.75
9	0.03	-0.12	0.36	0.30	0.67	0.43	1.17	0.84
10	0.00	-0.08	0.39	0.30	0.40	0.37	1.13	0.80
Average	**0.04**	**-0.07**	**0.41**	**0.26**	**0.60**	**0.40**	**1.15**	**0.72**
Ratio H/L			**1.59**	**1.760**	**1.73**	**1.32**	**1.1**	**1.39**

Air flow

The average air flow is calculated out of the air velocity and displayed in Table 4. The air flow is quite measurable and stable values are obtained down to air flow values of approximately $9 \cdot 10^{-4}$ m^3/s. However the G-15 values on Day 2 have the biggest ratio between highest and lowest value. This is probably because this measure range is close to the lower detection limit of the anemometer. It may also be noted that the value of the air flow changes between Day 1 and Day 2, giving higher flow during Day 1.

Table 4 Values of average air flow ($Q \cdot 10^{-4}$ m^3/s) per meter wall for each series, No C. stands for no cable, and Bo. C stands for G-15 and T-18 switched on together. D 1 and D 2 stands for Day 1 and Day 2 respectively. Ratio H/L stands for ratio between the highest and the lowest value.

Nr	No C. D1	No C. D2	G-15 D1	G-15 D2	T-18 D1	T-18 D2	Bo. C. D 1	Bo C. D 2
1	0	0	9.5	8.0	16.0	13.2	21.0	18.5
2	0	0	10.2	7.1	16.0	13.2	20.6	18.5
3	0	0.3	9.3	5.6	15.7	14.5	20.6	17.3
4	0.7	0	9.5	5.8	14.8	13.9	20.1	17.6
5	0.3	0.3	9.3	5.8	16.0	13.9	21.3	16.9
6	0.3	0.7	9.3	7.1	17.9	13.6	20.6	17.3
7	0	0.3	9.3	6.2	16.7	14.5	20.6	17.9
8	1	0	9.5	6,5	15.7	13.2	19.4	17.9
9	0	0.7	10.2	5.3	16,9	13.2	21.3	18.5
10	0	0.3	9.5	5.8	15.7	13.2	20.1	17.9
Av. $Q \cdot 10^{-4}$ (m^3/s)	**0.2**	**0.3**	**9.5**	**6.3**	**16,2**	**13,6**	**20,5**	**17,8**
Av. Q_D (m^3/24h)	**1.9**	**2.8**	**82**	**54**	**140**	**118**	**177**	**154**
Ratio H/L			**1.1**	**1.5**	**1.2**	**1.1**	**1.1**	**1.1**

Air flow versus ΔT

The air flow is plotted against the ΔT in Figure 18. The diagram shows rather spread values, but it is clear that flow increases with rising temperature difference, ΔT, between the air gap and the room. The figure also shows a clear null result, when the heating cable is switched of there is no raised ΔT and no air flow.

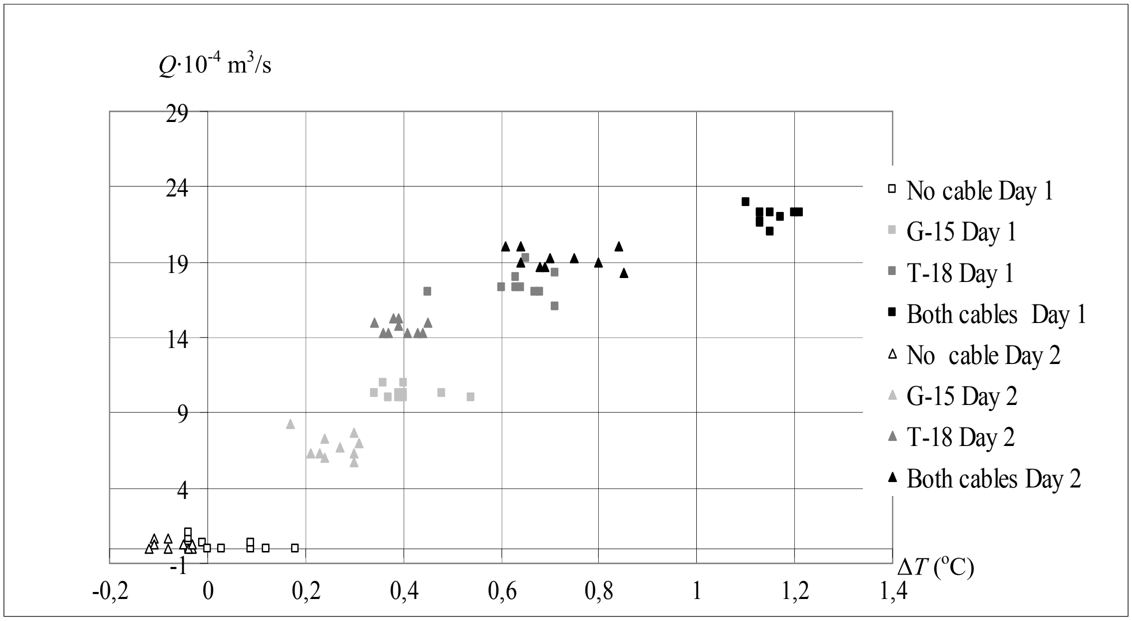


Figure 18 Air flow versus ΔT in the air gap wall, described in Figure 7.

Power of the heating cable, ΔT and air flow

The relation, from equation (1), between power, q, temperature difference, ΔT and air flow Q is displayed in Table 5 together with the power values stated by the manufacturer.

Table 5 q calculated out of equation (1) and the losses, compared to the stated power of the heating cable, expressed as a percentage.

Heating cable	Day	ΔT (°C)	$Q\cdot10^{-4}$ (m^3/s)	q_{HC} (W/m)	q (W/m)	Losses %
No cable	1	0.04	0.2	0	$9{,}6\cdot10^{-4}$	**-**
No cable	2	-0.07	0.3	0	$-2.5\cdot10^{-3}$	**-**
G-15	1	0.41	9.5	8	0.47	**94**
G-15	2	0.26	6.3	8	0.20	**97**
T-18	1	0.60	16.2	15	1.2	**92**
T-18	2	0.40	13.6	15	0.65	**96**
Both cables	1	1.15	20.5	23	2.8	**88**
Both cables	2	0.72	17.8	23	1.5	**93**

Table 5 shows that only a small part of the added energy goes to air flow and raised temperature. The system seems also more efficient as the power from the heating cable increases.

4.5 *RH* studies of a "slab on ground" construction

RH decrease in the slabs

The concrete slabs of the two rooms show different dry out processes. In the air gap floor construction, the *RH* level has gone down 12 %, from 97 % to 85 % over a time lapse of 56 days. The *RH* reduction, in the slab of the ordinary floor system, is 6 %, from 98 % to 92 %, see Figure 19.

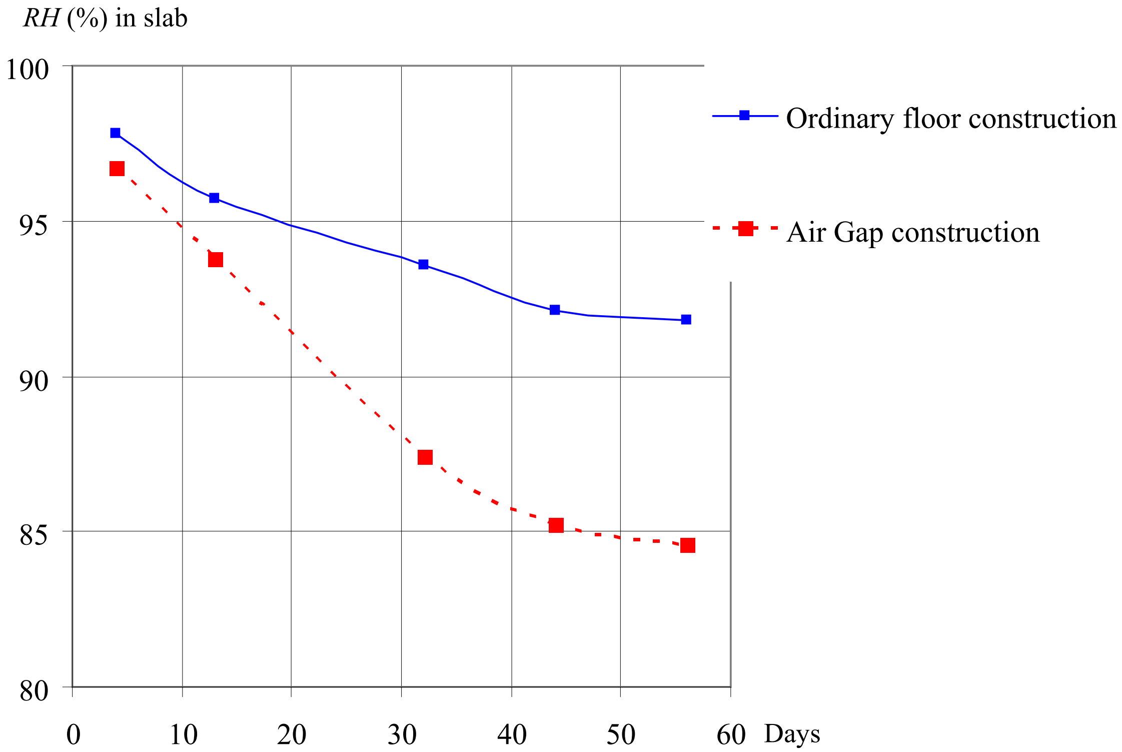


Figure 19 *RH* decrease in slabs on ground. A comparison between an ordinary floor construction and an air gap construction.

A sorption curve is presented in Figure 20 (Nevander and Elmarsson 1994); this curve is valid for a concrete K 40, which is similar to the concrete in this study. According to this curve, one cubic meter of concrete contains around 102 kg of water at 92 % *RH* and around 89 kg of water at 85 % *RH,* see point A and B in Figure 20. As the slabs contain approximately 0.6 m^3, the air gap system succeeds in evaporating around 8 litres more during this period, compared to the ordinary built system.

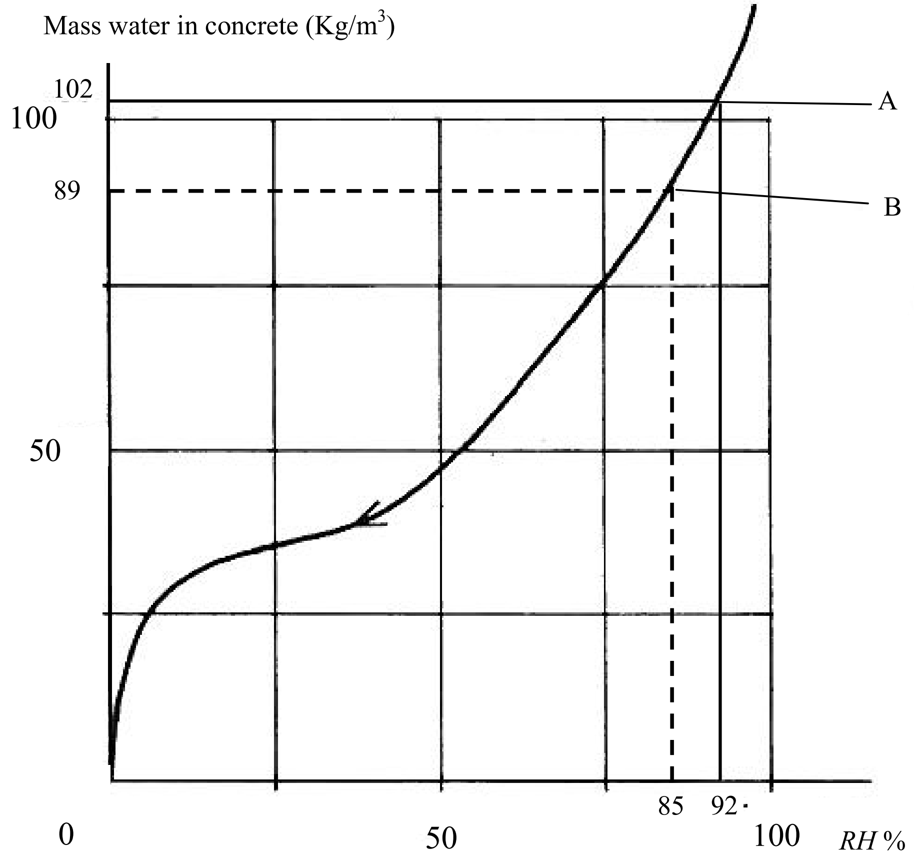


Figure 20 Dry out process in concrete K 40. The points “A” and “B” refer to the dry out level reached by the ordinary floor and air gap system respectively after 56 days.

RH levels between floor and concrete slab

The *RH* levels below the two floor constructions are plotted versus time in Figure 21, together with the comparable *RH* levels of the two rooms. The measure points are shown in Figures 12 and 13/ point D. The diagram shows that the ordinary construction has significantly higher *RH* levels compared to the air gap system. The ordinary floor values exceed 75 % for more than 20 days, while the *RH* level in the air gap floor is less than 75 %, all the period.

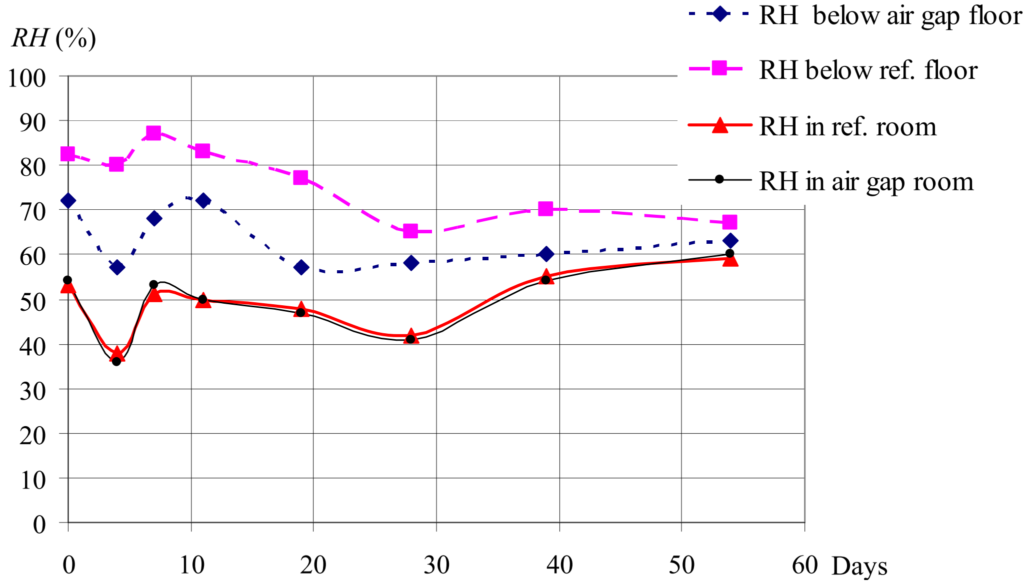


Figure 21 *RH* levels inside ordinary floor construction upon slab, inside air gap construction upon slab and in room air.

Distribution of vapour concentration in the air gap system

All results of *RH* and temperature measurements together with the calculated vapour concentrations are displayed in Tables A1 to A8, shown in Appendix. As an example, the results from day 28 are also displayed in Table 6 below. In these tables, "the moisture addition", Δv_x, is introduced as the vapour concentration from one measurement point A-M, see Figure 13 minus the vapour concentration at the inlet, point A.

The data of the Table 6 shows that there is an increase in moisture addition Δv_x in the floor from the air inlet at "A" to point "F". This moisture addition remains in principal at this level up to point "K" in the wall. The lower value at the air outlet "L" is explained by the process of mixing between air from the room and air from the air gap. The damp concrete slab is the only source for moisture in this construction.

Table 6 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 28.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	43.6	18.8	7.0	0
B Floor 25 cm	49.7	18.1	7.7	0.7
C Floor 75 cm	55.4	18.4	8.7	1.7
D Floor 125 cm	56.2	18.3	8.8	1.8
E Floor 175 cm	58.2	18.3	9.1	2.1
F Floor 225 cm	57.5	18.4	9.0	2.0
G Wall 20 cm	46.8	21.5	8.8	1.8
H Wall 70 cm	51.0	20.0	8.8	1.8
I Wall 120 cm	51.5	19.9	8.8	1.9
J Wall 170 cm	52.0	19.8	8.9	1.9
K Wall 220 cm	52.2	19.7	8.9	1.9
L Air outlet	43.5	20.0	7.6	0.9
M Room	40.7	20.0	7.1	0.1

Moisture addition over time

Figure 22 shows how the moisture addition at point "K", Δv_K in the outlet air varies over time. The average value for 54 days is 1.3 gram/m^3 air, which means that 1.3 grams of water leaves the construction with each cubic meter of air. It is also shown that the addition was zero at 54 days, when the moisture content was the same beneath the floor as well as above the floor.

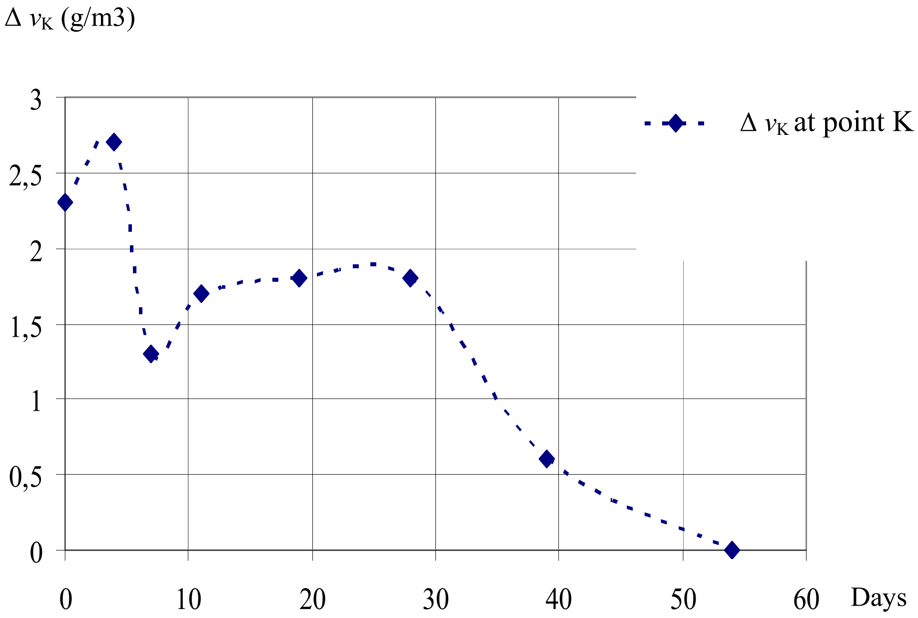


Figure 22 The moisture addition, Δv_K, in point K versus days

Air velocity in air gap

No air velocity could be detected, by the hot wire anemometer, inside the air gap at the "Air gap measuring point H, in Figure 13.

5. Discussion

5.1 Drainage, air flow and *RH* values

The general hypothesis for this thesis claims that it is possible to drain and evaporate dampness after water damage without demolition and also that it is possible to keep *RH* at a proportionately low level during this process. The function of the air gap method depends on two major operating parts, drainage and air flow. The importance of the latter is also divided into two parts, the dry out effect and the reduced *RH* values inside the construction, both parts mainly caused by the air flow.

Drainage

It was only 120 litres that entered the intermediate floor in paper 1, which is a rather small flooding. However as the construction has an inbuilt drainage, see point 16, Figure 2, the flooding could have been considerably bigger and the main part of the water would still drain out. This drainage works also as an early warning and makes it easier to localize the damage point. One difficulty when water damage occurs in real life is to determine where the leakage takes place. Hence fault-tracing is easier to do, by the air gap method.

Air flow

The results in paper 2, displayed in Tables 3 and 4 and Figure 18 also show a clear null result; when the heating cable is switched off, there is no increased temperature in the air gap, $\Delta T=0$, and there is no measurable air flow either. The air change rate per hour inside the wall construction varied between 13 times for the G-15 cable and 36 times for the stronger T-18 cable.

The air flow values in paper 2, displayed in Table 4, are rather well together; it is only the values for the G-15 cable during Day 2 that show a greater spread probably because these values come close to the lower detection limit of the hot wire anemometer.

Temperature

It is difficult to measure temperature with a resolution down to a tenth of a degree Celsius. Lamps and the persons who perform the investigation add heat to the system and an unexpected draught may change the basis for the experiment. General measure conditions are somewhat unstable and therefore it could be expected to obtain such spread results in the temperature as shown in Table 3. It is noted that ΔT for the T-18 cable for Day 2 (0.40 ^{o}C) is almost the same as ΔT for the G-15 for Day 1 (0.41 ^{o}C) although the air flows have different values for these days, $14.7 \cdot 10^{-4}$ m^3/s and $10.3 \cdot 10^{-4}$ m^3/s respectively.

Air flow and the dry out effect

The results from paper 1, displayed in Figure 16 show that the water disappears faster when the heating cable is operating, but the air flow was not measured so there are no direct proofs of ventilation in this case.

There are though proofs, see Figure 18, that the heating cable causes a raised temperature, which on its part causes an air flow. This air flow noted in paper 2 was possible to measure because the measure point was narrowed from 25 mm to 10 mm, see Figure 7 and the fact that the measure point was close to the heating cable. In a larger system with both horizontal and vertical building parts and when the air gap is wider, the air flow is harder to detect.

Table 5 shows that most of the power added from the heating cable disappeared from the air gap system, the energy used for temperature rise and air flow lies between 3 and 12 %. The rest of the energy could be lost as heat conduction through the OS-board and gypsum board. If the air gap could be better insulated it should lead to higher efficiency of the air gap system. This will be investigated in coming papers.

The results from *RH* studies in a “slab on ground” construction indicates that 8 extra litres of water has disappeared from the “air gap” concrete slab in 56 days compared to the reference slab. The air flow was found to be below the detection limit for the hot wire anemometer, but the results from Table 6 and Tables A1 to A8, shown in Appendix, indicate that the moisture finds its way towards the air outlet. As seen in these tables the moisture content measurements in the air gap wall and in the air gap floor correspond very well, which indicate that there are only small leakages in this type of system.

The results from the *RH* studies in a “slab on ground” construction can be used for a rough estimation of the air flow: The average Δv_K for the period was 1.3 grams per m^3 air, around 8 litres disappeared during this period and this will imply that around 6000 m^3 of air has ventilated through the system during 54 days (equal to 4 665 600 seconds). This leads to an air flow of 1.3 litres per second and as the wall is 2.25 m long, the air flow will be approximately 0.6 litres per second and meter.

As the air gap is 0.025 m wide, the air velocity should be around 0.024 m/s. This velocity in this range it is too low to be detected by the anemometer from TSI, which lower detection range is about 0.05 m/s. The task of developing a more sensitive method of measuring low air velocities will be undertaken in a coming paper.

This air flow may be compared to the air flow registered in paper 2 showing measured flows of 1.3 to 1.7 litres per second and meter for the same cable. The results are in the same magnitude and it is reasonable to believe that the air flow should be lower in a combined wall and floor system compared to a sole wall system presented in paper 2. The air gap is more than twice as long in the combined wall and floor construction, and the air flow is assumed to meet a stronger friction in this case.

As the area of the room is 6 m^2 and the air flow is 1.3 litres per second, it will lead us to an air flow of 0.2 litres of ventilating air per m^2 of the floor and second, which is in the same magnitude as the Nivell-floor, see page 6.

As the volume between the floor and the concrete slab is 1.5 m^3 it will lead us to an air change rate around 3 times per hour, to compare with an ordinary air change rate for a room, which is 0.5 times per hour (Boverkets byggregler 2006). The high air change rate is important, while it will lower harmful levels of *RH.*

Reduced *RH* values gives less fragility

If water has entered into a building construction, the dampness needs to be removed. It is also important that the relative humidity inside the construction is kept at a low level in order to avoid mould growth. The results displayed in Figure 21 show that the *RH* level below the floor in the air gap construction never exceeds 75 %. This is a rather big difference compared the reference floor, where the *RH* levels exceed 75 % during 20 days at the beginning of the study.

The low *RH* values also imply that there ought to be no mould growth on the rear side of the air gap floor. As this investigation is performed during summertime, with comparably high *RH*, it may be considered that the possibility to avoid mould growth would be even better during the rest of the year.

5.2 Mould growth in the flooded intermediate floor

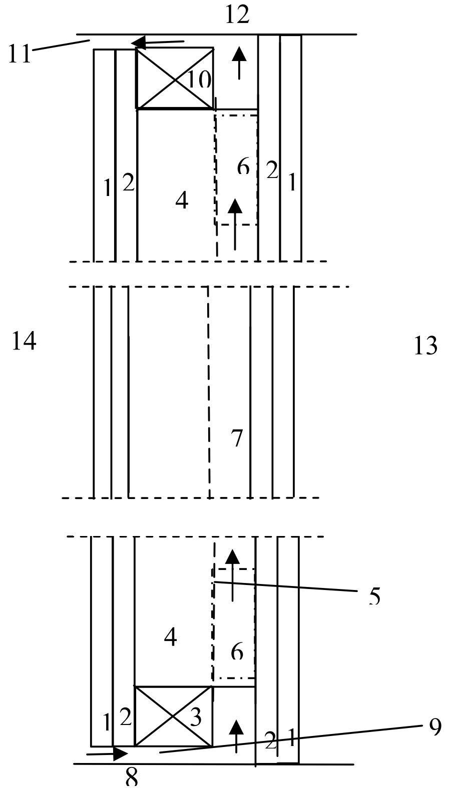
The mould species found in experiment A4 of paper 1 were Acremonium sp and Cladosporium sp and these species could be harmful to humans in high concentration (Gutarowska & Piotrowska 2007).

The growth of mould during experiment A4 could however be due to both high relative humidity at time, see Table 1, as well as reduced ventilation, because the heating cable was switched off. Further test could be done to investigate this matter.

The conclusion is anyhow that the method reduces the relative humidity inside a construction and that this reduced *RH* makes a building construction less fragile according to water damage and mould growth.

5.3 Air gap method inside a bathroom

When the investigation of the air gap wall in paper 2 was performed, the air inlet and outlet were situated at the same side as the air gap inside the wall, see Figure 7. If the inlet and outlet would be situated in the neighbour room as shown in Figure 23, it would be possible to obtain an air flow, without a heating cable in the air gap, provided there is a temperature difference between the rooms.



1. Gypsum board 13 mm
2. OS-board 13 mm
3. Bottom sill 45/45 mm
4. Stud 45/70mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap
8. Floor
9. Air inlet
10. Top plate
11. Air outlet
12. Ceiling
13. Bathroom
14. Neighbour room

Figure 23 Air gap wall where air inlet and outlet are situated in neighbour room. The arrows indicate an upwards going motion of the air flow

The results displayed in Table 3-4 and in Figure 18 show that it is possible to obtain an air flow, 50 m^3 per m wall and day, by a rather small temperature difference, 0.2-0.3 ^{o}C. Table 5 also indicates that heat could transfer rather easily from the air gap to the room and vice versa. A small difference in temperature between bathroom and neighbour room would therefore cause an air flow in the system.

It is also quite possible that the bathroom temperature differs from the surrounding rooms. A bathroom gets warmer when a person takes a shower and the bathroom can also become colder as this room can get a downdraught, since a bathroom often ventilates towards exterior air. This will imply that the air gap temperature also will differ from the temperature of neighbouring rooms. The air flow of the air gap could thus go in both directions, taking harmful water out of the construction. In this case it would not be necessary to use a heating cable.

5.4 Nordic building rules

An air gap solution is by the way desired by the Finnish building rules C2 (Haavisto and Särkijärvi 1998) where it is written: If there are two water tight layers in a building construction, no material that requires drying shall be placed between these layers, unless precautions have been taken to ensure the moisture to leave without hindrance. This is in fact a description of the aim of the air gap method; moisture should always be able to leave the construction and therefore make it less fragile.

Byggforskserien (Bad i underetasjer 30.055) in Norway has also solutions where an air gap can be used behind a panelling of a bathroom. This is recommended when a bathroom is placed in a cellar (Arfvidsson et al 2005).

6. Conclusions

The aim of the of the air gap method is to make a house less fragile according to water damage, where moisture can be removed without demolishing the construction.

When temperature and convective air flow in a vertical air gap was studied, it was noted how air flow increased with raised power of the heating cable. In this test the air flow for one meter of wall varied between 50 m^3/day (13 air changes per hour) and 140 m^3/day (36 air changes per hour). The lower value is caused by a temperature difference in the range 0.2-0.3 ^oC. Without heating there was no air flow.

In studies of moisture and *RH* in slab on ground constructions, it was noted how the slab in the room with the air gap method dried to a much higher extent than the slab in the room built in an ordinary way. It was also noted that moisture was transported from the air gap in the floor and up through the air gap in the wall, although the air velocity was too slow to be detected. In the room with the air gap construction, *RH* beneath the floor was at a lower level (and below 75 % *RH*) than *RH* beneath the floor of conventional construction.

In the study of a flooded intermediate floor, it was noted how the thermally driven convective air flow evidently speeded up drying of the construction. Mould growth was only noted in the case where the heating cables were turned off

The general conclusion is that the air gap method provides means to build houses in a less fragile way, minimizing the negative effects of water damage.

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9. Appendix

Table A1 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 0, one hour after the experimental start.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	53.9	15.5	7.1	0
B Floor 25 cm	59.3	14.6	7.4	0.3
C Floor 75 cm	71.8	14.2	8.8	1.7
D Floor 125 cm	68.0	14.6	8.5	1.4
E Floor 175 cm	70.8	15.5	9.4	2.3
F Floor 225 cm	69.0	15.6	9.2	2.1
G Wall 20 cm	54.3	17.3	8.0	0.9
H Wall 70 cm	55.4	16.0	7.5	0.4
I Wall 120 cm	56.0	15.9	7.6	0.5
J Wall 170 cm	56.0	15.9	7.6	0.5
K Wall 220 cm	54.8	15.8	7.4	0.3
L Air outlet	53.6	16.6	7.6	0.5
M Room	52.1	16.1	7.2	0.1

Table A2 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 4.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	36.4	15.1	4.7	0
B Floor 25 cm	41.5	13.9	5.0	0.3
C Floor 75 cm	48.4	13.7	5.7	1.0
D Floor 125 cm	53.0	14.0	6.4	1.7
E Floor 175 cm	57.2	14.2	7.0	2.3
F Floor 225 cm	55.9	14.4	6.9	2.2
G Wall 20 cm	51.1	16.8	7.3	2.6
H Wall 70 cm	54.3	15.8	7.3	2.6
I Wall 120 cm	55.1	15.7	7.4	2.7
J Wall 170 cm	55.0	15.7	7.4	2.7
K Wall 220 cm	54.5	15.9	7.4	2.7
L Air outlet	48.1	16.3	6.7	2.0
M Room	36.6	15.4	4.8	0.1

Table A3 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 7.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	52.8	12.1	5.7	0
B Floor 25 cm	57.5	11.7	6.0	0.3
C Floor 75 cm	62.5	11.5	6.5	0.8
D Floor 125 cm	64.4	11.6	6.7	1.0
E Floor 175 cm	67.2	11.7	7.0	1.3
F Floor 225 cm	68.1	11.9	7.2	1.5
G Wall 20 cm	58.0	14.3	7.1	1.4
H Wall 70 cm	60.8	13.0	6.9	1.2
I Wall 120 cm	61.9	12.8	6.9	1.2
J Wall 170 cm	62.4	12.7	7.0	1.3
K Wall 220 cm	62.3	12.8	7.0	1.3
L Air outlet	55.0	13.2	6.3	0.6
M Room	55.1	12.2	5.8	0.1

Table A4 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 11.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	54.1	10.4	5.2	0
B Floor 25 cm	59.9	9.4	5.4	0.2
C Floor 75 cm	63.2	9.6	5.8	0.6
D Floor 125 cm	66.6	10.0	6.3	1.1
E Floor 175 cm	71.7	10.2	6.8	1.6
F Floor 225 cm	71.3	10.4	6.9	1.7
G Wall 20 cm	61.6	12.9	6.9	1.7
H Wall 70 cm	66.8	11.6	7.0	1.8
I Wall 120 cm	67.4	11.6	7.0	1.8
J Wall 170 cm	67.1	11.5	6.9	1.7
K Wall 220 cm	66.8	11.6	6.9	1.7
L Air outlet	62.5	12.0	6.7	1.5
M Room	49.8	11.8	5.3	0.1

Table A5 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 19.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	46.6	14.5	5.8	0
B Floor 25 cm	46.4	14.4	5.7	-0.1
C Floor 75 cm	48.4	13.9	5.8	0
D Floor 125 cm	53.9	13.8	6.4	0.6
E Floor 175 cm	53.5	14.1	6.5	0.7
F Floor 225 cm	56.7	14.2	7.0	1.2
G Wall 20 cm	53.4	16.4	7.5	1.7
H Wall 70 cm	56.5	15.6	7.5	1.7
I Wall 120 cm	56.8	15.9	7.7	1.9
J Wall 170 cm	57.3	15.6	7.6	1.8
K Wall 220 cm	58.3	15.3	7.6	1.8
L Air outlet	49.6	15.4	6.5	0.7
M Room	46.6	14.5	7.1	0

Table A6 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 28.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	43.6	18.8	7.0	0
B Floor 25 cm	49.7	18.1	7.7	0.7
C Floor 75 cm	55.4	18.4	8.7	1.7
D Floor 125 cm	56.2	18.3	8.8	1.8
E Floor 175 cm	58.2	18.3	9.1	2.1
F Floor 225 cm	57.5	18.4	9.0	2.0
G Wall 20 cm	46.8	21.5	8.8	1.8
H Wall 70 cm	51.0	20.0	8.8	1.8
I Wall 120 cm	51.5	19.9	8.8	1.9
J Wall 170 cm	52.0	19.8	8.9	1.9
K Wall 220 cm	52.2	19.7	8.9	1.9
L Air outlet	43.5	20.0	7.6	0.9
M Room	40.7	20.0	7.1	0.1

Table A7 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 39.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	54.8	16.9	7.8	0
B Floor 25 cm	57.2	16.1	7.9	0.1
C Floor 75 cm	60.3	16.1	8.3	0.5
D Floor 125 cm	59.4	16.1	8.2	0.4
E Floor 175 cm	60.0	16.2	8.3	0.5
F Floor 225 cm	60.4	16.3	8.4	0.6
G Wall 20 cm	53.3	18.4	8.3	0.5
H Wall 70 cm	55.0	17.8	8.4	0.6
I Wall 120 cm	56.9	17.2	8.4	0.6
J Wall 170 cm	57.3	17.1	8.4	0.6
K Wall 220 cm	57.8	17.0	8.4	0.6
L Air outlet	59.4	17.5	8.9	1.1
M Room	53.5	16.9	7.9	0.1

Table A8 *RH*, temperature, vapour concentration and the moisture addition Δv_x of construction air, in wall, floor and by inlet and outlet at day 54.

Place	*RH* %	Temp. (C)	v_x g/m^3	Δv_x (g/m^3)
A Air inlet	58.8	19.9	10.0	0
B Floor 25 cm	62.1	19.0	10.0	0
C Floor 75 cm	63.0	18.8	10.0	0
D Floor 125 cm	62.4	18.9	10.0	0
E Floor 175 cm	62.3	18.9	10.0	0
F Floor 225 cm	62.1	19.0	10.0	0
G Wall 20 cm	56.0	21.1	10.0	0
H Wall 70 cm	59.4	20.0	10.0	0
I Wall 120 cm	59.2	20.0	10.0	0
J Wall 170 cm	59.3	20.0	10.0	0
K Wall 220 cm	59.3	20.0	10.0	0
L Air outlet	59.3	20.0	10.0	0
M Room	60.5	19.4	10.0	0

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Air gaps in building construction avoiding dampness and mould

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Abstract

Purpose – Water damage is a severe problem in modern construction, causing economic loss and health implications. The patented Air Gap Method, which is a slight modification of the common infill wall construction, provides means to build houses in a more robust way, minimizing the negative effects of water damage. This full-scale study of the method aims to show how walls and floors may be built to create ventilation within the construction, with air gaps equipped with heating cables. The general hypothesis is that the patented Air Gap Method drains and evaporates dampness after water damage. The purpose of this study is to show how the method is built and how the method deals with water damage, such as a flooding, and with mould growth.

Design/methodology/approach – The Air Gap Method is based on a common timber-framed construction and is completed by the provision of inlets, air gaps, slits, and outlets. The power for the convective airflow is given by an electrical heating cable. The study was carried out as a full-scale experiment using a 24 m^2 large apartment build by this method. This apartment was flooded with 120 litres of domestic wastewater and the drying period was compared when heating cables were switched on or not. Mould growth was also investigated.

Findings – The method dries out a flooded floor in nine days when two heating cables were switched on, in 13 days with one heating cable and 21 days when the heating cables were off. The method prevents all mould growth provided that the indoor RH is lower than 65 per cent.

Practical implications – The method provides means to build houses in a more robust way, minimizing the negative effects of water damage.

Originality/value – The issue of ventilated construction is rarely investigated in scientific research.

Keywords Water, Humidity, Buildings, Building conservation, Heating and ventilation services

Paper type Research paper

Introduction

Water damage and mould are connected to allergic reactions among children (Emenius, 2003) and when water and mould-damaged houses are remedied, the users' health is found to improve (Ekstrand-Tobin, 2003). One big difference in building methods nowadays, compared to the first half of the twentieth century, is the introduction of airtight materials such as gypsum wallboard, that have replaced matchboards and lining paper. The advantage of a board is that it is fast to erect. One possible disadvantage is that this construction may have less of air movement through the structure.

In the case of water damage the construction air (by which we mean the air inside walls and intermediate floors) may come close to 100 per cent relative humidity (RH). Mould needs satisfactory temperature, enough time and at least 75 per cent RH to grow. When the humidity rises, the growth of the mould will become more rapid (Sedlbauer, 2001).

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The possibility to remove dampness inside walls and intermediate floors has not been thoroughly investigated from a scientific and technological view point. The purpose of this paper is to present a technically achievable concept of solutions for construction of air gaps with convective airflow, along with a full-scale test of this concept in case of flooding. The growth of mould is also investigated.

The Air Gap Method

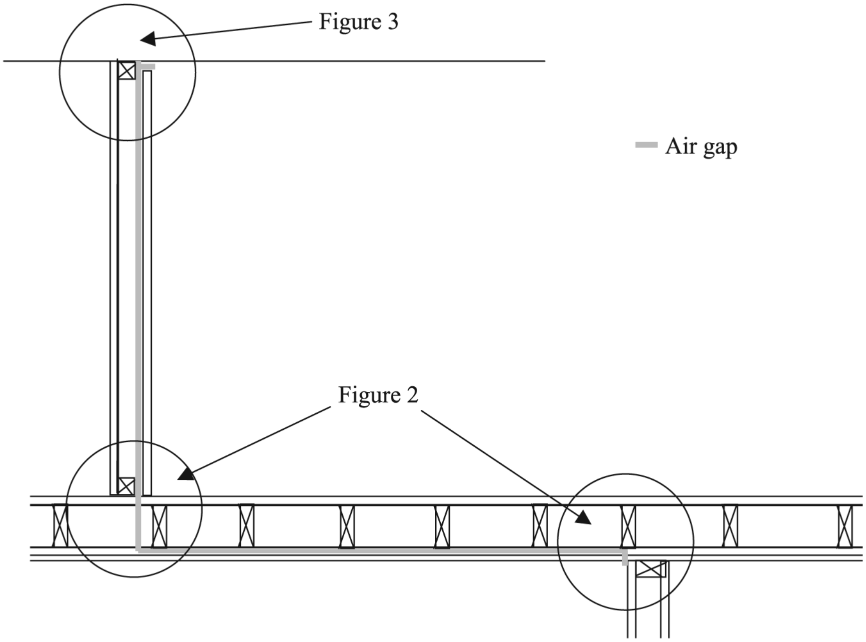
The Air Gap Method is a modification of the common way of constructing infill walls of houses. It is built by using the same materials and methods, but the Air Gap Method is also an accomplished and cost-efficient way of creating ventilation flux through the whole construction. The method creates and opening for convective airflow inside the construction. The aim of the method is to remove dampness from the construction and thus protect it from moisture-related damage such as mould.

The air gaps in infill walls and floors built in this way are shown in principle in Figure 1 where different applications of the Air Gap Method are shown.

This paper is the first of three papers describing the Air Gap Method from qualitative and quantitative aspects. The measured airflow and drying rate in this type of construction will be evaluated in forthcoming articles.

Other ventilated systems

Although building science has paid relatively little attention to the problem of low ventilation inside building constructions, there are at least two well-established



Note: The circles indicate the positions of the detail drawings to be seen in Figures 2 and 3

Figure 1.
Schematic cross-section of an air gap house

building methods that have dealt with the problem, the ventilated prefabricated bathroom (In Wall-method), and the floor on joists (Nivell floor).

The ventilated prefabricated bathroom (in wall method)

This method is used to build prefabricated bathrooms, which are installed inside an old bathroom, possibly with water damage (www.inwall.nu). There is an air-gap between the old and the new bathroom, where ventilating air can circulate. The in wall-method allows for removal of construction damp after the prefabricated bathroom is installed. The time for drying out could, according to experience, being about six to nine months.

The floor on joists, (Nivell floor)

The floor is built on joists attached to the structural slabs of the building and creates an air-gap below the insulation, (www.nivellsystem.se/content/view/15/69/). The floor system itself is rather cheap to build and gives the physical preconditions for construction air ventilation. This ventilation should be executed by mechanical appliances that are rather expensive and require service.

Construction

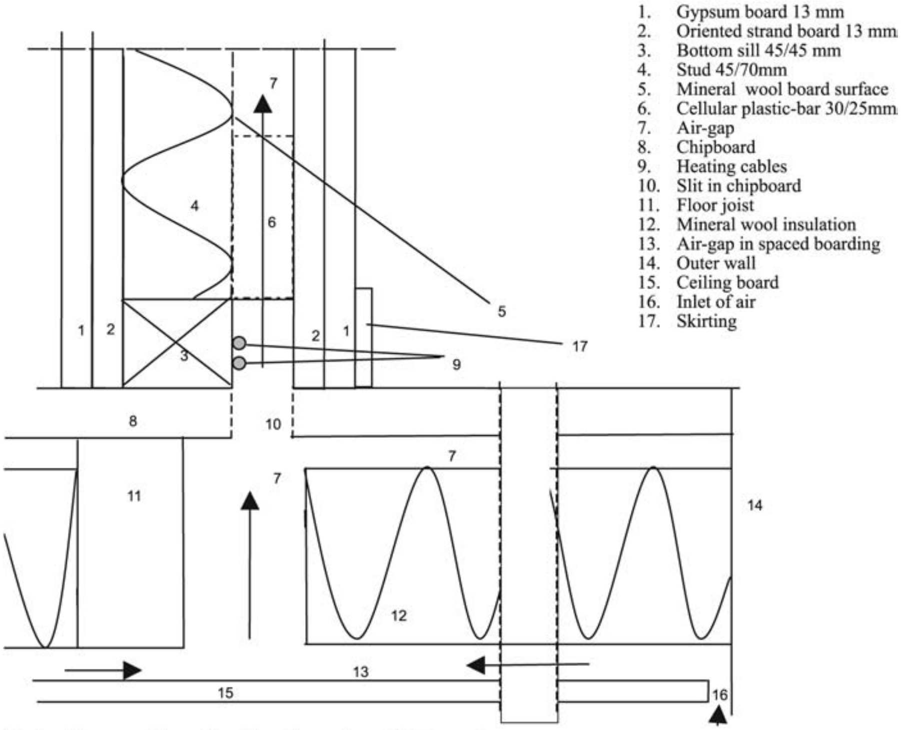
Building by the Air Gap Method

This air gap system is constructed by the provision of inlets, air gaps, slits and outlets, shown in Figures 1-5. Air gaps in floor construction and walls are connected with each other and have air inlets and outlets at corners between floor and wall and at corners between ceiling and wall. The ventilating air is interior air that goes through the building construction driven by an electrical heating cable inside the vertical gap. The Air Gap system inside infill wall houses is built in different ways if it is an interior wall, spine wall or intermediate floor respectively. These different ways are presented hereby.

Interior wall and intermediate floor construction. An interior wall does not have a load-bearing purpose, but separates rooms from each other. An interior wall goes often between the spine wall and the exterior wall and it is built on the line of the floor joists. By the Air Gap Method it is constructed with bottom sill, top sill and mineral wool wall boards that are not as thick as the width of the standing studs to create an air gap inside the wall. The boards (for acoustic insulation) are hindered from falling back into the air gap by a number of cellular plastic-bars 100 × 25 × 30 mm and a heating cable is attached to the bottom sill (see Figures 2 and 3).

The floor is cut beside the narrowed bottom sill and a vertical air gap is formed in the floor mineral wool insulation. These insulation boards lie upon the secondary spaced boardings and horizontal air gaps are formed between these. These air gaps are used in the air gap construction and a connection is thus created from the air inlet to the air gap in the wall.

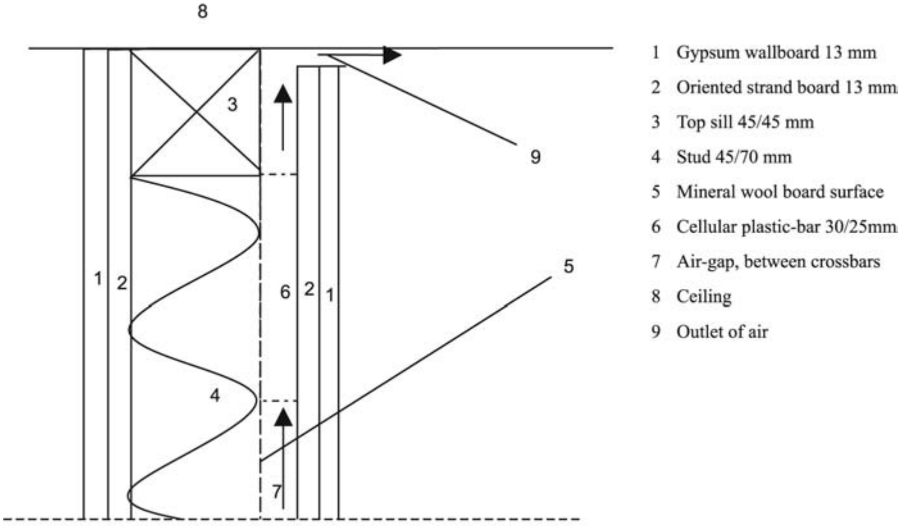
Air flow. The construction air enters the air gap in the corner between the exterior wall and the ceiling of the floor beneath at point 16 (see Figure 2). The construction air goes subsequently beneath the mineral wool insulation, point 13, to and through the air gap in the floor insulation, the slit, point 10, and up through the inside of the interior wall. The construction air outlet is in the corner between the interior wall and the ceiling (see point 9, Figure 3).



1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/45 mm
4. Stud 45/70mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap
8. Chipboard
9. Heating cables
10. Slit in chipboard
11. Floor joist
12. Mineral wool insulation
13. Air-gap in spaced boarding
14. Outer wall
15. Ceiling board
16. Inlet of air
17. Skirting

Note: Arrows show the direction of ventilating air

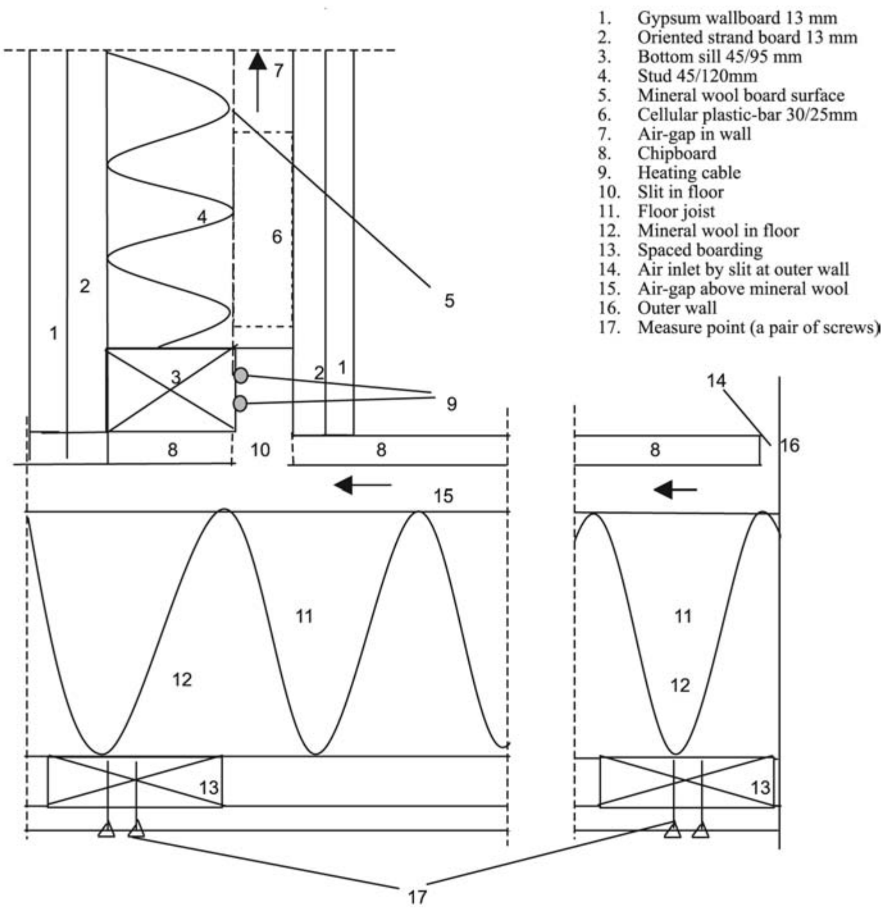
Figure 2.
Cross-section of an interior wall and intermediate floor



1 Gypsum wallboard 13 mm
2 Oriented strand board 13 mm
3 Top sill 45/45 mm
4 Stud 45/70 mm
5 Mineral wool board surface
6 Cellular plastic-bar 30/25mm
7 Air-gap, between crossbars
8 Ceiling
9 Outlet of air

Note: Arrows show the direction of ventilating air

Figure 3.
Cross-section of an interior wall and ceiling

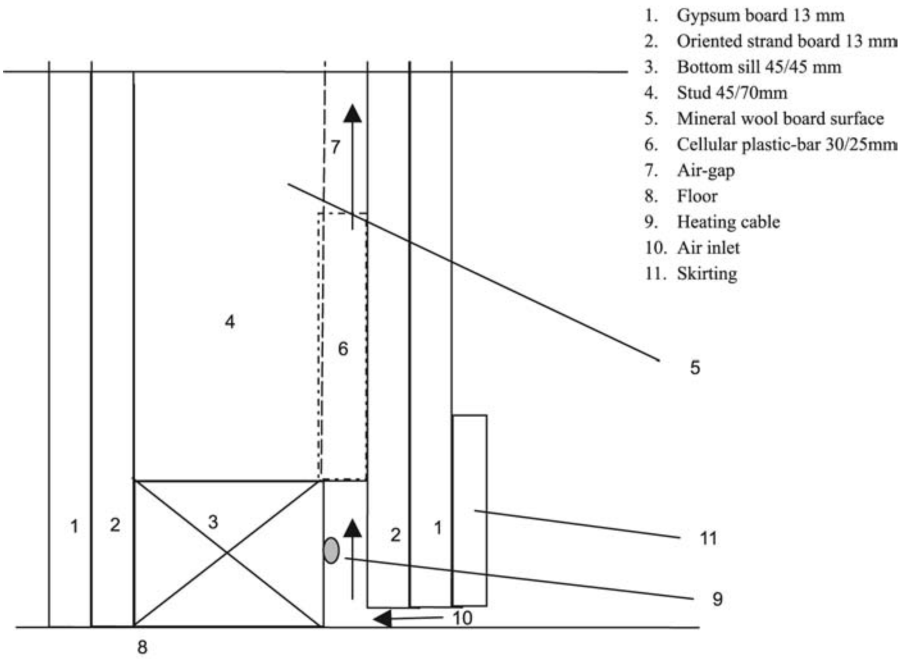


Note: Arrows show the direction of ventilating air

Figure 4.
Cross-section of a spine-wall and floor

Spine wall and intermediate floor construction. The spine wall goes between the short sides of a house and this wall is constructed of 45 × 120 mm standing studs. The bottom and top sills measure 45 × 95, which opens for an air gap at the top and bottom of the walls. The mineral wool wall boards (for acoustic insulation) are hindered from falling back into the air gap by a number of cellular plastic-bars 100 × 25 × 30 mm and a heating cable is attached to the bottom sill. The floor joists rest on the spine wall and the outer wall. There is an air gap between the floor chipboard and the floor mineral wool insulation since this insulation, used as acoustic insulation, is not as thick as the height of the floor joists. Figure 4 shows the cross-section of the connection between the spine wall and the floor.

Measuring points for the study of moisture ratio in wood are displayed as point 17 in this figure. These pairs of screws are important in this test but not included in the general way of building by the Air Gap Method.



Note: Arrows show the direction of ventilating air

Figure 5. Cross-section of an interior wall

Airflow. The ventilating air enters the air inlet, point 14, Figure 4, in the corner between the exterior wall and the floor. The air goes subsequently beneath the chipboard, point 15 to and through the slit, point 10 and up through the air gap inside the spine wall, point 7 in Figure 4. The outlet is at the ceiling angle built after the same principle as in the interior wall (see point 9 in Figure 3).

Interior wall. The Air Gap Method can also be applied to walls standing on a solid floor in buildings with a concrete slab foundation. In this case the gypsum and oriented strand boards as well as the skirting are lifted 10 mm from the floor, to create the air inlet, see point 10 in Figure 5.

Airflow. The construction air enters the air gap beneath the skirting board, the gypsum and oriented strand boards, passes the bottom sill and up through the inside of the interior wall, see Figure 5. The outlet is in the interior ceiling angle with the design shown in Figure 3.

Flooding simulation

This part of the paper reports mainly on the drying of a flooded floor and the growth of mould after a flood. However, as the damp has been registered as moisture ratio, it has also been necessary to carry out a calibration between the moisture ratio from the moisture meter and amount of water studied gravimetrically during a process of flooding and drying. Hence this section contains three parts:

(1) calibration of moisture meter;

(2) drying process of a flooded intermediate air gap floor; and
(3) investigation of mould breed inside a flooded intermediate air gap floor.

Calibration of moisture ratio meter

The moisture ratio was measured throughout the experiments, by a moisture meter, "Surveymaster SM" from Protimeter plc, England. This moisture meter has an instrument scale, which grades moisture ratio on a scale from 0 to 100 per cent. Tests are performed by putting the two-pin electrodes from the instrument in contact with the measure point. A stable value is shown on the display of the instrument after about ten seconds.

It is interesting to investigate what relation a certain reading of the instrument scale has to actual water content. There is also an uncertainty regarding how readings above 30 per cent on this equipment should be interpreted. Above this number, the timber cells are saturated with water (Ashrae, 1989) and it is not known what actually is measured on the instrument scale between 30-100 per cent. This experiment was carried out at ordinary indoor temperature and RH.

Experiment. In order to investigate this calibration task, a small part of a gypsum board ceiling was constructed (see Figure 6). The board was provided with six measuring points, "pair of screws", which are screwed through the gypsum board and into the spaced boarding wood, see point 4 in Figure 6. The area inside the water bank measured 0.125 m^2 and the amount of water, 157.8 grams, was chosen so it did not leak over the water-bank, see point 3 in Figure 6. The following evaporation of the water was measured both by weighing the board in a lapse of time and by "measurements of the moisture meter" in the following called MMM.

Result and discussion of calibration of moisture meter. The percentage decrease of weight and of the MMM was measured and displayed versus time in Figure 7. In this figure the evaporation is shown as the remaining part of the originally added amount of water as a percentage. For example 50 per cent means that 78.9 grams of the originally

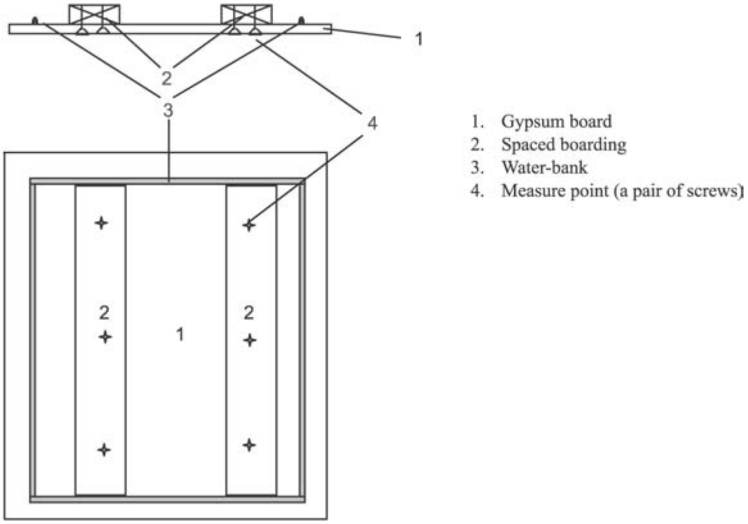


Figure 6.
Cross-section and plan of ceiling part for calibration of moisture meter

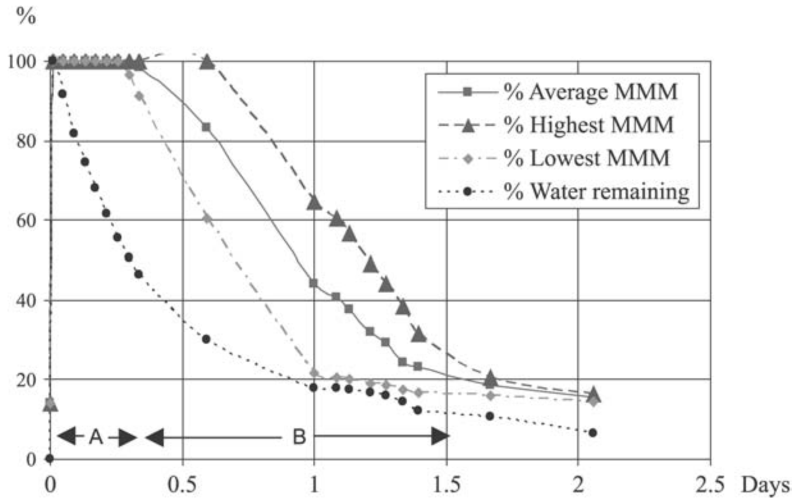


Figure 7.
% measurements of the moisture meter (MMM) and % water remaining versus days

added 157.8 grams of water still remain. The readings from the moisture meter (MMM) are shown with the highest and lowest value and a mean value of the six points measured.

In this diagram two regimes can be noted:

(1) "*Regime A*". (See A in Figure 7). The water evaporates at a rate of a little less than 10 per cent/hour and this decrease in weight is due to the fact that water dries both upwards and downwards from the gypsum board and that the whole area of the test set up is wet. The curves for MMM remain on a 100 per cent plateau and this relates to the very low electrical resistance between the screws occurring when a water film is formed between the gypsum board and the battens of the spaced boarding.

(2) "*Regime B*". (See B in Figure 7). The amount of remaining water has become smaller and so the rate of drying is decreased to a lower level. More than 90 per cent of the added water has evaporated after total two days. In this part the water that was stored between the gypsum board and the spaced boardings is dried out or taken up into the material. The readings from the MMM now goes quite rapidly down under the levels around the fibre saturation point (30 per cent).

This test show that the evaporation proceeds continuously, but the MMM values stay at level 100 for a quarter of a day before it starts to decrease. It can also be seen that half of the added water has evaporated before the value of the MMM becomes lower than 100 per cent. In spite of the different shapes of the percentage water remaining curve and the percentage MMM curves, the conclusion of this part is that the "Surveymaster SM" is useful in this context because:

- When the readings from the moisture meter have gone down to 20 per cent, more than 80 per cent of the water has evaporated.
- When the reading from the instrument is higher than 30 per cent, a decreasing trend in the readings still reflects a decrease in moisture content in the construction.

Due to this experiment, measure points were screwed into the spaced boarding in the intermediate floor of the laboratory apartment, see also point 17 in Figure 4.

Drying of a flooded intermediate floor

Laboratory apartment. The laboratory apartment is built on 1.2 m high posts and has a total area of 24 m^2. Thanks to the posts, the ceiling beneath the floor is available from the crawl space beneath. The apartment is divided into two rooms, "bedroom" 18 m^2, and "bathroom", 6 m^2. The walls are 2.5 m high. The intermediate floor spine wall and the interior wall are constructed by the Air Gap Method. There are two exterior walls, one spine wall, one interior wall and one wall belonging to the laboratory building. The spine wall and the interior wall are provided with two heating cables each, one extra due to the experiment, see Figures 2 and 4. As part of the experiment, two holes were drilled into the floor, to be inlets for flooding water. See the ground plan in Figure 8.

Measure points. The floor construction was provided with 98 measure points as shown at point 17 in Figure 4, attached to the spaced boarding from beneath, through the ceiling board. These measure points are pairs of screws as shown in Figure 4. There are 7 measure points in each of the 14 battens of spaced boarding (see Figure 9).

Experiments. There were four experiments performed in the laboratory apartment named A, B, C and D. For each experiment 120 litres of domestic wastewater was poured into the construction i.e. 60 litres into each "Inlet for water in the test". The amount of drain water was estimated and measurements of the moisture meter, MMM at the measure points shown in Figure 9 were intermittently taken during each experimental period.

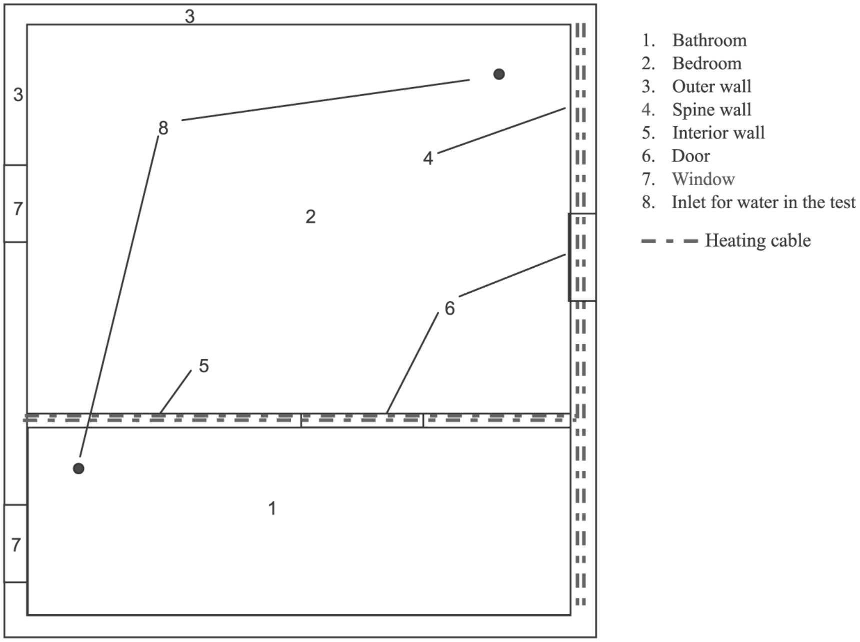


Figure 8.
Ground plan, laboratory apartment showing placing of heating cables and water inlets

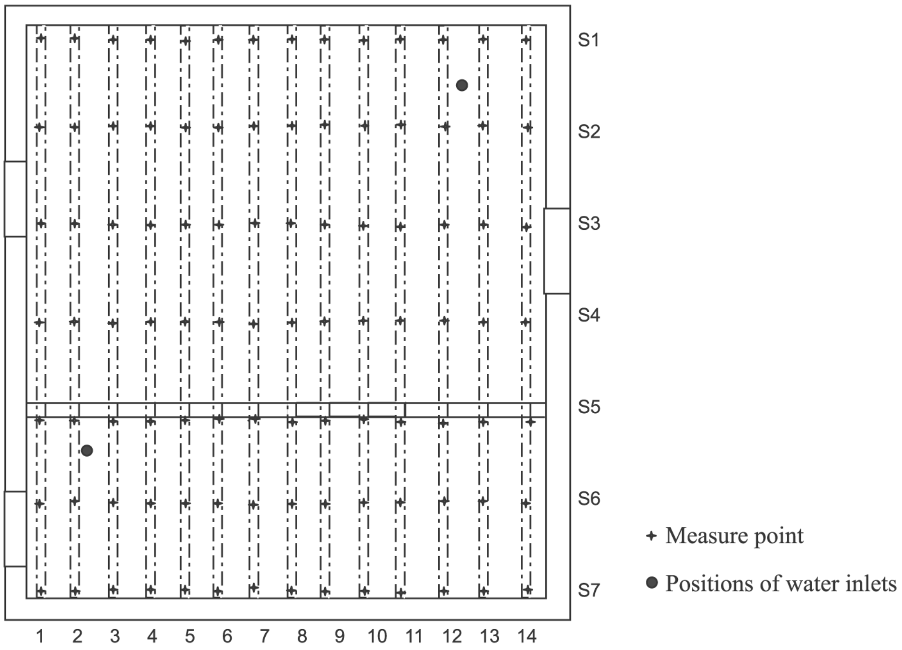


Figure 9. Ground plan of the intermediate floor – placing of spaced boarding, positions of water inlet and measure points

Experimental conditions. The preconditions for the laboratory apartment are described in Table I. The RH and temperature were continuously measured by a thermo hygrograph from Thies Göttingen.

Mould in the flooded intermediate floor

Experiments. After each experiment was performed, the intermediate floor was opened from above and also from below. Clear tape samples for microscopic investigations of mould and bacteria, (Gutarowska and Piotrowska, 2007) were taken from the battens of the spaced boardings and from the upper side of the ceilings gypsum board beside the measure points, point 17, see Figure 4. Samples were examined concerning mould species and quantity by a well-reputed mould laboratory (Aimex AB).

Results

Drainage. Between 90 and 105 litres of the 120 litres water added drained out immediately by the "inlet of air", see point 16 in Figure 2. Most of the drainage took

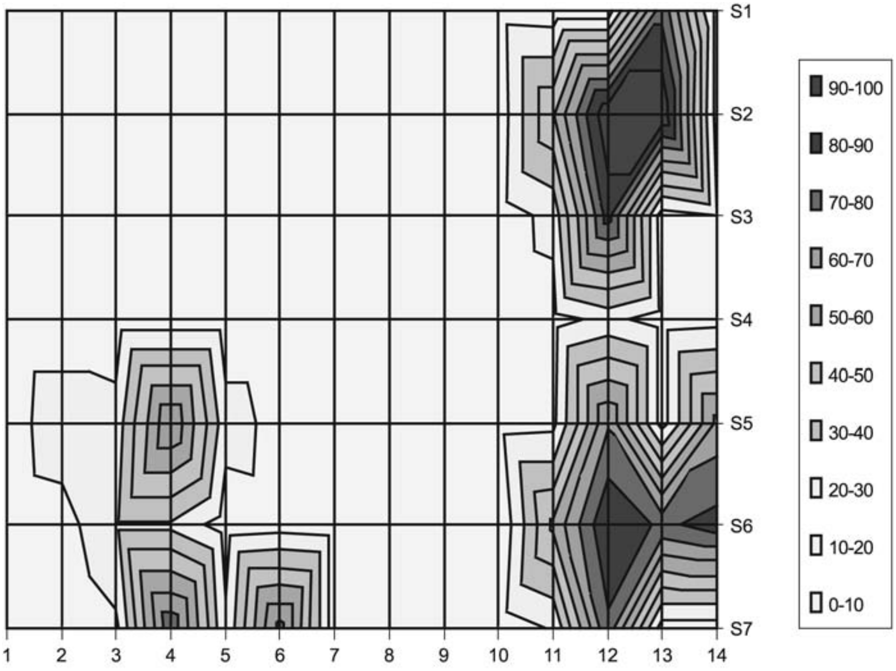
Experiment	A	B	C	D
Heating cables (W/m)	2p = 18.2	1p = 9.1	1p = 9.1	0p = 0
Temperature average (C)	19.7	21.2	19.8	19.9
Temperature max/min (C)	22/17	23/19	23/18	22/18
Relative humidity 5 days (C)	43.6	53.4	65.2	74.4
Relative humidity max/min (C)	48/40	65/47	74/50	77/63

Table I. Preconditions for experiments A-D place at this “inlet of air”, some water also dripped slowly from some joints between the gypsum boards. This drainage was noted quite early in the process, already when less than 10 litres were added into the floor. So possible reservoirs available could be considered to be filled up.

Drying rate

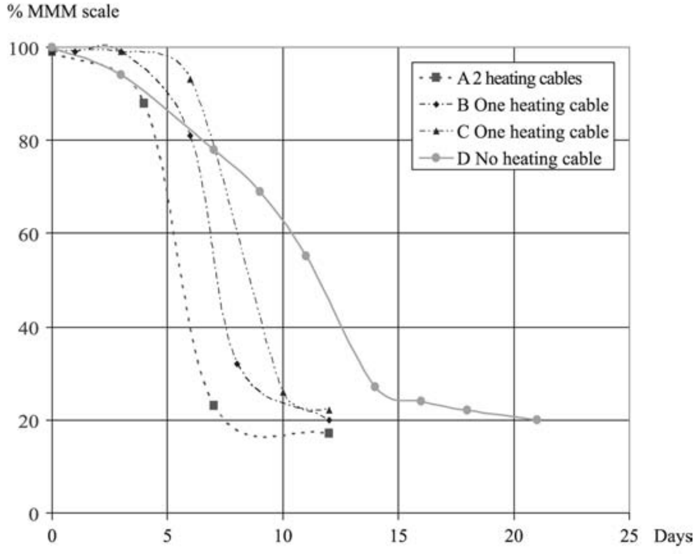
Iso-humidity map. The results from the measurement from one day are presented by mapping of iso-humidity lines shown on the ground plan of the floor in Figure 10. All the 98 measures from the moisture meter values are plotted onto this map. A map with iso-lines like this is a way to show how water will flow to certain areas while other parts will remain quite dry. The wet parts will also be the parts where mould growth could be anticipated. The values can be understood as follows: most of the area has not been flooded at all as those values lie between 10 to 20 on the MMM scale. The points S2/12 and S2/13 have values between 90 and 100 on the scale, while S5/4 measures between 60 and 70 on the same scale. In this case the point S2/12 was the one with the slowest drying process and results from this point will therefore be used for characterization of the drying process in experiments A, B, C and D.

The dampest measure point S2/12. The results are reflected in Figure 11 where the MMM readings for the very dampest measure point (S2/12) are plotted versus time for each test. It is shown that the flooding water evacuates faster when heating cables are switched on. This is displayed both by the time needed to fall to the level of 20 per cent, MMM scale and also by the slope of the curves. According to those slopes it is not



Note: The disposition of the MMM scale humidity is shown at the right side of the map

Figure 10.
Schematic map of ground plan, showing the iso-humidity lines



Note: %MMM scale versus days

Figure 11. Decrease of moisture meter measurements (MMM) as a function of time

certain that the drying rate of experiment A, (with two heating cables switched on) is faster compared to experiment B and C (with one heating cable switched on). The prolonged drying period for B and C could be due to the fact that more water was stored in the floor in those latter experiments. Still it is a significant difference both in slope and actual drying time between the experiments A, B and C with heating cables switched on compared to the experiment D, where the heating cable was switched off.

Mould in the flooded intermediate floor

Results. The mould was investigated concerning species, growth and occurrence of mould by Aimex AB (see Table II).

No mould growth was found after experiments A, B or C, based on visual examination or microscopic observation. After experiment D, where the heating cables were turned off there were an abundant growth of active *Acremonium* sp and *Cladosporium* sp seen in microscope upon an area less than 0.5 m^2. However, the growth of mould during experiment D could be due to both high relative humidity at time, see Table I, as well as reduced ventilation because of the absence of the heating cable working.

Experiment	A	B	C	D
Growth	No	No	No	Yes
Occurrence of spores and hyphas	Yes	Yes	Yes	Yes
Species mould	No	No	No	*Acremonium* sp *Cladosporium* sp

Table II. Occurrence and fouling or bacteria and mould inside intermediate floor

Discussion

Here the Air Gap Method is discussed from three different aspects. The first one is the extra material and effort needed to build by the method. The second is regarding circumstances around the dry out process in the intermediate floor and the third one relates to mould growth.

The Air Gap Method uses regular materials such as boards and common building methods. Extra material needed is:

- heating cable; and
- cellular plastic-bar.

The extra effort needed to fulfil the Air Gap Method is:

- sawing out slits in floor boarding;
- cutting out slits in the insulation inside the floor construction;
- attaching the heating cable to the bottom sill and installing it; and
- attaching the cellular plastic-bar to the standing studs.

The air gaps in the intermediate floor are created by the normal method of construction. There is one air gap in the bottom of the intermediate floor and another one above the mineral wool insulation. These air gaps are possible to use in the Air Gap Method, when they are connected to the air gaps in the walls as well as inlets and outlets.

It was only 120 litres that entered the intermediate floor, which is a rather small flooding. However as the construction has an inbuilt drainage, see point 16 Figure 2, the flooding could have been considerably bigger and the main part of the water would still drain out, because the possible reservoirs are already filled up. This drainage works also as an early warning and makes it easier to localize the damage point. One difficulty of when water damage occurs in real life is to determine where water enters the construction. By the Air Gap Method, fault tracing is easier to undertake.

In experiment D, with no heating cable switched on, it took 21 days to dry out the floor. In an ordinary built floor with no drainage, it might be assumed that the drying period would have been much longer. In such a floor much damage like this could proceed without any detection.

When 120 litres of water was poured into the floor construction between 90 and 105 litres drained out. It is impossible to create the same conditions for the ventilation part of the experiment every time. Anyhow, the slopes of the curves showing the drying rate in Figure 11 are almost the same, when cables have been switched on, despite the difference in level of drainage.

The ambient relative humidity happens to be the lowest during experiment A with the highest heating power and highest during the experiment with no heating, which could explain some of the difference in drying time. However there is a bigger difference in ambient relative humidity between experiment B and C with one heating cable, compared to experiment C and D. So there is reason to believe that the heating cable plays a significant role in the drying process. Forthcoming articles will quantify the airflow and the drying rate.

If water has entered into a building construction it is important that the dampness can get out. It is also important that the relative humidity inside the construction is kept at a low level in order to avoid mould growth. The results of this investigation show that the Air Gap Method manages to accomplish both these tasks. The fact that no mould growth was noted in experiment A, B and C, when the heating cable was switched on indicates that the method prevents mould growth. The experiments were done during summertime at a laboratory close to Stockholm, which is the time of the year when moisture content indoors is comparatively high. From this result it can be assumed that any mould will be limited after a heavy flooding, at least during the heating season from September to May.

The mould species found in the D experiment above were *Acremonium* sp and *Cladosporium* sp. These species could be harmful to humans in high concentration (Gutarowska and Piotrowska, 2007) but as the contaminated area measured less than $0.5\,\text{m}^2$ any harmful material coming from this area are probably not excessively high.

Conclusions

This full-scale study of drying after flooding of a building construction built according to the Air Gap Method which is a slight modification of the common way of building with infill wall construction resulted in the following findings:

- The method provides a means to build houses in a more robust way, minimizing the negative effects of water damage.
- The method managed to dry out a flooded floor in 13 days.
- The method did prevent all mould to growth provided that the indoor RH was lower than 65 per cent.

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Air Gap Method: measurements of airflow inside air gaps of walls

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Abstract

Purpose – Water damage is a severe problem in modern construction, causing economic loss and health implications. By using the patented Air Gap Method inside building constructions, harmful water in the construction can be dried out. The method drains and ventilates air gaps inside walls and floors with an airflow driven by thermal buoyancy caused by a heating cable in vertical air gaps. This paper aims to investigate this method and measurements of airflow inside air gaps of walls.

Design/methodology/approach – This study investigates the measured correlation between the power of the heating cable, the difference of temperature inside and outside the air gap, and the airflow. Data are collected by experimentation with a full-scale constructed wall.

Findings – The study finds that airflow increases with raised temperature difference between the air gap and room and with raised power of the heating cable. The measured airflow reaches values up to 140 m^3/metre wall and day for one cable. A small increase in temperature, between 0.2 and 0.3 °C inside the vertical air gap results in an air flow of approximately 60 m^3/metre wall and day. The air change rate per hour for the air inside the wall construction varies between 15 times for a 6 W/m cable and 37 times for a 16 W/m cable.

Practical implications – The method provides the means to build houses in a more robust way, minimising the negative effects of water damage. This investigation provides an understanding of how temperature and ventilation are related in this method of construction.

Originality/value – The issue of ventilated construction is rarely investigated in scientific research.

Keywords Air diffusion, Water, Humidity, Buildings, Temperature measurement

Paper type Research paper

Introduction and aim of this study

Background

Air Gap Method. The Air Gap Method is a method to transport dampness out of a building construction. This dampness could have entered the construction during the building phase or the maintenance phase, through leakage, flooding or condensation.

The overarching idea of the method is: “In case dampness has entered the construction it must have a way out.” This is achieved by creating air flow in an air gap system in floors and walls and that is obtained by thermal buoyancy caused by a heating cable. The purpose of this article is to investigate this flow.

Slow air flow. We have not yet found any descriptions of experimental studies of air flows caused by heating cables but there are at least four other research fields where

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slow air movements are of interest: air flow inside air gaps of enclosure walls; convection air flow supposed to cool electrical devices; convection that causes natural ventilation in houses; and thermal plumes around persons or electrical devices:

- *Air flows inside air gaps inside a building envelope*. These air gap systems play an important role in drying exterior walls. This has been shown both by experiments and mathematically (Davidovic *et al.*, 2006; Gudum, 2003) and is also the topic in ground level education material (Johannesson, 2006). The geometry of this type of air gap resembles the studied air gap of this article but the air gap of the exterior wall has no heating cable. The temperature in these air gaps differ from the outdoor temperature because of solar radiation on the wall, etc. and this difference in temperature causes an air flow as well as wind pressure.
- Laminar convection in heated vertical channels is of interest in electronic cooling applications, (Burch *et al.*, 1985; Campo *et al.*, 2005; Androzzi and Manca, 2002). These articles consider wall conduction, wall and air gap temperatures and air velocity but the geometry of the gap and the amount of power added differ greatly from that used in the Air Gap Method.
- Natural convection, occurring in a heated column of air, is described by the stack equation (Skistad, 1995; Ashrae Handbook Fundamentals, 2005) and this is further investigated in this article. Foster and Down (1987) have compiled a number of different expressions that describe this effect.
- Convective airflow is the reason for thermal plumes around persons and electrical devices in dwellings. This flow has been measured (Mierzwinski, 1981; Popiolek, 1981) as well as calculated (Mundt, 1996; Mundt in Skistad *et al.*, 2002). These works are interesting as they relate the flow with an estimated power from a line source.

Parameters of study. In af Klintberg *et al.* (2007), it is shown that an air gap system, called the Air Gap Method, (supplied with heating devices, in this case a heating cable), managed to drain and dry out a flooded intermediate floor in 13 days. This was a way to avoid damage relating to extended periods of dampness such as mould growth inside the construction.

However that study raises one general question: “What are the mechanisms behind this drying out effect?” The heating cable gives the thermal power in this system and the first parameter to determine is the power properties of the actual cables. The second parameter in this context is the temperature rise thanks to the heating cable, as well as the temperature difference between the air gap temperature and the room temperature.

The third parameter to study is the airflow, which has two aspects – the quantity of the air flow and flow characteristics. The airflow provides conditions for the system to both dry out water in the construction and also to keep the relative humidity at a low level, which will prevent mould from growing. A predictable airflow out of a certain cable power would thus be useful in the context of constructing buildings by the Air Gap Method. The second aspect is whether the airflow could be laminar or turbulent because these types of flow have different relationships to friction.

The major part of this study investigates a stable phase of airflow and heating. Some efforts have been made to investigate the first initial phase, when the heating cable has just been switched on and when air starts to flow.

The general hypothesis of this paper is that the heating cable warms the air inside the air gap and causes an airflow through the air gap system. The aim of this work is also to quantify this airflow and show the relationship between this flow on one hand and the power of the heating cable and the increased temperature in the wall on the other hand.

It should be noted that the Air Gap Method deals only with walls and floors inside the vapour barrier of a house and this investigation has been carried out in an interior wall.

Nomenclature

The notations shown in Table I are used in this study.

Construction

This study was carried out as a full scale experiment in a wall construction that is 2.3 m high and 0.12 m thick, the inside volume of the wall is 0.16 m^3 per metre wall. The wall was in the main built as an infill wall with wooden sills and studs, mineral wool boards and on both sides covered first by a layer of oriented strand board and on top of

Abbreviation	Explanation	Denomination
A	Area of inlet	m^2
d_h	Hydraulic diameter	m
d_I	Width of inlet to air gap	m
η	Viscosity	Ns/m^2
g	Acceleration of gravitation	m/s^2
H	Height of air gap	m
I	Current of heating cable	A
l_{Cab}	Length of heating cable	m
l_W	Length of wall	m
μ	Contraction factor	–
n	Measure point in air gap	–
Q	Air flow	m^3/s
Q_D	Total air flow per meter wall during 24 hours	$m^3/24\,h$
Q_n	Air flow at measure point n	m^3/s
q	Power of heating cable per meter	W/m
q_{Tot}	Power of heating cable	W
r	Air density	kg/m^3
Re	Reynolds number	–
Rn	Measure point in room	–
T	Absolute temperature in room	K
T_n	Temperature at the height of measure point n inside air gap	℃
T_{Rn}	Temperature at the height of measure point Rn in room	℃
T_{AG}	Average temperature inside air gap	℃
T_R	Average temperature in room	℃
ΔT	Temperature difference between T_{AG} and T_R ℃	℃
dT	Temperature difference between air gap and room, at one height	℃
U	Voltage of heating cable	V
v	Air velocity at air inlet	m/s
v_{ag}	Air velocity inside air gap	m/s
v_{max}	Maximum air velocity measured in air gap	m/s

Table I.

this a layer of gypsum board. However, this construction differs from a common infill wall by the bottom and top sills that are of size 45 × 70 mm compared to the standing studs which measure 45 × 95 mm. The wall is provided with an air inlet, air outlet and two heating cables attached to the bottom sill (af Klintberg *et al.*, 2007). The heating cables differ in power strength so that conditions for the experiments may be varied. A sketch of the cross-section of the wall is provided in Figure 1. If this air gap system were built in a bathroom wall, the air inlet and outlet would be situated in the neighbouring room, on the other side of the wall.

For the purpose of the experiments, ten holes were drilled in the panelling for insertion of temperature sensors, numbered T_1-T_{10}. The holes were drilled 5, 15, 25, 35, 65, 95, 125, 155, 185 and 215 cm in one vertical line above the heating cable, (only two of the holes are presented in Figure 1). The sensors were inserted through a vapour barrier tape (used to tighten the holes) and placed in the centre of the air gap at each height. The room temperatures were measured simultaneously at the heights of 0.10, 1.15 and 2.20 m by the temperature sensors T_{R1}-T_{R3}, these sensors were placed 0.01 m from the surface of the wall.

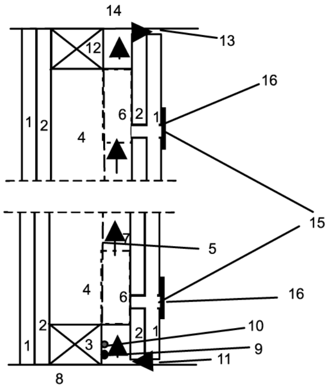
Experimental studies

The experimental work was carried out on two occasions, which are referred to as day 1 and day 2. The temperature in the room was approximately 1.5°C higher on day 2 than day 1.

Heating cables

The heating cables, named T-18 and G-15, were manufactured by Ebeco AB. The intended use for T-18 is to melt ice inside drainpipes and the intended use for G-15 is to perform floor heating. The cables are made of two electrical conductors embedded in a semiconductor material whose resistivity increases with temperature, so the maximum temperature of the cables lies in the range of 28-40°C.

The cables are supposed to give different levels of power because of the temperature of the surrounding air "If this air is colder it takes more power to reach the maximum



1. Gypsum board 13 mm
2. Oriented strand board 13 mm
3. Bottom sill 45/70 mm
4. Stud 45/95mm
5. Mineral wool board surface
6. Cellular plastic-bar 30/25mm
7. Air-gap
8. Floor
9. T-18 heating cable
10. G-15 heating cable
11. Air inlet
12. Top sill 45/70 mm
13. Air outlet
14. Ceiling
15. Measure hole for T
16. Tape covering measure hole

Note: The arrows indicate the direction of the ventilating air

Figure 1.
Cross-section of air gap wall

temperature of the cable" (Ebeco AB, Kent Svensson, personal communication). The manufacturer also states that T-18 gives a power of 15 W/m ± 3 – W/m and G-15 a power of 8 W/m ± 2 W/m at 20°C. Each batch (around 3,000 metre length of the cable) gives different levels of power, because of minor variations in the properties of the semiconductor material.

For this study the cables installed in the wall were tested using a combined volt and ampere meter, Metra Hit 14s from Gossen Metra Watt. The voltage, current and length were measured for each cable separately and also for the cables together, at two occasions with different room temperatures. The measurements were carried out twice on each occasion, the first when the heating cables had been switched on for one hour and the second when the heating cable had been on for two hours. The power per metre of the heating cable was calculated by the equation:

$$q = IU/l_{\mathrm{Cab}}. \tag{1}$$

Temperature and air velocity studies

When a heating cable warms the air inside the air gap, it will result in a temperature difference between the average air gap temperature and the average room temperature, hereby called ΔT. A positive value of ΔT gives a lower air density inside the air gap compared to room air. This lower density makes a pressure gradient that will create an upward airflow inside the air gap and this temperature rise is measured in this study, as well as the air velocity. The measurements of temperature and air velocity were performed simultaneously during stable conditions, when the heating cable had been switched on for at least 60 minutes.

Temperature

Temperatures in the air gap and in the room at heights indicated previously were measured with thermistors connected to a data logger Mitec AT 40. When thermistors were compared by putting them into a bowl of water measuring 10°C, they gave readings from 9.95 to 10.05°C and the uncertainty in these sensors was found to be in the range of 0.05°C.

The order of the measurements differed from day 1 to day 2. During day 1 the measurements started with both cables switched on, followed by T-18, G-15 and finally no cable. During day 2 the measurements started with no cables switched on, followed by both cables, T-18 and finally G-15. There was an intermission of 60 minutes between each series of measurements.

Calculation of ΔT

The different temperature measurements were recorded at heights chosen after pilot tests showing that the heating cable gave the greatest impact of temperature at the lower part of the air gap, close to the heating cable. Thus thermistors were placed at each decimeter in the interval of 0 to 40 cm and at every third decimeter for the rest of the height. A weighted mean value of the air gap temperature was calculated by multiplying each measured temperature with the height for which the result could be valid. For the temperature in the bottom, this is the distance from the floor up to a point half the way to the second thermistor. The distance half way between the thermistors is then used until the thermometer on top, where the distance to the ceiling is used. The sum of these products is divided by the total height of the wall (2.3 m), resulting in the average temperature of the air gap, T_{AG}.

The mean temperature for the room was calculated in a similar way, although this measurement only contains three measuring points, resulting in the average temperature of the room T_R. T_{AG} subtracted by T_{R} gives ΔT, the mean value of the air gap temperature minus the mean value of the exterior room temperature. Thus the equations are written as:

$$\Delta T = T_{\mathrm{AG}} - T_R \tag{2}$$

$$\Delta T = \frac{0.1 \cdot T_1 + 0.1 \cdot T_2 + 0.1 \cdot T_3 + 0.2 \cdot T_4 + 0.3 \cdot T_5 + 0.3 \cdot T_6 + 0.3 \cdot T_7 + 0.3 \cdot T_8 + 0.3 \cdot T_9 + 0.3 \cdot T_{10}}{2.3} - \frac{0.675 \cdot T_{r1} + 1.05 \cdot T_{r2} + 0.575 \cdot T_{r3}}{2.3}. \tag{3}$$

Quantity of airflow

The airflow, calculated from the air velocity, is supposed to be the important agent of the Air Gap Method, resulting in a drying out effect and lower relative humidity (RH) inside the building construction. The air velocity was measured by the air inlet, see point 11 in Figure 1, at three measurement points side by side with 10 cm in between. The central point was right below the temperature measurement points. As the standing studs, which measure 0.045 m in thickness and are placed at 0.6 m intervals, reduce the horizontal air gap area by 7.5 percent the calculated air flow will be multiplied by 0.925. The air velocity measurements were recorded simultaneously with the temperature measurements, by a hot wire anemometer from TSI, Finland. The lower detection limit of this anemometer is 5 cm/s. The measurements were performed for; no cable, T-18 cable, G-15 cable and both cables at day 1 and 2 respectively and the air flows per metre wall were calculated from air velocity by the equation:

$$Q = v \cdot d_I \cdot l_W \cdot 0.925 \tag{4}$$

where:

d_{I} = 0.01 m; and

l_{W} = 1 m.

Characteristics of airflow

Reynolds number

When discussing airflows at low velocities in narrow air gaps, it is important to consider whether the airflow is laminar or turbulent. A turbulent flow has higher friction at the same velocity compared to a laminar flow (Levin, 1991), which means a lower flow at a given pressure. If a flow is laminar or turbulent is determined both by the velocity of the medium and the geometry and surfaces in the gap where the medium flows. A flow remains laminar at higher velocities inside smooth rounded systems compared to systems that contain sharp edges. An airflow turns from laminar to turbulent when the velocity exceeds a critical limit. Whether a flow is laminar or turbulent is also theoretically determined by the Reynolds number (Prandtl and Tietjens, 1934) expressed as:

$$\mathrm{Re} = \frac{\rho \cdot v_{\mathrm{ag}} \cdot d_h}{\eta} \tag{5}$$

where:

d_{h} $= 0.05\,\mathrm{m}$;

η $= 15 \cdot 10^{-6}$; and

r $= 1.2\,\mathrm{kg/m^3}$.

In these experiments, the density ρ, the hydraulic diameter d_{h}, and the viscosity η are considered to be almost constant so the Reynolds number varies only with the velocity v. The hydraulic diameter d_{h} is considered to be two times the width of the air gap (Johannesson, 2006), which in this case is 0.025 m.

The velocity was measured at the air inlet, see point 11 in Figure 1, which is 10 mm wide. The vertical air gap inside the wall is 0. m wide and because of geometry the velocity of the air flow should here be 40 per cent of the velocity by the inlet. The possibility of turbulence ought to be higher at the inlet.

An airflow is considered to be stable laminar, when the Reynolds number is less than 2,300 (Johannesson, 2006). Stable turbulent flows occur when the Reynolds number exceeds 10,000. These values are valid for ducts, which do not have the same geometry as an air gap system. In this study the Reynolds number is calculated for the highest air velocity v_{max} found among the measurements.

Turbulent air flow and the stack equation

A turbulent airflow can be described by the stack equation and there are a number of different expressions that describe this effect, (Foster and Down, 1987, *Ashrae Handbook Fundamentals*, 2005 and Skistad, 1995). Skistad's (1995) equation (equation (6)) is chosen for this work because it refers to inlet and outlet areas that are small and of equal area. This expression also displays airflow as a function of inlet area and ΔT, the average difference between the air gap and room temperature, this ΔT is measured and calculated in this paper:

$$Q = \mu \cdot A \cdot \sqrt{\frac{g \cdot \Delta T \cdot H}{T}} \tag{6}$$

where:

A $= 0.01\,\mathrm{m}$;

g $= 9.81\,\mathrm{m/s^2}$; and

H $= 2.3\,\mathrm{m}$.

The equation describes the airflow generated by passive ventilation (Skistad, 1995; *Ashrae Handbook Fundamentals*, 2005). The contraction factor μ is an empirical constant which depends on the geometry of the air gap. For instance, a chimney usually has a μ-factor between 0.6 and 0.7. Equation (6) is valid for turbulent flow under normal circumstances according to passive ventilation. If the air flow according to the Air Gap Method is turbulent, μ should have the same value irrespective of the level of the air flow. Equation (6) gives:

$$\mu = \frac{Q}{A \cdot \sqrt{\frac{g \cdot \Delta T \cdot H}{T}}}. \tag{7}$$

μ-factors will here be calculated from the results from the different temperature and air flow measurements. If these values are homogeneous the airflow could be considered to be turbulent.

The initial phase

When the heating cable is switched on, it will probably take some time before temperature and air velocity become stable. The duration of this unstable phase was investigated by measurements of air velocity and temperature.

The temperature sensors were placed in the centre of the air gap at the heights 0.05 and 0.35 m above the heating cable. The room temperatures were measured simultaneously at the same heights and these sensors were placed 0.01 m from the surface of the wall.

In this part of the study, temperature was measured every five minutes both inside the air gap and at the corresponding heights in the room, during a time lapse of 60 minutes. The difference in temperature dT was calculated for each height and time. The air velocity at the inlet was measured at equal intervals during the same time. This investigation was carried out during a separate day before the main study.

Results

Heating cables

Results from measurements of the power of the heating cables are presented in Table II. There were no differences in power regardless of whether the cable had been switched on for one hour or two, but it was found that a low room temperature led to a higher power of the heating cable as the manufacturer stated. The power ratio between the different days is 1.2 for all sets of cables meaning that the power is 20 per cent higher on the day with the lower room temperature. This agrees with the principal information from the manufacturer although the company has not provided any data of this ratio.

Table II. Length, voltage and amperage. Calculated power and power/m for T-18, G-15 and combination of both, according to cable measuring days

Date	T_{R1} (C)	Cable	l_{Cab} (m)	U (V)	I (A)	q_{Tot} (W)	q (W/m)
Day 1	15.0	T-18	6.0	217.5	0.43	93.3	*15.5*
Day 1	15.0	G-15	5.8	217.5	0.18	39.5	*6.8*
Day 1	15.0	Both cables		217.5	0.61	132.8	*22.3*
Day 2	17.4	T-18	6.0	217.3	0.36	78.4	*13.0*
Day 2	17.4	G-15	5.8	217.3	0.15	33.7	*5.7*
Day 2	17.4	Both cables		217.3	0.51	112.6	*18.7*

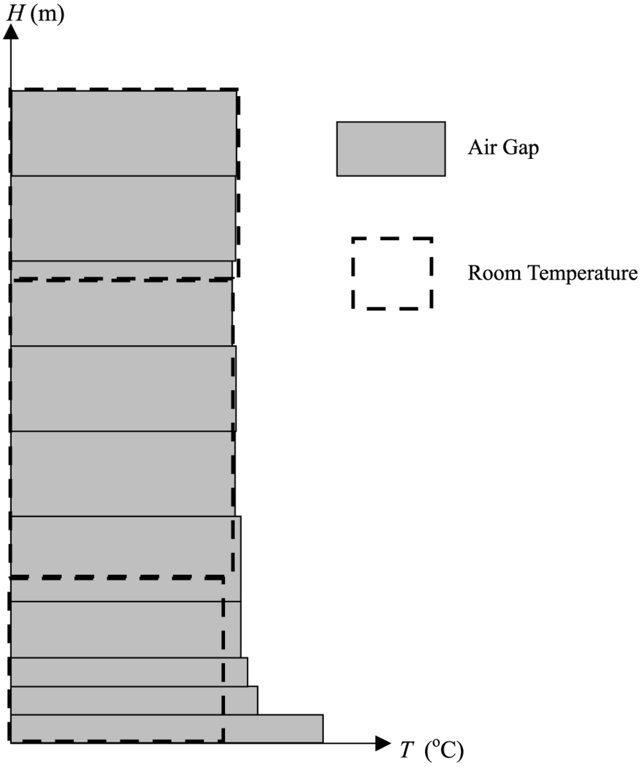
Temperature

The heating cable creates a temperature difference, ΔT, between the air gap and the room temperatures. This difference is shown by overlapping histograms, see Figure 2, showing data from Table III. The shaded horizontal bars show the air gap temperatures T_1-T_{10} and the transparent blocks show the room temperatures T_{R1}-T_{R3}. The air gap temperature exceeds the room temperature in the lower part of the wall, as could be expected because of the heating cable. ΔT is given by the area of the shaded bars minus the area of the transparent bars and divided by the height of the wall. This is calculated in equation (3).

All the temperature data for each day and each heating cable settings are given in Tables III-X and all values of ΔT are also displayed in Table XI.

Temperature difference ΔT

The values of ΔT are shown in Table XI. The measurements are displayed in time order, which means that they started with number 1 and ended with number 10. The values show a rather big disparity in the measured series for the same set of cable, with ratios up to 1.76 between the highest and lowest values in the same sequence. There is



Notes: Histogram over temperature in air gap (shaded bars) and in room (inside dashed lines). The data are taken from Table 4 nr 1

Figure 2. Histogram over temperature in air gap (shaded bars) and in room (inside dashed lines)

Table III.
Temperatures inside air gap and exterior air gap together with ΔT – Day 1: no heating cable switched on

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_R	ΔT
1	17.5	16.6	16.5	16.3	16.5	16.1	16.2	16.1	16.3	16.3	16.34	15.7	16.2	16.5	16.16	0.18
2	17.3	16.6	16.5	16.4	16.4	16.1	16.2	16.1	16.35	16.35	16.34	15.8	16.2	16.6	16.22	0.12
3	17.1	16.5	16.7	16.6	16.3	16.1	16.7	16.1	16.35	16.35	16.40	16.0	16.3	16.6	16.31	0.09
4	17.1	16.5	16.7	16.4	16.3	16.1	16.2	16.1	16.4	16.4	16.33	16.1	16.3	16.7	16.37	−0.04
5	17.1	16.5	16.7	16.4	16.3	16.1	16.2	16.2	16.45	16.45	16.36	16.1	16.3	16.7	16.37	−0.01
6	17.3	16.6	16.7	16.4	16.3	16.1	16.2	16.1	16.35	16.35	16.33	15.7	16.3	16.6	16.24	0.09
7	17.1	16.4	16.8	16.4	16.3	16.1	16.2	16.1	16.4	16.4	16.33	16.1	16.3	16.7	16.37	−0.04
8	17.2	16.3	16.8	16.4	16.1	16.3	16.2	16.1	16.4	16.4	16.33	16.1	16.3	16.7	16.37	−0.04
9	17.1	16.5	16.7	16.6	16.3	16.1	16.2	16.1	16.35	16.35	16.34	16.0	16.3	16.6	16.31	0.03
10	17.1	16.6	16.7	16.4	16.3	16.2	16.2	16.2	16.45	16.45	16.37	16.1	16.3	16.7	16.37	0.00

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table IV.
Temperatures inside air gap and exterior air gap together with ΔT – Day 1: T-18 switched on, 15.5 W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_R	ΔT
1	22.0	17.4	16.7	16.2	16.2	15.8	15.9	15.6	15.85	15.85	16.27	15.1	15.7	16.1	15.67	0.54
2	22.1	17.5	16.7	16.4	16.3	15.8	15.9	15.6	15.85	15.85	16.30	15.1	15.8	16.1	15.71	0.59
3	22.1	17.6	17.2	16.7	16.2	15.9	15.9	15.6	15.9	15.9	16.37	15.1	15.8	16.2	15.74	0.63
4	22.1	17.6	17.1	16.6	16.5	16.0	15.9	15.6	15.9	15.9	16.41	15.1	15.8	16.2	15.74	0.67
5	21.6	17.2	16.6	16.2	16.1	15.7	15.7	15.5	15.75	15.75	16.14	14.8	15.7	16.0	15.56	0.58
6	21.9	17.5	16.9	16.1	16.2	15.8	15.8	15.7	15.9	15.9	16.28	15.1	15.7	16.1	15.68	0.60
7	22.0	17.6	16.7	16.4	16.2	15.9	15.9	15.6	15.85	15.85	16.30	15.1	15.8	16.1	15.71	0.69
8	21.9	17.8	17.2	16.7	16.2	16.0	15.9	15.6	15.9	15.9	16.38	15.1	15.8	16.2	15.74	0.64
9	22.0	17.5	17.3	16.6	16.4	16.1	15.9	15.6	15.9	15.9	16.41	15.1	15.8	16.2	15.74	0.67
10	22.0	17.4	17.0	16.3	16.1	15.9	15.7	15.4	15.9	15.9	16.25	15.1	15.9	16.4	15.85	0.40

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table V.
Temperatures inside air gap and exterior air gap together with ΔT – Day 1: G-15 switched on, 6.8–W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_R	ΔT
1	18.5	17.1	16.6	16.1	16.2	16.1	16.4	16.2	16.2	16.2	16.36	15.3	16.0	16.2	15.88	0.48
2	18.5	17.0	16.5	16.1	16.2	16.2	16.4	16.2	16.25	16.25	16.38	15.4	16.1	16.3	15.98	0.40
3	18.4	17.0	16.4	16.1	16.2	16.2	16.3	16.2	16.35	16.35	16.38	15.4	16.1	16.5	16.04	0.37
4	18.6	16.9	16.4	16.1	16.2	16.4	16.3	16.2	16.35	16.35	16.41	15.4	16.1	16.5	16.04	0.40
5	18.4	16.9	16.4	16.1	16.3	16.3	16.3	16.2	16.35	16.35	16.40	15.4	16.1	16.5	16.04	0.39
6	18.5	17.1	16.6	16.1	16.4	16.5	16.6	16.2	16.25	16.25	16.48	15.4	16.0	16.3	15.94	0.54
7	18.5	17.1	16.4	16.1	16.2	16.2	16.4	16.2	16.25	16.25	16.38	15.4	16.1	16.3	15.98	0.40
8	18.6	17.0	16.2	16.1	16.2	16.2	16.3	16.2	16.35	16.35	16.38	15.4	16.1	16.5	16.04	0.34
9	18.5	16.9	16.5	16.0	16.2	16.4	16.3	16.2	16.35	16.35	16.40	15.4	16.1	16.5	16.04	0.36
10	18.4	16.9	16.3	16.2	16.3	16.5	16.3	16.2	16.35	16.35	16.43	15.4	16.1	16.5	16.04	0.39

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table VI. Temperatures inside air gap and exterior air gap together with ΔT – Day 1: both heating cables switched on, 22.3 W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_{R}	ΔT
1	22.1	17.5	16.8	16.2	16.5	16.1	16.4	16.8	16.3	16.3	16.70	15.6	15.4	15.8	15.57	1.13
2	22.6	17.5	16.9	16.4	16.6	16.1	16.7	16.7	16.25	16.25	16.77	15.6	15.4	15.8	15.57	1.20
3	22.3	17.5	17.0	16.4	16.6	16.3	16.7	16.7	16.25	16.25	16.78	15.6	15.4	15.8	15.57	1.21
4	21.8	17.4	16.8	16.2	16.4	16.2	16.6	16.8	16.3	16.3	16.70	15.6	15.4	15.8	15.57	1.13
5	21.5	17.4	16.8	16.1	16.4	16.2	16.5	16.8	16.3	16.3	16.67	15.6	15.4	15.8	15.57	1.10
6	22.4	17.6	17.3	16.5	16.6	16.2	16.7	16.7	16.35	16.35	16.83	15.7	15.5	16.0	15.70	1.13
7	22.6	17.5	17.2	16.4	16.6	16.2	16.6	16.7	16.3	16.3	16.79	15.6	15.5	15.9	15.64	1.15
8	22.5	17.7	17.1	16.5	16.6	16.3	16.6	16.7	16.35	16.35	16.85	15.7	15.5	16.0	15.70	1.15
9	22.4	17.7	17.3	16.4	16.7	16.1	16.5	16.8	16.35	16.35	16.81	15.6	15.5	15.9	15.64	1.17
10	22.6	17.5	17.4	16.4	16.7	16.2	16.4	16.7	16.3	16.3	16.79	15.6	15.5	15.9	15.64	1.16

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table VII. Temperatures inside air gap and exterior air gap together with ΔT – Day 2: no heating cable switched on

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_{R}	ΔT
1	16.4	16.5	16.6	16.5	16.6	16.6	16.7	16.7	17.0	17.2	16.74	16.1	16.9	17.3	16.82	−0.08
2	16.4	16.5	16.6	16.5	16.6	16.6	16.7	16.7	17.0	17.2	16.74	16.1	16.8	17.3	16.77	−0.03
3	16.4	16.5	16.6	16.5	16.6	16.6	16.7	16.7	17.0	17.2	16.74	16.1	16.8	17.3	16.77	−0.03
4	16.4	16.5	16.6	16.5	16.6	16.6	16.7	16.7	17.0	17.3	16.75	16.1	16.8	17.4	16.80	−0.05
5	16.4	16.5	16.6	16.5	16.7	16.6	16.7	16.7	17.0	17.3	16.76	16.1	16.8	17.4	16.80	−0.04
6	16.4	16.5	16.6	16.5	16.7	16.6	16.7	16.8	17.0	17.3	16.77	16.1	16.8	17.4	16.80	−0.03
7	16.4	16.5	16.6	16.5	16.7	16.6	16.7	16.8	17.0	17.3	16.77	16.1	16.9	17.5	16.88	−0.11
8	16.4	16.5	16.6	16.5	16.7	16.6	16.7	16.8	17.1	17.3	16.79	16.2	16.9	17.5	16.90	−0.11
9	16.4	16.5	16.6	16.5	16.7	16.6	16.8	16.8	17.1	17.3	16.80	16.2	16.9	17.5	16.90	−0.12
10	16.5	16.6	16.6	16.6	16.7	16.6	16.8	16.8	17.1	17.3	16.82	16.2	16.9	17.5	16.90	−0.08

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table VIII. Temperatures inside air gap and exterior air gap together with ΔT – Day 2: T-18 switched on, 13 W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_{R}	ΔT
1	23.3	19.8	19.4	18.5	18.5	18.1	17.7	17.8	17.9	17.5	18.35	17.7	17.9	18.1	17.91	0.44
2	23.6	19.8	19.0	18.3	18.3	18.1	17.7	17.8	18.0	17.5	18.31	17.7	18.0	18.1	17.95	0.36
3	23.7	19.8	18.9	18.3	18.4	18.1	17.8	17.8	18.0	17.5	18.33	17.7	18.0	18.1	17.95	0.38
4	23.7	19.8	19.1	18.4	18.4	18.1	17.7	17.7	17.9	17.4	18.32	17.8	18.0	18.1	17.99	0.34
5	23.7	19.7	18.9	18.3	18.5	18.2	17.8	17.8	18.0	17.5	18.36	17.7	17.9	18.1	17.91	0.45
6	23.3	19.7	18.9	18.4	18.7	18.3	17.5	17.9	18.0	17.5	18.37	17.8	18.0	18.1	17.98	0.39
7	23.6	19.6	19.0	18.4	18.8	18.2	17.4	17.9	17.9	17.6	18.37	17.7	18.0	18.2	17.98	0.39
8	23.7	19.7	19.1	18.5	18.7	18.2	17.5	17.8	18.0	17.6	18.39	17.7	18.0	18.2	17.98	0.41
9	23.9	19.7	19.1	18.5	18.7	18.2	17.6	17.8	18.0	17.6	18.41	17.7	18.0	18.2	17.98	0.43
10	23.3	19.8	19.2	18.6	18.7	18.2	17.6	17.8	18.0	17.6	18.40	17.7	18.1	18.2	18.03	0.37

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table IX. Temperatures inside air gap and exterior air gap together with ΔT – Day 2: G-15 switched on, 5.8 W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_{R}	ΔT
1	20.1	18.9	18.5	18.2	18.3	18.2	17.8	17.8	17.9	18.0	18.17	18.0	18.0	18.0	18.0	0.17
2	20.6	18.9	18.5	18.2	18.3	18.2	17.8	18.1	18.0	18.0	18.24	18.0	18.0	18.0	18.0	0.24
3	20.6	18.8	18.5	18.2	18.3	18.2	18.1	18.2	18.0	18.0	18.29	18.0	18.1	18.0	18.05	0.24
4	20.1	18.8	18.5	18.2	18.3	18.2	18.2	18.2	18.0	18.0	18.28	18.0	18.1	18.0	18.05	0.23
5	20.0	18.7	18.5	18.2	18.2	18.6	17.8	18.2	18.0	18.0	18.26	18.2	18.0	18.0	18.05	0.21
6	19.9	18.8	18.5	18.2	18.3	18.5	18.2	18.3	18.0	18.0	18.33	18.1	18.0	18.0	18.03	0.30
7	19.6	18.7	18.5	18.2	18.5	18.4	18.1	18.3	18.1	18.0	18.32	18.0	18.1	18.0	18.05	0.27
8	19.6	18.7	18.5	18.2	18.4	18.5	18.1	18.2	18.1	18.0	18.31	18.0	18.0	18.0	18.0	0.31
9	19.6	18.6	18.6	18.3	18.5	18.5	18.1	18.2	18.1	18.0	18.33	18.1	18.0	18.0	18.03	0.30
10	19.6	18.7	18.7	18.3	18.3	18.5	18.2	18.2	18.1	18.0	18.33	18.1	18.0	18.0	18.03	0.30

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table X. Temperatures inside air gap and exterior air gap together with ΔT – Day 2: both heating cables switched on, 18.7 W/m

Nr	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{AG}	T_{R1}	T_{R2}	T_{R3}	T_{R}	ΔT
1	23.4	18.9	18.4	17.7	17.9	17.6	17.1	17.9	18.1	18.0	18.08	16.9	17.5	17.9	17.47	0.61
2	23.7	19.0	18.4	17.9	18.0	17.7	17.1	17.8	18.2	18.1	18.16	17.0	17.5	18.0	17.52	0.64
3	23.3	19.0	19.1	18.2	18.0	17.8	17.1	17.8	18.1	18.1	18.20	17.0	17.5	18.0	17.52	0.68
4	23.2	19.2	18.9	18.2	18.0	17.6	17.2	17.8	18.1	18.1	18.18	17.0	17.6	18.0	17.57	0.64
5	23.7	19.2	19.4	18.5	18.2	17.9	17.2	17.9	18.2	18.1	18.34	17.0	17.5	17.9	17.49	0.85
6	24.4	19.3	18.9	18.2	18.1	17.8	17.2	17.9	18.1	18.1	18.29	17.0	17.6	18.1	17.60	0.69
7	24.3	19.3	19.2	18.3	18.1	17.7	17.2	17.9	18.1	18.1	18.29	17.1	17.6	18.0	17.59	0.70
8	24.0	19.4	19.4	18.7	18.1	17.8	17.3	17.9	18.0	18.1	18.34	17.1	17.6	18.0	17.59	0.75
9	24.3	19.5	19.4	18.6	18.3	18.0	17.3	17.9	18.1	18.2	18.43	17.1	17.6	18.0	17.59	0.84
10	23.7	19.5	19.1	18.5	18.3	17.9	17.3	18.0	18.2	18.2	18.39	17.1	17.6	18.0	17.59	0.80

Notes: No measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XI. Values of ΔT for each series – Day 1, no heating cable switched on

Nr	No C. D1	No C. D2	G-15 D1	G-15 D2	T-18 D1	T-18 D2	Bo. C. D 1	Bo C. D 2
1	0.18	− 0.08	0.48	0.17	0.54	0.44	1.13	0.61
2	0.12	− 0.03	0.40	0.24	0.59	0.36	1.20	0.64
3	0.09	− 0.03	0.37	0.24	0.63	0.38	1.21	0.68
4	− 0.04	− 0.05	0.40	0.23	0.67	0.34	1.13	0.64
5	− 0.01	− 0.04	0.39	0.21	0.58	0.45	1.10	0.85
6	0.09	− 0.03	0.54	0.30	0.60	0.39	1.13	0.69
7	− 0.04	− 0.11	0.40	0.27	0.69	0.39	1.15	0.70
8	− 0.04	− 0.11	0.34	0.31	0.64	0.41	1.15	0.75
9	0.03	− 0.12	0.36	0.30	0.67	0.43	1.17	0.84
10	0.00	− 0.08	0.39	0.30	0.40	0.37	1.13	0.80
Average	*0.04*	*− 0.07*	*0.41*	*0.26*	*0.60*	*0.40*	*1.15*	*0.72*
Ratio H/L			*1.59*	*1.760*	*1.73*	*1.32*	*1.1*	*1.39*

Notes: "No C." stands for no cable, and "Bo. C" stands for G-15 and T-18 switched on together. D 1 and D 2 stand for day 1 and day 2 respectively; ratio H/L stands for ratio between the highest and the lowest value also a big disparity between the different days, giving lower values for day 2 compared to day 1. The ratios between day 1 and day 2 are 1.6 for G-15, 1.5 for T-18 and 1.6 for both cables.

Quantity of air flow

Air flow versus ΔT. The average airflow is calculated from the air velocity by the equation (4) and displayed in Table XII. These values are more homogenous, compared to the Delta;*T* values in Table XI, it is only the G-15 values on day 2 that have wider dispersion, which could be because this measured range came close to the lower detection limit of the anemometer. The G-15 also shows a large difference between day 1 and day 2 compared to the other measurements. The ratios between day 1 and day 2 are 1.5 for G-15, 1.2 for T-18 and 1.2 for both cables. Table XII shows only the average values of airflow and all the measurement results are displayed in Tables XIII-XX.

The airflow is also plotted against the Delta;*T* in Figure 3. The diagram shows rather widely dispersed values, but it is clear that flow increases with rising Delta;*T* between the air gap and the room.

Characteristics of air flow

Reynolds number. The highest air velocity obtained in all measurements was $v_{\max} = 0.25\,\mathrm{m/s}$, at day 1, nr 2, see Table XVII. This value was measured when both cables were switched on and the laboratory temperature was 15.6°C. This air velocity was measured at the inlet, but the geometry of the construction suggests that velocity in the air gap should be 40 per cent of the inlet velocity (as described above under the heading "Experimental Studies"). The maximal velocity inside the air gap was thus approximately 0.10 m/s.

Using equation (5), the Reynolds number turns out to be 400, which is well below the limit of 2,300 and the air flow ought to be stable laminar according to air velocity at least inside the air gap.

Nr	No C. D1	No C. D2	G-15 D1	G-15 D2	T-18 D1	T-18 D2	Bo. C. D 1	Bo C. D 2
1	0	0	9.5	8.0	16.0	13.2	21.0	18.5
2	0	0	10.2	7.1	16.0	13.2	20.6	18.5
3	0	0.3	9.3	5.6	15.7	14.5	20.6	17.3
4	0.7	0	9.5	5.8	14.8	13.9	20.1	17.6
5	0.3	0.3	9.3	5.8	16.0	13.9	21.3	16.9
6	0	0.7	9.3	7.1	17.9	13.6	20.6	17.3
7	1	0.3	9.3	6.2	16.7	14.5	20.6	17.9
8	0	0	9.5	6,5	15.7	13.2	19.4	17.9
9	0	0.7	10.2	5.3	16,9	13.2	21.3	18.5
10	0	0.3	9.5	5.8	15.7	13.2	20.1	17.9
Av. $Q \cdot 10^4$ (m^3/s)	*0.2*	*0.3*	*9.5*	*6.3*	*16.2*	*13.6*	*20.5*	*17.8*
Av. QD ($m^3/24\,h$)	*1.9*	*2.8*	*82*	*54*	*140*	*118*	*177*	*154*
Ratio H/L			*1.1*	*1.5*	*1.2*	*1.1*	*1.1*	*1.1*

Notes: No C. stands for no cable, and Bo. C stands for G-15 and T-18 switched on together. D 1 and D 2 stands for day 1 and day 2 respectively; Ratio H/L stands for ratio between the highest and the lowest value

Table XII. Values of average air flow ($Q \cdot 10^4\,\mathrm{m^3/s}$) per metre wall for each series

Table XIII.
ΔT and measured and average air flow at air inlet – Day 1, no cable switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	0.18	0	0	0	0
2	0.12	0	0	0	0
3	0.09	0	0	0	0
4	−0.04	0	0	2	0.7
5	−0.01	1	0	0	0.3
6	0.09	0	1	0	0.3
7	−0.04	0	0	0	0
8	−0.04	1	2	0	1
9	0.03	0	0	0	0
10	10 0.00	0	0	0	0
Average	0.04	0.2	0.3	0.2	0.2

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XIV.
ΔT and measured and average air flow at air inlet – Day 1, T-18 switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	0.54	18	17	17	17.3
2	0.59	18	17	17	17.3
3	0.63	17	16	18	17
4	0.67	17	16	15	16
5	0.58	17	17	18	17.3
6	0.60	20	19	19	19.3
7	0.69	18	18	18	18
8	0.64	17	17	17	17
9	0.67	18	19	18	18.3
10	0.40	17	17	17	17
Average	*0.60*	*17.7*	*17.3*	*17.4*	*17.5*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XV.
ΔT and measured and average air flow at air inlet – Day 1, G-15 switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	0.48	10	10	11	10.3
2	0.40	11	11	11	11
3	0.37	12	10	8	10
4	0.40	10	11	10	10.3
5	0.39	10	10	10	10
6	0.54	10	10	10	10
7	0.40	9	11	10	10
8	0.34	11	10	10	10.3
9	0.36	11	11	11	11
10	0.39	10	11	10	10.3
Average	*0.41*	*10.4*	*10.5*	*10.1*	*10.3*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XVI. ΔT and measured and average air flow at air inlet – Day 1: both heating cables switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	1.13	23	23	22	22.7
2	1.20	20	25	22	22.3
3	1.21	22	23	22	22.3
4	1.13	22	20	23	21.7
5	1.10	23	23	23	23
6	1.13	22	23	22	22.3
7	1.15	23	22	22	22.3
8	1.15	19	22	22	21
9	1.17	22	22	25	23
10	1.13	22	24	19	21.7
Average	*1.15*	*21.8*	*22.7*	*22.2*	*22.2*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XVII. ΔT and measured and average air flow at air inlet – Day 2: no heating cable switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) Average
1	-0.08	0	0	0	0
2	-0.03	0	0	0	0
3	-0.03	1	0	0	0.3
4	-0.05	0	0	0	0
5	-0.04	0	1	0	0.3
6	-0.03	2	0	0	0.7
7	-0.11	0	1	0	0.3
8	-0.11	0	0	0	0
9	-0.12	2	0	0	0.7
10	-0.08	0	1	0	0.3
Average	*− 0.07*	*0.5*	*0.3*	*0*	*0.3*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XVIII. ΔT and measured and average air flow at air inlet – Day 2, T-18 switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	0.44	15	14	14	14.3
2	0.36	14	15	14	14.3
3	0.38	15	15	16	15.7
4	0.34	15	15	15	15
5	0.45	15	15	15	15
6	0.39	14	15	15	14.7
7	0.39	15	15	16	15.7
8	0.41	14	14	15	14.3
9	0.43	14	14	15	14.3
10	0.37	15	14	14	14.3
Average	0.40	14.6	14.6	14.9	14.7

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XIX.
ΔT and measured and average air flow at air inlet – Day 2, G-15 switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) average
1	0.17	8	9	8	8.7
2	0.24	6	9	7	7.7
3	0.24	8	6	4	6
4	0.23	6	6	7	6.3
5	0.21	6	8	5	6.3
6	0.30	8	7	8	7.7
7	0.27	6	6	8	6.7
8	0.31	8	6	7	7
9	0.30	6	5	6	5.7
10	0.30	7	7	5	6.3
Average	*0.26*	*6.9*	*6.9*	*6.5*	*6.8*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

Table XX.
ΔT and measured and average air flow at air inlet – Day 2, both heating cables switched on

Nr	ΔT (C)	$Q_1 \cdot 10^4$ (m^3/s)	$Q_2 \cdot 10^4$ (m^3/s)	$Q_3 \cdot 10^4$ (m^3/s)	$Q \cdot 10^4$ (m^3/s) Average
1	0.61	20	20	20	20
2	0.64	19	20	21	20
3	0.68	19	18	19	18.7
4	0.64	19	19	19	19
5	0.85	19	18	18	18.3
6	0.69	18	19	19	18.7
7	0.70	19	19	20	19.3
8	0.75	19	19	20	19.3
9	0.84	19	21	20	20
10	0.80	20	18	20	19.3
Average	*0.72*	*19.1*	*19.0*	*19.6*	*19.2*

Notes: See point 11 Figure 1; no measurements were taken at level 185 and 215 cm during day 1; for the calculation part the average measure between T_{R3} and T_8 was used for those levels

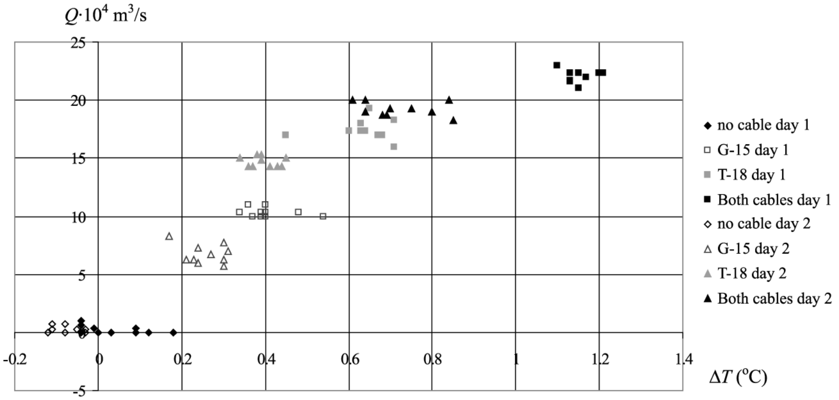


Figure 3.
Airflow versus ΔT

Stack equation. Equation (7) gives the μ-values for data, presented in Tables II and III. The average value of these calculations is 0.71 (see Table XXI). This value lies almost in line with ordinary μ values which are in the range of 0.6-0.7. However this calculated μ value show a great variation from 0.48 to 0.83 and this implies that the measured conditions do not actually correlate to the stack equation. This in its turn implies that the airflow is not turbulent. However, if the values from the weaker G-15 cable are excluded, the μ-values coincide rather well.

The initial phase. Shortly after the heating cable has been switched on, the air velocity is zero while temperatures start to rise directly inside the air gap reaching a maximum after 30 minutes. It then reduces to a lower stable value after about 45 minutes (see Figure 4). The air velocity is still zero, five minutes after that the heating cable is turned on and it takes about 45 minutes for the velocity to reach the stable highest level 17-18 cm/second (see Figure 5).

Discussion

Temperature

It is difficult to measure temperatures within a tenth of a degree Celsius. Lamps and the personnel conducting the investigation add heat to the system and an unexpected

Cable	Day	$Q \cdot 10^4$ (m^3/s) average	ΔT (K) average	H (m)	μ
T-18	1	17.5	0.60	2.3	0.81
G-15	1	10.3	0.41	2.3	0.58
Both cables	1	22.2	1.15	2.3	0.74
T-18	2	14.7	0.40	2.3	0.83
G-15	2	6.8	0.26	2.3	0.48
Both cables	2	19.2	0.72	2.3	0.81
Average all					*0.71*
Average T-18/both C					*0.80*

Table XXI. Calculation of μ from average air flow Q, height of section of heated air H and increased mean temperature in this section, ΔT

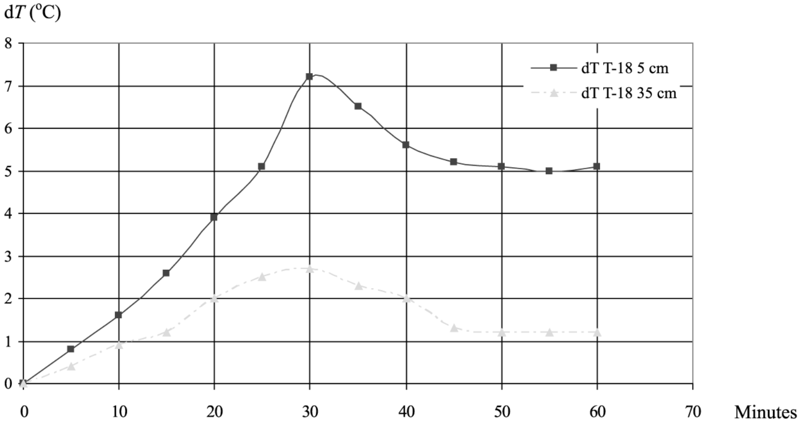


Figure 4. Temperature difference P versus time at the height of 5 and 45 cm above heating cable

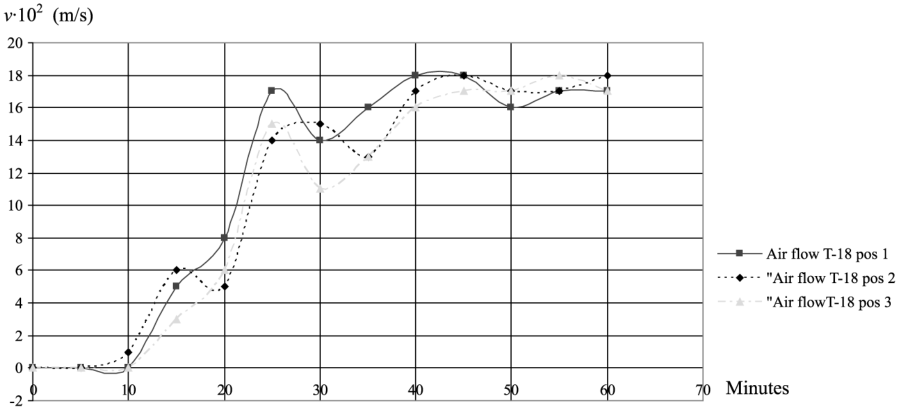


Figure 5.
Air velocities versus time

draught may change the basis for the experiment. General measurement conditions are rather insecure and therefore the dispersed results as shown in Table XXI could perhaps be anticipated.

It is noted in Table XXI that ΔT for the T-18 cable for day 2 (0.40°C) is almost the same as ΔT for the G-15 for day 1 (0.41°C) although the air flow is not the same, but $14.7 \cdot 10^{-4}\,\mathrm{m}^3/\mathrm{s}$ versus $10.3 \cdot 10^{-4} - \mathrm{m}^3/\mathrm{s}$.

There are also unexpected results that may point out how future studies should be carried out. In Table VI, the values of T_7 and T_8 are considerable higher than the corresponding values in the room $T_{\mathrm{R}2}$ and $T_{\mathrm{R}3}$. It seems like there is a warmer air bubble somewhere in the air gap. If we imagine that the airflow meanders up inside the wall the flow will distribute temperature differences inside the wall. One conclusion is that it could be of interest to take measurements over the entire area of the wall, not just along one vertical line.

Airflow

The air flow measurements for each day do not vary that greatly, it is only the values for the G-15 cable during day 2 that show a greater dispersion and that may be because these values come close to the lower detection limit of the hot wire anemometer.

However the airflow per day varies between 50 and 80 m^3/meter wall for G-15, between 120 and 140 m^3/meter wall for T-18 and between 150 and 180 m^3/metre wall for both cables together. As the volume of 1 metre run of wall is 0.16 m^3 this gives an air change rate between 13-21 times for the G-15 cable and 31-36 times for the stronger T-18 cable.

Air flow versus ΔT

There is a clear null result. If the heating cable is switched off, there is no increased temperature in the air gap, ΔT and there is no measurable air flow either. The results in Tables XI and XII show a rather great disparity of the temperature values and this could be due to either insecure measurement or to the fact that it is only one vertical position that has been measured.

It may be noted that even a low raise of temperature ($\Delta \mathrm{T} = 0.26$°C for G 15 day 2) results in an air flow of approximately 50 m^3/metre wall. This is the vertical air flow inside one metre wall, which has an inside volume of approximately 0.16 m^3. The air change rate per hour is around 13 times for the G-15 case, day 2.

Air gap method inside a bathroom

The results indicate that it would be possible to obtain an airflow without a heating cable in some cases. Considering that it is quite possible to obtain an air flow, 50 m^3 per m wall and day, by a rather small temperature difference, 0.26°C, it may be enough if there is a minor temperature difference between rooms.

For instance, if an air gap system were to be used inside an ordinary bathroom wall, the air inlets and outlets would be situated at the rear side of the wall in the neighbouring room. It is quite possible that the bathroom temperature differs from the surrounding rooms resulting in a different air gap temperature from the temperature of these neighbouring rooms. In this case it would not be necessary to use a heating cable.

Measurements versus stack equation

The stack equation is an empirical equation describing passive ventilation with turbulent type of airflow. The slow airflow inside the air gap described above is presumably laminar according to the Reynolds number and the disparity of the μ-factor. However if we use the average value of the μ-factor $= 0.8$ taken from the T-18 and "both cables" measurements, we will obtain a curve that fits fairly well with the measurements of those cables, see Figure 6. The conclusion may be that the airflow could be turbulent if the velocity rises and this turbulence could be due to geometry such as sharp edges in the air inlet rather than velocity, because the calculated values of the Reynolds number are still low.

Conclusions

This experimental study of important factors relating to the Air Gap Method in wall construction has resulted in a number of useful results and conclusions. It is found that:

- The measured airflow reaches values up to 140 m^3/metre wall and day for the stronger T-18 cable.
- A low raise of temperature, $\Delta T = 0.2$ to 0.3°C inside the vertical air gap results in an air flow of approximately 50 m^3/metre wall and day.

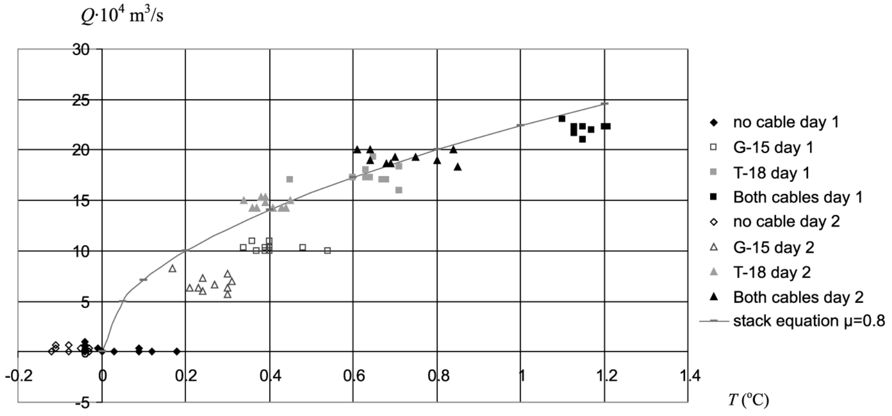


Figure 6.
Air flow versus ΔT, together with stack equation

- The air change rate per hour for the air inside the wall construction varies between 13 times for the G-15 cable and 36 times for the stronger T-18 cable.
- The airflow increases with raised temperature difference between air gap and room.
- The airflow increases with raised power of heating cable.
- The airflow is theoretically laminar due to the velocity of the air, some of the data, however, align to the stack equation, which indicates that it is partly turbulent

For optimising the air flow the construction should be designed to avoid turbulent flow.

Further work

This study focuses on the airflow in a wall construction. One future study will be to investigate the air flow in a complete construction built by the Air Gap Method with air gaps in both wall and floor units. Now it is hard to measure such a flow, because we have not found any measuring instrument that manages to detect the low air velocities to be anticipated. Another future study is to investigate what will be the required power of the heating cable to obtain a certain airflow.

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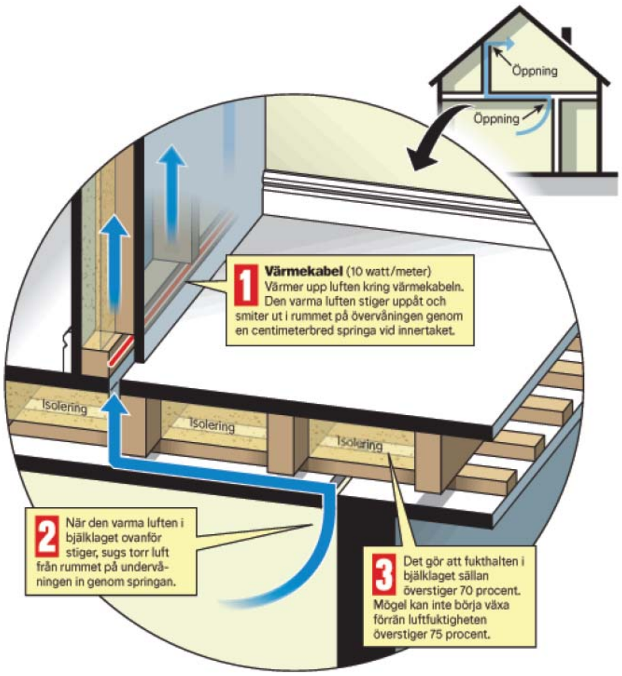
Heated Air Gaps

A Possibility to dry out Dampness
from Building Constructions

Tord af Klintberg



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