Distribution of Ventilation Air and Heat by Buoyancy Forces Inside Buildings

An experimental study

Doctoral thesis

by

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Abstract

The main task of the ventilation system in a building is to maintain the air quality and (together with the heating or cooling system) the thermal climate at an acceptable level within the building. This means that a sufficient amount of ventilation air at the appropriate temperature and quality must be supplied to satisfy thermal comfort and air quality demands and that this air is distributed to the parts of the building where people reside.

Air movements caused by buoyancy forces can determine the distribution of ventilation air within buildings. The purpose of this thesis is to advance the state of knowledge of buoyancy-driven air movements within buildings and to determine their importance both for ventilation air distribution and the maintenance of thermal comfort and air quality in buildings. The work is focused on studying thermally-driven air movements through large openings, both horizontal and vertical (i.e. doorways). The properties of a special type of thermally-driven currents, so called gravity currents, have also been explored.

Large vertical openings like doorways are important for air exchange between rooms within a building. Air movements through doorways separating rooms with different air temperatures are often bidirectional and the buoyancy-driven flow rates are often greater than those caused by the mechanical ventilation system alone. Bidirectional flows through doorways can effectively spread contaminants, for example, from a kitchen or a hospital rooms, yet the results of this study indicate that the conversion of a thermally-driven bidirectional flow to a unidirectional flow via an increase of the mechanically forced flow rate requires forced flows that are more than three times greater than the thermally-driven flows.

Experiments conducted in this project indicate that the resistance to buoyancy-driven flows in horizontal openings is significantly greater than that in vertical openings. Model tests have shown, however, that this problem may be mitigated if a simple model of a staircase located in the centre of the room (being ventilated) is linked to the horizontal ventilation opening.

Gravity currents in rooms occur in connection with so called displacement ventilation as cool gravity currents propagate along the floor that are driven by the density difference of the ventilation air and the ambient, warmer air within the room. As these gravity currents easily pass obstacles and to a certain extent are self-controlling, they can effectively distribute the cool air within rooms in a building.

Likewise, warm gravity currents occur when warmer air introduced in a room rises and spreads along the ceiling plane. One application where warm gravity currents may be used to advantage is when converting buildings from electric heating to district hot water heating thus, avoiding the introduction of an expensive hydronic heating system. This report includes a full-scale laboratory study of the basic properties of thermally-driven warm air gravity currents in a residential building and examines the possibilities of using the resulting air movements for the distribution of ventilation air as well as heat. Results from laboratory tests show that this conversion method may prove effective if certain conditions on the layout of the building are fulfilled.

Keywords: building ventilation, thermal forces, buoyancy, gravity currents, large openings, heating, air quality, forced convection, free convection
List of symbols

\( A \) \quad \text{area of opening} \quad [m^2]

\( Ar \) \quad \text{Archimedes number} \quad (Ar = \frac{g}{u^2}) \quad [-]

\( B \) \quad \text{buoyancy flux} \quad [m^4/s^3, m^3/s]

\( B(x) \) \quad \text{buoyancy flux at distance} \ x \quad [m^4/s^3, m^3/s]

\( c_p \) \quad \text{specific heat at constant pressure} \quad [\text{J/kg} \cdot \text{K}]

\( C \) \quad \text{proportional coefficient} \quad [-]

\( D \) \quad \text{equivalent diameter of horizontal opening} \quad [m]

\( Fr \) \quad \text{Froude number} \quad (Fr = q / \sqrt{g' \cdot D^3}) \quad [-]

\( g \) \quad \text{acceleration of gravity} \quad (g = 9.81) \quad [m/s^2]

\( g' \) \quad \text{reduced gravity} \quad (g' = g \cdot \Delta \rho / \rho = g \cdot \Delta T / T) \quad [m/s^2]

\( Gr \) \quad \text{Grashof number} \quad (Gr = g \cdot \beta \cdot \Delta T \cdot h^3 / \nu^2 = g' \cdot h^3 / \nu^2) \quad [-]

\( h \) \quad \text{height} \quad [m]

\( H \) \quad \text{height of room} \quad [m]

\( L \) \quad \text{Thickness of horizontal partition wall} \quad [m]

\( P \) \quad \text{heat load} \quad [\text{W}]

\( q \) \quad \text{volume flow rate} \quad [\text{m}^3/\text{s}, \text{l/s}]

\( T \) \quad \text{temperature} \quad [\text{°C, K}]

\( u \) \quad \text{fluid velocity} \quad [m/s]

\( w \) \quad \text{width} \quad [m]

\( W \) \quad \text{width of room} \quad [m]

Greek symbols

\( \alpha \) \quad \text{heat transfer coefficient} \quad [\text{W/m}^2 \cdot \text{K}]

\( \beta \) \quad \text{gas expansion coefficient} \quad [1/\text{K}]

\( \Delta \) \quad \text{difference} \quad [-]

\( \nu \) \quad \text{kinematic viscosity} \quad [\text{m}^2/\text{s}]

\( \rho \) \quad \text{density} \quad [\text{kg/m}^3]

Subscripts:

a \quad \text{ambient}

c \quad \text{cold}

e \quad \text{exchange}

fl \quad \text{floor}

h \quad \text{hot}

n \quad \text{neutral}

ff \quad \text{forced flow}

w \quad \text{wall}
List of papers and author's contribution

The thesis is based on the following papers:
I have initially planned the tests together with my main supervisor but I have independently made the measurements, analyzed the results and written the papers

Paper I  Blomqvist C., Sandberg M.
To what extent can one with mechanical ventilation control air motions within a building, *Proceedings of ROOMVENT ’96*, Yokohama, Japan, 1996

Paper II  Blomqvist C., Sandberg M.

Paper III  Blomqvist C., Sandberg M.

Paper IV  Blomqvist C., Sandberg M.

Paper V  Blomqvist C., Sandberg M.
A Note on Air Movements through Horizontal Openings in Buildings, *Proceedings of ROOMVENT 2002*, Copenhagen, Denmark, 2002

Paper VI  Blomqvist C., Sandberg M.

Paper VII  Blomqvist C.

The thesis also contains additional material not published earlier, reporting on a study of gravity currents passing obstacles of various heights in a scale model with water as the operating fluid (paragraph 5.2.5).

The section reporting on moisture spread from a bathroom by buoyancy-driven air movements has been translated from a licentiate thesis written in Swedish (Blomqvist, 2000).
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1. Introduction

The main task of the ventilation in a building is to keep the air quality and (together with the heating system) the thermal climate at an acceptable level within the building. This means that a sufficient amount of ventilation air at the appropriate temperature is supplied to fulfill the demands on the thermal climate and that the air is distributed to the parts of the building where people reside. The ventilation system must also meet the demands on indoor air quality in an efficient way to remove the contaminants that are emitted from building materials and from activities within the building.

The two most common principles used to ventilate residential buildings in Sweden are stack ventilation and forced extract ventilation. Both systems use extract openings located in kitchen and sanitary areas while the replacement air is taken either through porous external walls or through openings made close to the windows in rooms as far as possible from the extract openings. As the supply air is taken directly from outside without pre-heating there are frequent complaints during the cold season about cold draught caused by the incoming air.

The distribution of air in a building occurs to a large extent through doors (vertical openings) that have been left open. Horizontal openings like stairwells are also of importance for distribution of air. The air movements through large openings are caused by density differences due to temperature differences between the different parts of a multi-room building. Gravity currents are one type of thermally-driven air movements studied that have properties that could be useful for distribution of air and heat within the building.

The purpose of this work is to get extended knowledge about thermally-driven air movements within buildings and the importance of these air movements on the indoor climate of a building. The work is focused on studying thermally-driven air movements through large openings, both horizontal and vertical (i.e. doorways). Special attention has been paid to transition from bi-directional to unidirectional air movements in doorways under influence of forced flow with the aim of exploring the possibility of controlling the air motions. Experiments have also been carried out to study the impact of open bathroom doors on the humidity load on the bathroom in connection with showering and laundry drying.

The thesis includes also a study of the basic properties of thermally-driven air movements in a residential building and examination of the possibilities of using the air movements for distribution of ventilation air as well as heat to combine the heating and ventilation systems. One example is when houses with electric heating are converted to district heating, thus avoiding the introduction of an expensive hydronic system.

Buoyancy-driven flow is difficult to study. Therefore different experimental settings have been used ranging from a full-scale test apartment to different scale models with water as operating fluid. The different settings make it possible to use complementary techniques for exploring the flow. In the apartment, temperature and velocity field have been recorded. Tracer gas technique has been used to record the flow rate. In the scale models the density (temperature) difference has been simulated by using salt water. An advantage of using water as operating fluid is that the flow can easily be visualised by adding dye to the water and the density differences can be visualised by using shadowgraph technique.
2. Overview: thermal-induced flow patterns within buildings

Within rooms there are temperature differences between different masses of air. The presence of the temperature difference implies that there is a difference in density between air masses of different air temperature. Perhaps the most well known example is the temperature difference between the air close to a cold window pane during the winter and the room air. The corresponding density difference gives rise to a downdraught of cold air; see Figure 2.8. Another example is the temperature (density) difference between rooms separated by a doorway. This difference in density will cause air movements through the opening. A flow pattern will be established consisting of two layers with the warmer layer on top (see Figure 2.1) of the layer with colder air.

![Figure 2.1 Sketch of flow between rooms with different air temperatures](image)

Thermal-induced flow is also called density-driven flow because it is gravity that causes the air motion due to the difference in density, $\Delta \rho$, between air masses. The density of air is proportional to the reverse absolute temperature. Therefore the force of gravity will cause air movements in spaces where temperature differences are present. The strength of the forces is thus dependent on the density difference and is often expressed by the so-called reduced gravity, $g'$:

$$g' = g \frac{\Delta \rho}{\rho}$$

where $g$ is the acceleration of gravity and $\rho$ is the density.

Air can be regarded as an ideal gas for the small temperature differences occurring in rooms and the reduced gravity can be expressed as

$$g' = g \frac{\Delta T}{T}$$

where $\Delta T$ is the temperature difference and $T$ is the temperature expressed in Kelvin.

In this overview we will deal with the following types of thermal-induced airflows:

1. Air movements in large vertical openings
2. Air movements in large horizontal openings
3. Transport of air through two openings at different heights
4. Gravity currents

The first three types are generated by temperature differences whereas the last one is generated by supply of air, with low velocity, which is warmer or colder than the room air.
1. Air movements in large vertical openings

There are two types of thermal generated flow between two rooms connected by a large vertical opening, bulk density flow and boundary layer flow, and they are characterised by the “isothermality factor” (Scott et al., 1988).

Isothermality factor: $\frac{\Delta T}{\Delta T_w} = \frac{T_h - T_c}{T'_h - T'_c}$

$T_h$: bulk temperature in hot partition
$T_c$: bulk temperature in cold partition
$T'_h$: hot wall temperature
$T'_c$: cold wall temperature

Bulk density flow (Figure 2.2) will develop when the isothermality factor is near unity and the temperature differential between the bulk and wall temperatures is small. When the difference in temperature between the room air and the wall becomes larger, the isothermality factor approaches zero and boundary layer flow (Figure 2.3) can arise. In ventilated rooms in a building we can expect that the conditions are such that bulk density flow is predominant.

2. Air movements in large horizontal openings

In horizontal openings the flow pattern is more complex than in vertical openings. The velocity in the opening is randomly distributed (Figure 2.4) and the flow resistance becomes significantly larger than in a vertical opening. A staircase connected to the opening (Figure 2.5) may contribute to more ordered flow and subsequently somewhat lower flow resistance.
3. Transport of air through two openings at different heights

Through two openings at different levels in a partition wall between two spaces with different temperatures air will flow in opposite directions (see Figure 2.6) caused by buoyancy forces. This can be used to distribute ventilation air as well as heat due to the temperature difference that is the prerequisite for the air movements. Both flow rate and heat transfer will increase with increased temperature difference.

4. Gravity currents

A gravity current can be generated when a flow of air with a volume airflow rate \( q \) and with an air temperature different from the ambient is introduced to a room at a low momentum flux. The momentum flux is defined as \( \rho \cdot q \cdot \bar{u} \) [N] where \( \bar{u} \) is the mean velocity. In addition to the reduced gravity \( g' \) (m/s\(^2\)) we now have the volumetric flow rate \( q \) (m\(^3\)/s) and they are combined into the specific buoyancy flux \( B \) defined as

\[
B = q \cdot g' \quad \text{[m}^4\text{/s}^3\text{]} \quad (2.2)
\]

The current is driven by its own buoyancy flux and relation (2.2) is the specific buoyancy flux at the source based on supply flow rate and the temperature difference between the supply air and the room air.
**Cool gravity currents**

Cool gravity currents are common in connection with displacement ventilation where cool air is supplied to the room at a low level (see Figure 2.7). The natural heat sources in the room such as occupants and lighting devices help the distribution of the air in the direction of the extract devices, which are usually located at a level close to the ceiling. A special property of gravity currents is their ability to easily pass obstacles.

![Figure 2.7 A cool gravity current passing an obstacle. The clean supply air is distributed into the occupied zone by internal heat sources](image)

**Warm gravity currents**

Buoyancy forces can be used for distribution of heat when warm air is carrier of heat and distributed between rooms in a building through openings at different levels in the internal walls (Figure 2.8). Within each room the heat will spread as a warm gravity current to the parts of the room where the requirement is greatest. Heat sinks like cold windows contribute to lead the air down into the occupied zone as downdraught of cold air. However, the heat sinks are fewer than the corresponding heat sources for the case of displacement ventilation described above.

![Figure 2.8 Warm air is driven from a warm space to a colder one by thermal forces; a warm gravity current is developed distributing heat and ventilation air.](image)
3. Literature review

Air movements through large vertical openings (windows and doors)

As early as 1945, Rydberg reports on measurements in a scale model with saline water as working fluid. These measurements were however conducted with the purpose of investigating the efficiency of window-airing, and thus a transient course of events was being studied.

Nordquist (1998, 2002) has also touched on the subject. Here the ventilation process in window-airing is treated as a complement to the basic mechanical ventilation in schools. The experimental work has been made at full scale.

This work has focused on air movements in internal openings where the conditions can be considered as steady.

For a door opening in a wall where the driving force is only caused by the density difference between the rooms, two airflows, equal in size with respect to the mass flow rate, and in opposite directions, arise in the opening. Within buildings the temperature differences between rooms are so small that the effect on the volumetric flow rate can be neglected. The size of these airflows, $q_e$, depends on the geometry and the airflow's reduced gravity, $g'$ and can be described as:

$$ q_e = f \left( \frac{w}{h}, \frac{W}{H}, Gr \right) \cdot A \cdot (g' h)^{1/2} \quad [\text{m}^3/\text{s}] \quad (3.1) $$

Where the first three factors are aspect ratio of the doorway, contraction in width and contraction in height.

The Grashof number: $Gr = g \cdot \beta \cdot \Delta T \cdot h^3 / \nu^2 \quad [-]$ 

For ideal gases it is applicable that the volume expansion coefficient, $\beta = 1/T$ and the reduced gravity can be written:

$$ g' = g \cdot \Delta \rho / \rho = g \cdot \Delta T / T \quad [\text{m/s}^2] $$

Thus the densiometric Grashof number, $Gr$, can be written:

$$ Gr = g' h^3 / \nu^2 \quad [-] $$

For a defined geometry and if it is assumed that $Gr$ is sufficiently large, which is reasonable for ventilated rooms at normal temperatures, expression (3.1) can be written as:

$$ q_e = C_e \cdot A \cdot (g' h)^{1/2} \quad [\text{m}^3/\text{s}] \quad (3.2) $$

where $A$ and $h$ is the area and height of the opening respectively. $C_e$ is a proportional coefficient that contains influence of several effects and must be determined by experiments. $g'$ is the reduced gravity.
Air movements in large internal openings generated by differences in density between rooms have been studied previously, both in full scale and in scale models with various operating fluids. Most of these experiments have been conducted under conditions where no forced airflow has been present.

In van der Maas (1992) there is an extensive account of the work conducted before 1992 and in Etheridge & Sandberg (1996) work conducted before 1995 are reported.

The coefficient, $C_e$, in expression (3.2) has been determined in several reported experiments:

- Allard et al. (1990) has obtained a value of 0.27 in a full scale test.
- van der Maas (1992) reports a value of 0.15 which was obtained with several test arrangements.
- Kiel & Wilson (1989), in a test arrangement consisting of two adjacent rooms, have obtained the value $0.13 + 0.0025\Delta T$.
- Lane-Serff (1989) took measurements in a scale model with saline water and obtained the value $0.207 \pm 0.005$.

Certain experiments (Kiel & Wilson, 1989) done for determination of $C_e$ indicate that this coefficient is weakly dependent on the temperature difference between the rooms.

Brown & Solvasson (1962) have reported on natural convection through rectangular vertical openings.

Dalziel & Lane-Serff (1991) have presented the two-layer hydraulic model to describe the bi-directional air motions in doorways. Flourentzou et al. (1998) have reported on measurements of discharge coefficients in the context of natural ventilation for passive cooling.

Transition between so-called bulk density flow and boundary layer flow has been treated by Anderson (1986) and Scott et al (1988) and is summarised by van der Maas (1992) in the report from IEA Annex 20, subtask 2 and by Etheridge & Sandberg (1996).

Walton (1984) has implemented numerical predictions for inter-room flows in the context of multi-zone models describing distribution of air, contaminant and temperature in multi-room buildings.

*Transition from bi-directional to unidirectional flow in a doorway*

If we want to convert the bidirectional flow into unidirectional using an increase of the mechanical forced air flow, the lowest forced flow rate, $q_{ff}$, required for this according to simplified theory can be written as:

$$q_{ff} = \sqrt{8} \cdot q_e \quad \text{(orifice model, described in Etheridge & Sandberg 1996)} \quad (3.3)$$

or:

$$q_{ff} = \frac{1}{C_e} \cdot q_e \quad \text{(two-layer hydraulic model, Dalziel and Lane-Serff, 1991)} \quad (3.4)$$

Because these expressions do not take all parameters affecting the flow into account either, the expression for $q_{ff}$ must also be determined by experiment. The flow then can be described with the following expression:

$$q_{ff} = C_{ff} \cdot A \cdot (g' \cdot h)^{1/2} \quad (3.5)$$

where $C_{ff}$ is the coefficient that has to be determined experimentally.
There are few works in the literature dealing with air movements through doorways when a forced flow is present. Etheridge & Sandberg (1996) present simplified theory describing the forced flow rate required to obtain unidirectional flow in a doorway when temperature difference is present. No experiments studying this issue, however, have been found in literature. Therefore one part of this thesis reports on a series of experiments carried out to study transition between bi-directional and unidirectional flow in doorways (Paper III).

**Air movements through internal horizontal openings**

In horizontal openings the flow pattern is more complex than in vertical openings and therefore the flow resistance is greater. The flow rate can be described similarly to the case for vertical openings using the following expression:

$$ q_e = C_e \cdot \left( g' \cdot \sqrt{A} \right)^{1/2} $$  \hspace{1cm} (3.6)

There are relatively few studies found in literature on buoyancy-driven flow through horizontal openings.

Natural convection through rectangular horizontal openings has been reported on by Brown (1962). The work is focused on heat transfer and involves both theory and experiments. In a doctoral thesis, Davis (1993) has reported on a series of experiments carried out in a water tank including determination of the coefficient $C_e$ for a horizontal opening. Davis found the value to be $0.063 \pm 0.002$.

An extensive study on a model scale using the salt bath method has been carried out by Epstein (1988). Epstein divided up the flow characteristics in four flow regimes according to the ratio $L/D$ where $L$ is the thickness of the partition wall, $q$ is the exchange flow rate and $D$ is the equivalent diameter of the aperture through which the flow exchange take place.

**Regime I** Oscillatory Exchange Flow

$$ q = 0.055 \cdot \sqrt{g' \cdot D^5} \quad \frac{L}{D} < 0.15 $$  \hspace{1cm} (3.7)

**Regime II** Bernoulli Flow

$$ q = 0.147 \cdot \sqrt{g' \cdot D^5} \cdot \left( \frac{L}{D} \right)^{1/2} \quad 0.15 < \frac{L}{D} < 0.4 $$  \hspace{1cm} (3.8)

**Regime III** Combined Turbulent Diffusion and Bernoulli Flow

$$ q = 0.093 \cdot \sqrt{g' \cdot D^5} \cdot \frac{1}{\sqrt{1 + 0.084 \left( \frac{L}{D} - 0.4 \right)^3}} \quad 0.4 < \frac{L}{D} < 3.25 $$  \hspace{1cm} (3.9)

**Regime IV** Turbulent Diffusion

$$ q = 0.32 \cdot \sqrt{g' \cdot D^5} \cdot \left( \frac{L}{D} \right)^{3/2} \quad 3.25 < \frac{L}{D} < 10 $$  \hspace{1cm} (3.10)
The non-dimensional Froude number, \( Fr \), can be used to normalize the flow caused by buoyancy forces in a horizontal opening. It is defined as:

\[
Fr = \frac{q}{\sqrt{g^*D^5}} \quad [-]
\]  

(3.11)

Figure 3.1 shows a graph of the Froude number versus \( L/D \) according to Epstein’s equations. The four flow regimes defined by Epstein are marked in the diagram.

![Graph of Fr versus L/D](image)

Figure 3.1 \( Fr \) as function of \( L/D \) according to expressions 3.7-11.

Richard et al. (2003) have studied the effect of partition thickness on buoyant exchange flow in horizontal openings on a model scale using water as the operating fluid. The \( L/D \) ratio was varied between 0.0376 and 1.0 and the results were similar to those reported on by Epstein.

Some works related to buildings are Blay et al. (1994) carried out in a scale model, Reynolds et al. (1988) with focus on numerical simulations and Peppes et al. (2001, 2002) including both physical experiments and numeric simulations.

Two full scale studies on counter-current flow in horizontal openings have been found: Heiselberg and Li (2007) focusing on the flow rate and Blay et al. (1998) where the heat exchange was studied. Heiselberg and Li have compared the result of the full scale tests to Epstein’s result and found both similarities and differences.

Blay’s report includes a study where a staircase has been linked to the horizontal opening and the results show that for this case the flow rate decreased by about 30% compared to the case without staircase.

Kuhn et al. (2001) have studied density stratification caused by buoyancy-driven exchange flow in horizontal openings.
Gravity currents
In a book, Simpson (1987) has treated theories and experiments about gravity currents and their occurrence in the environment. There are few works found in literature about gravity currents related to building ventilation. One is by Etheridge & Sandberg (1996), which treats cool gravity currents occurring in connection with ventilation by displacement.
4. Methodology

This work is mainly experimental and has been carried out both in full scale and on a model scale. For the full scale tests a test apartment built up in the laboratory hall of the Department of Indoor Environment has been used and the model scale experiments have taken place in various 2D and 3D models where the salt bath method has been used to achieve the appropriate density differences.

4.1 Full scale tests

The layout and exterior of the apartment that was used for the full scale tests are shown in Figure 4.1. The test apartment has been used for the studies of thermally generated air movements within the building and was designed to be like the type of dwelling common in Sweden since the 1970s.

Figure 4.1a Plan view of the test apartment

![Plan view of the test apartment](image)

Figure 4.1b Exterior of the apartment in the laboratory hall

![Exterior view of the test apartment](image)

Table 4.1 Specifications of the test apartment

<table>
<thead>
<tr>
<th>Area [m²]</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>22</td>
</tr>
<tr>
<td>Bedroom</td>
<td>14.5</td>
</tr>
<tr>
<td>Kitchen</td>
<td>14</td>
</tr>
<tr>
<td>Hall</td>
<td>14.5</td>
</tr>
<tr>
<td>Bathroom</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
</tr>
</tbody>
</table>

The internal height is 2.5 m.

Figure 4.2 shows the bathroom with bathtub shower and stand for laundry drying. The laundry weight was recorded during the drying process to determine when the laundry was dry. For that purpose the stand with the laundry was placed on an electronic balance connected to a computer. Temperature and humidity in a number of locations were also recorded. During these tests the size of the bathroom was reduced to 3.1 m².

![Laundry drying in the bathroom](image)
The cooling chamber adjacent to the kitchen and bedroom of the apartment is equipped with a cooling machine that can lower the air temperature in the chamber down to -25°C in order to simulate outdoor climate during winter time.

The test apartment was originally designed to study ventilation efficiency in a multi-room building and is equipped with instruments for measurements of temperature, pressure, gas concentration and relative humidity at a number of points within the building. The apartment is heated by electric radiators in each room and a computer-based system is used to control the temperature very accurately in the rooms individually. This last facility is crucial when one studies thermally-driven air movements that often are large even when very small temperature differences are present.

To follow air and contaminant movements within the apartment various tracer gas methods have been used. For example, when the outdoor air flow rate that enters each room was measured, the constant concentration method was used and for determining the air change efficiency the decay method was used.

**Tracer gas methods:**

**The constant concentration method**

The principle of the constant concentration method is to keep the tracer gas concentration in all zones in the actual building at a constant target value. This is achieved using a control system for supply of tracer gas. The time average of the tracer gas flow rate in each zone will be a measure of the air supplied to the different zones. One advantage with the method is that interchange of air between the different zones will not influence the result because the concentration of tracer gas in all zones is equal.

**The decay method**

Using the decay method tracer gas is spread in the building and mixed to uniform concentration by mixing fans. When the concentration is even the gas supply and the mixing fans are stopped and the concentration decay is recorded. From the decay curve the mean age of air, the nominal time constant of the room and the air exchange efficiency can be determined.
In order to measure airflow through the doorways computer-controlled traversing systems have been installed in each of the four doorways in the building. Thermistor anemometers have been placed at ten heights on vertical rods that were moved across the doorways to measure the air speed in order to find the airflow rate in each direction (see Figure 4.3). The anemometers were of constant temperature type and developed at our department and presented at ROOMVENT’90 in Oslo (see Lundström H. et al., 1990).

![Figure 4.3 The anemometer probe and arrangement of the probes in the door opening. The rightmost picture shows smoke visualisation in the doorway.](image)

The apartment has been used for studies of:

- Air movements through internal doorways with and without influence forced airflow (Papers I-II)
- Transition from bi-directional to unidirectional flow in a doorway (Paper III)
- Spread of air and heat by gravity currents
- Conversion of electric heating in buildings (Paper VII)
- Spread of contaminants (moisture) from sanitary spaces (bathroom)

### 4.2 Model scale tests

Model scale tests have been carried out using water as the operating fluid. To obtain appropriate density differences the salt bath method has been used. The following cases have been explored:

- Study of gravity current passing through a doorway
- Study of a 2D gravity current passing obstacles of various heights
- Measurement of propagation velocity for a 2D gravity current
- Studies of thermally-driven flow through a horizontal opening
- Observations of air distribution in a scale model of the test apartment
Scale models used for studies of 2D gravity currents.

Figure 4.4 shows a model for study of developing bi-directional flow in a doorway shortly after opening of the door. The flow pattern has been visualised using coloured dye. The dimensions of the model are: 0.70m x 0.07m x 0.20m (length x width x height).

Figure 4.4 Plexiglas model for study of gravity current in a doorway.

Figure 4.5 Photograph of model used to study properties of 2D gravity currents.

Figure 4.6 Side view of the model.
Figures 4.5 and 4.6 show a photograph and a sketch of a model used for studying the behaviour of two-dimensional gravity currents using the salt bath method. Propagation velocity and ability to pass obstacles of various heights have been studied. The model is made of Plexiglas and the size is 1.80m x 0.07m x 0.20m (length x width x height). When one works with the salt bath method, the operating fluid is water and the temperature difference is simulated by adding salt, usually common sodium chloride, to the supply fluid to obtain the desired difference in density. The reduced gravity, $g^*$, should be the same as for the full scale case. A property with this method is that the result is not affected by heat transfer which is an advantage when the aim is to identify the basic physics of the flow.

Shadowgraph visualisation
For visualisation the shadowgraph technique has been used (see Settles 2001). This method uses the phenomena that the refractive index of the pure water is different from that of the salt water. The model is lit from far behind using a small light source; in this case a slide projector was used (see Figure 4.7). The front side of the model is covered by a semi-opaque screen on which the saline current will be visible and can be videotaped or photographed for later evaluation.

Models for studying three-dimensional flow.

The distribution of thermal driven flow in a multi-room building has been visualised in a Plexiglas scale model (1:10) of the full scale test apartment (see Figure 4.8). Clean water has been used as initial fluid in the model and saline water as supply fluid in the low rear part of the hall. The supply fluid was visualised using coloured dye and observed and videotaped from below by means of a mirror arrangement.
Horizontal openings

Vertical movements through horizontal openings have been studied in a Plexiglas model that is shown in Figure 4.9. The model was divided in two parts of equal size by a horizontal plane. In the centre of the plane was a square opening with a side length that could be varied from 20 mm to 80 mm. Shadowgraph technique has been used for visualisation and the flow rate through the opening is calculated from measurements of the density decay in the upper part of the model during the course of the test. The density meter that has been used is an Anton Paar DMA 35n with a resolution of 0.1 kg·m⁻³.

A detailed description of the study can be found in Paper VI.
5. Results

5.1 Large internal openings
The distribution of air in a building occurs to a large extent through doors (vertical openings) that have been left open. Horizontal openings like stairwells are also of importance for the distribution of air.

In a building consisting of several rooms the distribution of air is governed by a number of mechanisms of which the two most important are pressure differences caused by the mechanical ventilation system and density differences caused by temperature differences within the building. In practise the air movements are caused by a combination of both mechanisms. For vertical openings like doors we can distinguish between two cases: the closed door where the opening can be considered small and the effect of the pressure difference predominates, and the open door, which is a large opening where the thermal forces will predominate.

This work focuses on thermal-generated air movements and therefore studies of air transport through small openings like closed doors have been omitted because thermal-driven air flow through small openings are of insignificant size and thus not useful in this context.

5.1.1 Vertical openings
In a vertical opening in a building, such as a doorway, that connects two rooms in a building with different temperatures, a flow pattern like that in Figure 5.1 will develop in the doorway. The air will move from the warm to the cold room in the upper half of the doorway and in the opposite direction in the lower half of the door. Since there is no external ventilation the two flow rates will be equal. At about half of the height, the so-called neutral height, the air speed will be zero.

![Figure 5.1 Example of theoretic temperature and velocity profiles in a door opening with parallel temperature profile in two adjacent rooms and no forced flow](image)
If a forced extract flow is imposed on one of the rooms the velocity profile will be shifted towards that room (see Figure 5.2 and Figure 5.2a-d), the neutral height will move upwards or downwards and, if the forced flow rate is large enough, the flow will change from bidirectional to unidirectional.

Figure 5.2  Measured temperature and velocity profiles in a doorway with forced flow present
Impact of forced extract airflow on the flow through the kitchen door.

Figures 5.2 a-d show a series of diagrams describing the measured velocity profile in the kitchen door for extract airflow rates in the kitchen from 25 l/s to 100 l/s. We can see that the velocity profile (blue) is shifted to the left as the extract flow rate increases and the neutral height is moved upwards. It is also obvious that despite a temperature difference as low as 0.6°C and a flow rate four times the prescribed ventilation rate for the whole apartment, unidirectional flow is not obtained.

In Figure 5.3 the airflow in a door opening according to expression (3.2) has been plotted as the function of the temperature difference between the rooms. Here the value of 0.15 for the coefficient \( C_e \) has been used (van der Maas, 1992). The height of the door was 2.0 m and the width was 0.70 m.
Figure 5.3 Airflow rate in each direction in the door opening as a function of the temperature difference

We can see in the diagram in Figure 5.3 that even very small differences in temperature cause relatively large airflow rates. From the diagram we can read out that a temperature difference of half a degree generates a flow rate of 40 l/s in the door opening. As a comparison the dashed line in the diagram represents the airflow rate prescribed in the Swedish building code for a dwelling of the same size as the test apartment.

For the corresponding heat transfer the following expression applies:

\[ P = \rho \cdot c_p \cdot q_e \cdot \Delta T = \rho \cdot c_p \cdot C_v \cdot A \left( \frac{g \cdot h}{T} \right)^{1/2} \cdot \Delta T^{3/2} \]  

[W]  

(5.1)

In Figure 5.4 this heat transfer has been illustrated in a diagram. Here the coefficient also has been assumed to be equal to 0.15 (van der Maas, 1992).
In Section 3 we learned that a superimposed forced flow across the doorway can, if the flow rate is sufficiently large, change the bi-directional flow through the opening into a unidirectional flow. The least forced flow rate, \( q_{ff} \), required for this can be written as:

\[
q_{ff} = C_{ff} \cdot A \cdot (g' \cdot h)^{1/2} \quad [\text{m}^3/\text{s}] 
\]

where \( C_{ff} \) is a coefficient that has to be determined experimentally.

As no experiments to find the coefficient \( C_{ff} \) have been found in literature, one aim of this work is to carry out such measurements. The measurements described below aim to determine this coefficient.

The experiments have been conducted in the kitchen door of the test apartment, with exhaust airflow and temperature difference between kitchen and hall as parameters. In order to be able to determine the airflow through the door, anemometer probes were arranged in the manner described in Figure 4.3 in section 4. The air temperature was measured by means of thermocouples placed at four different heights at the cross marks in Figure 5.5. The test data which has been used is shown in Table 5.1. A total of 18 cases have been measured. Table 5.1 shows the conditions for the 18 test cases. The table shows that for most of the cases the actual temperature differences have not differed more than 0.1°C from the target (set) value.
<table>
<thead>
<tr>
<th>Flow rate [l/s]</th>
<th>Temperature differences between rooms</th>
<th>Set value [°C]</th>
<th>Actual value [°C]</th>
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<tbody>
<tr>
<td>25</td>
<td>0.0</td>
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<td></td>
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<tr>
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<td></td>
</tr>
<tr>
<td>37.5</td>
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<td></td>
</tr>
<tr>
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<td>0.3</td>
<td>0.36</td>
<td></td>
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<td>50</td>
<td>0.6</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
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<td>0.0</td>
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</tr>
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<td>0.32</td>
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<td></td>
</tr>
<tr>
<td>100</td>
<td>0.6</td>
<td>0.62</td>
<td></td>
</tr>
</tbody>
</table>

The velocity profile has been recorded at ten different heights for 7 horizontal positions. At each horizontal position the velocities have been averaged during a 10-min. period. The anemometer which was used has been developed at the department and is primarily intended for measurement of draughts in rooms where the direction of the air velocity is unknown (Lundström et al., 1990). The velocity sensors have therefore been designed so that they measure the absolute value of the air velocity independently of its direction. Because the air in a door opening is driven by density differences between the air in the adjacent rooms, air transport occurs in both directions, which is not indicated by the velocity sensors which were used. The velocity vector is not perpendicular to the door opening either as a rule, and because the intention has been to determine the airflow through the door, this condition entailed that the determination of flow is marred by some degree of uncertainty. In order to determine whether the horizontal component of the velocity is positive or negative, a special method of assessment has been resorted to. Figure 5.6 shows examples of measured vertical velocity profiles for 7 horizontal positions in the kitchen door. The width of the door is 0.70 m and the x-value in the figure represents the distance from the locking side of the door.
In order to determine the direction of air movements, visualization with smoke has been used (see Figure 4.3 right). Guided by the form of the velocity profiles and the smoke visualization, the profiles have been corrected and the direction has been determined. Figure 5.7 shows the final assessment of the profiles. The differences in the profiles with x=0.05 and x=0.65 may possibly be explained by which side the hinges happen to be on (x=0.70).

From the profiles the height where the velocity is zero, the so-called neutral height, $h_n$, can then be determined. By integrating the velocities across the door's entire opening area, the airflow rate in each direction can be determined. Because the velocity field in the door opening is three-dimensional, the size of the airflow must, however, be handled carefully. It is probable that the calculated flow is greater than the actual flow.

The purpose has been to determine the coefficient, $C_f$, in expression (3.5), which describes the least forced airflow rate required to produce unidirectional flow in the door opening at various temperature differences between the rooms.

During the tests it has only been possible to achieve unidirectional flow in the doorway for very small temperature differences. Therefore two methods of evaluation of measured data have been used, both of which make use of extrapolation. One method focuses on the neutral height and the other uses the measured flow rate.
In Figure 5.8 the neutral level, \( h_n \), in the door opening has been graphed as a function of exhaust flow. The neutral level has been normalized with the door height and the exhaust flow with the expression \( A(g'h)^{1/2} \). When the normalized neutral level reaches the value 1 unidirectional current arises in the doorway. The measurement points have been adapted to the following function:

\[
\frac{h_n}{h} = 1.206 \left( \frac{q}{A(g'h)^{1/2}} \right)^{0.305} \quad [-]
\]  

(5.7)

If the function is extrapolated to the value 1 for the normalized neutral height, the smallest normalized exhaust flow required for unidirectional current to arise is obtained. Through identification with expression (5.7) the value of \( C_{nf} \) can be determined as 0.54.
Figure 5.9 Measured flow rate from kitchen to hall versus the normalized forced extract flow rate

In Figure 5.9 the airflow toward the hall has been graphed as a function of the normalized exhaust flow. When the airflow in the direction of the hall becomes zero, there is current only in the direction towards the kitchen. The measurement points have been adapted to the following function:

\[ q_{hall} = -16.543 \ln (x) - 10.187 \]  

Where the function intersects the x-axis the flow toward the hall is equal to zero and there is unidirectional current toward the kitchen. The normalized exhaust flow at this point is equal to the desired coefficient \( C_{fr} \). With this method of evaluation, the value will also be 0.54.

Because the uncertainty in measurement of the temperature differences with the smallest values is of the same magnitude as the measurement values, these have not been included in the evaluation.

Figure 5.10 shows a graph of the predicted extract flow rate required to obtain unidirectional flow in the kitchen door of the test apartment as a function of the temperature difference. We can see for example that when the difference is 0.3°C the required flow rate is 100 l/s which, is four times the prescribed ventilation flow rate for the whole apartment.
Moisture spread by thermal forces
The effect on air distribution due to door openings may affect indoor air quality in various ways. The air movements in the doors may be an advantage if you want to reduce a high concentration of a certain contaminant in a space where the concentration otherwise exceeds an acceptable level, and in this way spread the contaminant to other parts of the building where it is diluted to levels that are acceptable. Water vapour is such a contaminant, which can be propagated from e.g. bathrooms (showering, laundry drying) whereby the humidity load in the bathroom is reduced. There are also other aspects of the effect of door openings on air and contaminant distribution, which will be discussed in more detail below.

Experiments have been conducted to chart humidity load in bathrooms for various ventilation airflows and how humidity load is affected by whether the door to the bathroom is open or closed (Merbom, 1996). To measure humidity propagation from the bathroom from showering and drying of laundry, air humidity transducers have been mounted in all rooms of the test apartment. In the bathroom, additional sensors were mounted in order to measure the distribution of humidity in the room. The transducers were connected to the data collection system for recording during the desired time period. Upon measurement, the dimensions of the bathroom were 1.90m x 1.65m x 2.50m (length x width x height), which is the most commonly occurring size of bathroom in Swedish multi-family housing. Arrangement of the ventilation is shown in Figure 5.11.

Figure 5.10 Predicted flow rate required to get unidirectional flow as a function of temperature difference; expression (3.5) with $C_{fl}=0.54$
In the investigation of humidity conditions in the apartment with drying of laundry, laundry has been hung on a drying rack as shown in Figure 5.12 and its weight recorded during the drying process so that drying time and drying velocity (source strength) could be determined. A precision balance connected to a computer for recording with a resolution of 1g has been used for weighing. The dry weight of the laundry was 2.4 kg and consisted of standardized cotton test laundry which was dampened to contain 50% water calculated by dry weight. In determining the drying time, the laundry has been considered dry when the remaining dampness has been reduced to 3% of the dry weight. Humidity load in the form of showering has been achieved by running the shower with 38°C water in the bathtub for five minutes.
The size of the ventilation airflow for a residence resembling the test apartment should, according to applicable determinations, be 15 l/s in the bathroom and 10 l/s in the kitchen, to obtain a total of 0.35 l/s·m². In field studies in a selected population of bathrooms without window in multi-unit apartment buildings in Gävle, ventilation airflows in the bathrooms have been measured (Borgström et al., 1996). The results of the field measurements show that the exhaust airflow in these apartments did not fulfil the normal requirements in any case; instead they varied between 6 and 14 l/s. In order to calculate the humidity load in the bathroom, in the laboratory tests an exhaust airflow rate of between 6 l/s and 15 l/s in the bathroom has therefore been used. During these measurements the total airflow rate has been reduced in proportion to the flow in the bathroom.

Results from the measurements of distribution of humidity from the bathroom with drying of laundry with 6 l/s and 15 l/s exhaust flow rates are shown in Figures 5.13-14. The curves in the diagram show the weight reduction in the laundry and relative air humidity in the bathroom and hall during the drying process. The solid lines represent the values measured with the door closed and the dotted lines show the values measured with open door. Drying times become significantly shorter and the bathroom is exposed to high humidity levels in the air for a shorter time with an open door than with a closed door. It is also shown by the measurements with open door that the highest humidity is recorded at the measurement point described as “RH supply”. This is due to the measurement point being placed at the floor outside the bathroom and is intended to measure the air that is supplied through the slot under the door when the door is closed. When the door is open, the current in the bathroom will change through the emission of humidity from the laundry, lowering the air temperature and generating a cool, damp airflow which “runs” out of the bathroom across the threshold.

In Figure 5.15 drying times and humidity load are summarized for the bathroom with various exhaust flows and with closed vs. open bathroom door.

The humidity load has been expressed as the time in hours that the relative air humidity has exceeded 60% in the middle of the bathroom. The measurements show that with bathroom door closed, drying times increase with reduced exhaust flow, while drying times with open door are almost independent of the exhaust flow and of the same order of magnitude as when the exhaust flow is as prescribed. The drying velocity is a measure of source strength of the contaminant (dampness) and is constant for the greater part of the drying process. The humidity load in the bathroom becomes significant with small exhaust flows and door closed while it is strongly reduced with door open due to air exchange through the door. It thus appears that despite high emission of humidity (short drying time) with open bathroom door, the humidity load in the bathroom becomes insignificant even with small exhaust flows. Measurements of air humidity in other rooms also show that air humidity only increases marginally due to the humidity being spread within the entire apartment volume. We can also note that when the extract flow rate is 15 l/s (which is the flow rate prescribed in the Swedish building code) the position of the door has insignificant influence on both drying time and humidity load.
Figure 5.13 Drying of laundry. Exhaust airflow rate 6 l/s

Figure 5.14 Drying of laundry. Exhaust airflow rate 15 l/s
5.1.2 Horizontal openings

While in a vertical opening connecting two volumes of fluid of different densities a flow pattern develops looking like the one in Figure 5.16, the flow pattern in a horizontal opening is much more complex and can be described like the one in Figure 5.17.

Model tests have been accomplished to examine the thermal-driven flow in an opening in a horizontal partition wall. The experiments have been carried out in the Plexiglas model that is shown in Figure 4.9, section 4.2. Influence of a sloping plane attached to one side of the square shaped opening has also been studied (see Figure 5.18).

The result from experiments shows that buoyancy-driven flow in a horizontal opening is about one third that in a vertical opening for the same temperature conditions and that the sloping plane, which could be for example a staircase, has a small positive impact on the flow. The flow rate increased by 10-15% when the sloping plane was attached to the opening.

An extensive series of tests on buoyancy-driven counter-current flow in horizontal openings has been conducted by Epstein (1988) and the only full scale tests in this area found in the literature are reported by Blay et al. (1998) and Heiselberg and Li (2007).
Figure 5.18 Visualisation of counter-current flow through a horizontal opening with and without a “staircase”

Figure 5.19 Normalized flow represented by the Froude number as a function of L/D

The diagram in Figure 5.19 shows a comparison of test results from model and full scale tests on buoyancy-driven counter-current flow through an opening in a horizontal partition wall. The solid line in the diagram shows the \( Fr \) number according to the four expressions (5.10)-(5.13).

The cross marks in the diagram represent the measured values for the case with a sloping plane (“staircase”) below the opening (see Figure 5.18). The \( Fr \) number is significantly larger for those measurements, which indicates that the flow rate has increased when the sloping plane was attached to the opening. The measurements with the sloping plane have been carried out for a limited range of the ratio, L/D, but the range is covering common values for an opening for a staircase in a horizontal partition in building construction.
5.2 Gravity currents

5.2.1 General properties of gravity currents
A gravity current consists of moving fluid that propagates along a horizontal surface which is not too steep, driven by gravitational (thermal) forces. Special properties make such currents suitable for our purpose of the ventilation and heating of buildings.

In ventilation context, gravity currents are connected to ventilation by displacement when cool air is introduced to a room at low momentum flux and develops a gravity current along the floor driven by its higher density.

With respect to the geometry of supply and possibility of spreading, gravity currents can be divided into two-dimensional gravity currents or three-dimensional gravity currents. If for example air with higher or lower temperature than the ambient air is supplied over the whole width of a corridor with a width of \( w \) meters, then the air cannot be spread sideways and we have a two-dimensional gravity current. Its specific buoyancy flux is the buoyancy flux per unit width \( B/w \) with unit \( m^3/s^3 \). A three-dimensional gravity current is characterised by its specific buoyancy flux \( B \) with dimension \( m^4/s^3 \). A special case of a three-dimensional gravity current is a radial gravity current.

Figure 5.20 shows a smoke visualisation of a gravity current originating from a slot under the door. The spread is constrained by the walls and radial gravity current is established. In the right Figure 5.21 the air is entering the room at greater momentum flux and the air begins to form a jet instead of a gravity current.

Figure 5.20 Cool gravity current

Figure 5.21 Transition to jet
5.2.2 Two-dimensional gravity currents without influence of heat transfer

The characteristics of a gravity current are governed by the reduced gravity, $g'$, and the velocity of the inflowing fluid. The relationship between the effect of the gravitational force and the momentum in the intake can be described with Archimedes number, $Ar$.

Reduced gravity: 
\[ g' = g \cdot \frac{\Delta \rho}{\rho} \quad [\text{m/s}^2] \]
where
$g$ is the acceleration due to gravity (9.81 m/s$^2$) and $\rho$ is the density of the inflowing medium. $\Delta \rho$ is the difference between the densities of the inflowing and the ambient medium.

Archimedes number: 
\[ Ar = \frac{g' \cdot h}{u^2} \quad [-] \]
where $h$ is the height of the inlet device and $u$ is the inlet velocity. A local Archimedes number can be defined in a corresponding manner. For a fully developed two-dimensional gravity current, the flow is critical when the local $Ar=1$.

The gravity current may also be described by its buoyancy flux, $B$.

For a two-dimensional gravity current the following relationship applies:
\[ B(x) = \frac{q(x)}{w} g \frac{\Delta \rho(x)}{\rho(x)} = \frac{q(x)}{w} g' \quad [\text{m}^3/\text{s}^3] \quad (5.9) \]

A dimensional analysis provides the following relationship for the velocity of the gravity current:
\[ u = k \cdot B(x)^{1/3} \quad [\text{m/s}] \quad (5.10) \]

After entering the velocity into the continuity equation, $\frac{q}{w} = u \cdot h$, an expression is obtained for the height of the gravity current:
\[ h(x) = \frac{\frac{q(x)}{w}}{B(x)^{1/3}} \quad [\text{m}] \quad (5.11) \]

where
$k$ = a dimension-less coefficient \quad [-]
$q(x)$ = the current’s local flow including entrained medium from the environment \quad [m$^3$/s]
$w$ = width of the current \quad [m]
$\Delta \rho(x)$ = local density difference between current and surrounding medium \quad [kg/m$^3$]
$\rho(x)$ = local density of current \quad [kg/m$^3$]
$\rho(0)$ = density of supply fluid \quad [kg/m$^3$]
$\rho_a$ = density of ambient fluid \quad [kg/m$^3$]
The notations are illustrated in Figure 5.22

A consequence of the relationship (5.11) is that when the buoyancy flux increases, the height of the gravity current decreases.

At the intake ($x=0$) applies:

$$B(0) = \frac{q(0) \Delta \rho(0)}{w \rho(0)}$$

(5.12)

The downstream intake increases the flow through mixing of surrounding fluid and simultaneously reduces the density difference between the gravity current and the surroundings. If the quantity of mixed fluid at a distance $x$ from the intake is called $\Delta q$ the resulting expression is:

$$B(x) = \frac{q(0) + \Delta q}{w} \frac{\Delta \rho(0) \cdot q(0) + \Delta \rho(0)}{\rho(x) \cdot (q(0) + \Delta q)} = \frac{q(0) + \Delta \rho(0)}{w} \frac{\Delta \rho(0)}{\rho(x)}$$

(5.13)

Because $\rho(x) \approx \rho_a$ it also applies that $B(x) \approx B(0)$, i.e. the buoyancy flux is nearly constant. According to expression (5.10) the velocity of the gravity current will then develop to be nearly constant. If it is assumed that the mixture of surrounding fluid after the initial process is negligible, according to expression (5.11) the height of the current will also be constant.

![Diagram of gravity current in the water model](image)

Figure 5.22 Diagram of gravity current in the water model
Figure 5.23 shows a graph derived from a videotaped 2D gravity current in the scale model described in Figure 4.5-7. The front position of the current is plotted versus time and the result is almost a straight line which indicates that the speed of the front is constant and equal to the slope (derivative) of the line. A compilation of the test data for the measurements in the water model is found in Table 5.2 below. We find using curve fitting that the velocity of the front of the current is 0.032 m/s. The third root of the buoyancy flux \(B(0)^{1/3}\) of the flow from Table 5.2 is 0.034 m/s. When we apply expression (5.10) on the test data we find that the coefficient, \(k\), in the expression becomes 0.93 which is fairly close to unity.

Table 5.2  Test data for the model tests

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>m</td>
<td>Height of intake device</td>
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<tr>
<td>Width of the model</td>
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<td>m</td>
<td>Width of supply device</td>
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<td>Supply flow rate</td>
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<td>m³/s</td>
<td>Free area</td>
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</tr>
<tr>
<td>Density of supply fluid</td>
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<td>kg/m³</td>
<td>Supply fluid velocity</td>
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</tr>
<tr>
<td>Density of ambient fluid</td>
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<td>kg/m³</td>
<td>Buoyancy flux, (B(0))</td>
<td>(4.07 \times 10^{-5})</td>
</tr>
<tr>
<td>Reduced gravity, (g')</td>
<td>0.0982</td>
<td>m/s²</td>
<td>(B(0)^{1/3})</td>
<td>0.0343</td>
</tr>
</tbody>
</table>
5.2.3 Two-dimensional gravity current under influence of heat transfer

When cool air is supplied to a long narrow room with low momentum, a two-dimensional gravity current is formed whose characteristics are mainly determined by the under-temperature (buoyancy flux, \(B\)). Because the density of the air depends on its temperature, the current will be affected primarily by heat transfer from the floor, which has a higher temperature than the supplied air. In this context the air may be considered an ideal gas and the reduced gravity, \(g'\), can be written as:

\[
g' = g \cdot \frac{\Delta \rho}{\rho} = g \cdot \frac{\Delta T}{T} \quad \text{[m/s²]}
\]

For a two-dimensional case with notations according to Figure 5.24, a heat balance for the gravity current can be established:

Absorbed heat:

\[
\rho(x + \Delta x) \cdot \frac{q}{w} \cdot c_p \cdot T(x + \Delta x) - \frac{q}{w} \rho(x) \cdot c_p \cdot T(x) = \alpha \cdot (T_n - \frac{1}{2} \cdot (T(x) + T(x + \Delta x))) \cdot \Delta x
\]

Heat output from floor:

\[
P = \alpha \cdot (T_n - \frac{1}{2} \cdot (T(x) + T(x + \Delta x))) \cdot \Delta x
\]

where

- \(c_p\) = thermal capacity of air at constant pressure [J/kg·K]
- \(\alpha\) = heat transfer coefficient [W/m²·K]
- \(q\) = volume flow rate of current [m³/s]
- \(T_n\) = temperature of floor, considered constant [K]
- \(T_a\) = surrounding air temperature [K]
- \(w\) = width of current [m]

Heat absorbed from the gravity current and output from the floor are set as equal

\[
\rho(x + \Delta x) \cdot \frac{q}{w} \cdot c_p \cdot T(x + \Delta x) - \frac{q}{w} \rho(x) \cdot c_p \cdot T(x) = \alpha \cdot (T_n - \frac{1}{2} \cdot (T(x) + T(x + \Delta x))) \cdot \Delta x
\]

For air with the temperatures which are relevant here it applies that \(\Delta \rho/\rho = \Delta T/T\). \(\Delta T\) can be assumed to be less than 10K which for normal room temperatures means that \(\Delta T/T \approx 0.03 = \Delta \rho/\rho\) by which \(\rho\) can be considered as constant and equal to the density of the surrounding fluid, \(\rho_a\). If \(1/2 \cdot (T(x) + T(x + \Delta x))\) is set as equal to \(T(x)\) the thermal balance equation can be written as a difference equation:

\[
\rho_a \cdot \frac{q}{w} \cdot c_p \cdot (T(x + \Delta x) - T(x)) = \alpha \cdot (T_n - T(x)) \cdot \Delta x
\]

Taylor series expansion of \(T(x + \Delta x)\) gives:

\[
T(x + \Delta x) = T(x) + \frac{dT}{dx} \cdot \Delta x + \cdots \text{+ higher order terms omitted}
\]
After entering and simplification, the difference equation transforms into the following differential equation:

\[ \rho_a \cdot \frac{q}{w} \cdot c_p \cdot \frac{dT}{dx} = -\alpha \cdot (T(x) - T_\theta) \]  \hspace{1cm} (5.16)

If it is assumed that \( T_l \approx T_a \) then equation (5.16) can be rewritten as:

\[ \rho_a \cdot \frac{q}{w} \cdot c_p \cdot \frac{dT}{dx} = -\alpha \cdot (T(x) - T_a) \]  \hspace{1cm} (5.17)

Because \( T_a \) is constant the following also applies: \( \frac{dT}{dx} = \frac{d}{dx} (T(x) - T_a) \)

Multiply both terms by \( \frac{q}{w} \cdot g \cdot \frac{1}{T} \)

\[ \rho_a \cdot c_p \cdot \frac{q}{w} \cdot \frac{d}{dx} \left( \frac{q}{w} \cdot g \cdot \frac{T(x) - T_a}{T} \right) = -\alpha \cdot \frac{q}{w} \cdot g \cdot \left( \frac{T(x) - T_a}{T} \right) \]

but because \( B = \frac{q}{w} \cdot g \cdot \frac{\Delta T}{T} \) where \( \Delta T = T(x) - T_a \) the differential equation can be rewritten as:

\[ \rho_a \cdot c_p \cdot \frac{q}{w} \cdot \frac{dB}{dx} = -\alpha \cdot B \]; or \( \frac{dB}{dx} = -\frac{\alpha}{\rho_a \cdot c_p \cdot \frac{q}{w}} \cdot B \)

We can solve this equation whereby we get the expression below for how \( B \) diminishes with distance from the intake device. According to equation (5.9) the velocity will also decrease at increased distance from the intake.

\[ B(x) = B(0)e^{-\frac{\alpha x}{\rho_a c_p \frac{q}{w}}} \]  \hspace{1cm} (5.18)

![Figure 5.24 Gravity current with addition of heat from below](image-url)
5.2.4 Full scale study of 2D gravity current with heat transfer

With supply of cool air using a low-momentum device (Figures 5.26 and 5.27) in the hall (see Figure 5.25), air velocity measurements have been made at various distances from the device (Törnström, 1998). In Figure 4.11 the air velocity of the gravity current has been graphed as a function of the distance from the device. The air velocity diminishes here with distance from the intake device. This agrees with expressions (5.10) and (5.18) which were derived in section 5.2.2 and 5.2.3. Also introduced into the diagram in Figure 5.28, is the constant velocity obtained if data for the intake device is entered in expression (5.10) in section 5.2.2 with the coefficient, \( k = 1 \). This value represents the order of magnitude for the velocity that the gravity current should theoretically have if no heat transport took place between the current and the surroundings. The under-temperature of the incoming air was 3.1°C. Measurements of the velocity were also carried out using other values of the under-temperature. These measurements show the same tendency as those shown in the diagram Figure 5.28.

The supply flow rate was 25 l/s during the tests and the initial velocity for the supply air was 0.25 m/s,

![Diagram](image-url)

Figure 5.25 Placement of the low momentum supply device in the hall during test
5.2.5 Gravity currents passing obstacles

As mentioned in Chapter 2, a useful property of a gravity current is the possibility for it to pass over obstacles. With the aim of exploring the interaction between gravity currents and obstacles, some tests were undertaken with water as operating fluid. The scale model used for these experiments was the one shown in Figures 4.5-7. The density difference was generated by adding salt. To visualise the flow the shadowgraph technique was used.

In Figure 5.29 some parameters \((h_1, h_2, h_3)\) concerning gravity currents passing obstacles are defined. The values of these parameters for eight of the experiments are listed in Table 5.3. The test conditions for all tests were identical with respect to the flow rate and reduced gravity of the supply fluid.

All Figures 5.30a-e show visualisation of a two-dimensional gravity current passing obstacles of various heights. For moderate obstacle heights the current will reshape downstream to the
height it would have had without the obstacle, indicating that the loss of energy is small. However, if the height of the obstacle becomes large compared to the initial height, the current behaves differently as can be seen on the last three pictures and it is reasonable to assume that the energy loss becomes larger and contributes more to the dissolution of the gravity current.

Figure 5.29
$h_1$ – Height of current without obstacle
$h_2$ – Height of obstacle
$h_3$ – Height of current upstream obstacle

a.) $h_2=0.015$ m
b.) $h_2=0.020$ m
c.) $h_2=0.045$ mm
d.) $h_2=0.062$ mm
e.) $h_2=0.092$ mm

Figure 5.30 a-e Visualisation of a cool gravity current passing obstacles of various heights (water model)
Table 5.3 Height of current for various height of obstacles

<table>
<thead>
<tr>
<th>Height of obstacle, $h_2$[m]</th>
<th>Height of current upstream obstacle, $h_3$[m]</th>
<th>$\Delta h = h_3 - h_1$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.023</td>
<td>0.000</td>
</tr>
<tr>
<td>0.010</td>
<td>0.033</td>
<td>0.010</td>
</tr>
<tr>
<td>0.015</td>
<td>0.038</td>
<td>0.015</td>
</tr>
<tr>
<td>0.020</td>
<td>0.044</td>
<td>0.021</td>
</tr>
<tr>
<td>0.030</td>
<td>0.060</td>
<td>0.037</td>
</tr>
<tr>
<td>0.045</td>
<td>0.072</td>
<td>0.049</td>
</tr>
<tr>
<td>0.062</td>
<td>0.085</td>
<td>0.062</td>
</tr>
<tr>
<td>0.092</td>
<td>0.108</td>
<td>0.085</td>
</tr>
</tbody>
</table>

An interesting observation from Table 5.3 is that in most cases the increase, $h_3 - h_1$, in height of the gravity current is almost the same as the height, $h_2$, of the obstacle. As the flow rate is equal for all the cases this follows from continuity reasons if the velocity of the flow passing over the obstacle is the same.

5.3 Visualization of thermally generated flow

5.3.1 Flow pattern after opening of a door

Figure 5.31 shows a visualisation in the model described in Figure 4.4. A series of pictures show how the dense fluid in the left partition is developing a gravity current when the door is opened. It is also possible to see that bi-directional flow arises in the opening in the right picture.

![Figure 5.31 Visualisation of a 2D gravity current in doorway shortly after opening of the door](image)

5.3.2 Fluid distribution in a model of the test apartment

In Figure 5.32 a-f a series of pictures is shown from an experiment in the scale model of the test apartment where coloured saline water was supplied in one end of the hall and removed at the upper, outer edge of the bathroom (Törnström, 1998). The lower part of the doors to the living room, bedroom and kitchen are equipped with slots. It can be seen how the coloured fluid gradually also flows into the rooms that lack drainage.
5.4 Conversion of direct electric heating using thermal forces

Paper VII reports on experiments carried out in order to explore the possibilities of using air as heat carrier when converting houses with direct electric heating to other heat sources, particularly in conjunction with district heating or air-to-air heat pumps. Thermal forces are used to distribute the warm air to the different rooms and gravity currents along the ceiling will distribute the warm air within the rooms. This might be a cost-effective alternative to installing an expensive hydronic system.
6. Discussion

6.1 Air movements in vertical openings

Many works can be found in literature reporting on thermally-driven air movements through open internal doors in buildings. They all point out that these flow rates are large compared to the flow rate caused by the mechanical or stack ventilation system. It is also obvious that air movements caused by thermal forces inside buildings contribute significantly to the distribution of ventilation air, especially in buildings where the total ventilation rate is low, like in dwellings.

From the results presented in Section 5 we learn that spread of moisture by thermal forces is important for the humidity load on the bathroom and also that the ventilation airflow rate has to be in accordance with the actual regulations in order to avoid too high humidity load on the bathroom.

Spread of moisture by thermal forces

Today it is common to shower often in apartment bathrooms and even dry laundry in the bathroom. This puts a high humidity load on the bathroom, which means that for extended periods of time the air humidity exceeds levels where microbial activity is promoted. Field measurements also indicate that the ventilation airflow is often significantly below the prescribed airflow level. The consequences of this are that the humidity load, and thereby the risk of microbial activity, further increases. With low ventilation airflows, drying times for laundry hanging in the bathroom are also very long, especially during late summer when the air humidity outside is normally at its highest. If the bathroom door is open after showering and when laundry is dried the moisture will distribute within the whole apartment and the humidity load on the bathroom will decrease significantly while the rise of humidity in the rest of the apartment will be small. However, generally speaking it is not desirable to spread moisture within dwellings; therefore one has to ensure that the spread does not only simply relocate moisture problems from the bathroom to other parts of the building.

Transition from bidirectional to unidirectional flow

The thermally generated bi-directional flow that exists in a doorway separating two spaces of different temperatures can be changed to unidirectional if a forced air flow is superimposed in one of the rooms. Experimental works to determine the flow rate required to achieve unidirectional flow have not been found in literature.

The required flow rate can be expressed as follows:

\[ q_{ff} = C_{ff} \cdot A \cdot (g' \cdot h)^{1/2} \]

where \( C_{ff} \) is an experimental coefficient depending on several parameters. In Section 5 is the result of measurements to determine \( C_{ff} \) presented. The values obtained from the experiments can be compared to the result of two different theoretical models: the two-layer hydraulic model (3.4) and the orifice model (3.3). The value on \( C_{ff} \) found from the experiments is 0.54 using two different evaluation methods.

The two-layer hydraulic model gives \( C_{ff} = 0.42 \) if we assume that \( C_e = 0.15 \) (van der Maas 1992), which is within the same magnitude as the result from the experiments. The orifice
model, however, gives the value $C_{fr}=1$ independently of the value chosen for $C_e$, which indicates that this model is not able to describe the flow conditions with sufficient accuracy.

Many contaminants may be damaging to health or have strong odours and thereby cause inconvenience for the persons who are in the building. Examples of such inconveniences are cooking odours, microorganisms and foul-smelling or poisonous gases. These contaminants are spread by air and therefore transported through open doors by the airflows that are generated by the ventilation system and by the forces that arise from differences in density in the air in adjacent rooms. To prevent the air in the room where the contaminant is from being emitted, either the door can be closed (which is the most effective way), or exhaust flow in the room can be sufficiently increased so that the air in the entire door opening only flows in the direction towards the contaminated room. Another way is to remove the contaminant as close to the source as possible by using some form of local extractor, e.g. where cooking odours are concerned by using an efficient range hood. If it is not possible to close the door or use a local extractor but instead a high exhaust flow is relied on, it appears that a very large airflow is required to achieve unidirectional flow in the door opening, even if the temperature differences between the rooms are small. Thus, to prevent cooking odours from spreading from the kitchen, it is important either to use an efficient range hood or keep the door to the kitchen closed.

In hospitals where the contaminants of greatest concern are microorganisms and removal by local extractor may be inefficient, special attention must be paid to the design and operation of the ventilation system. It is often also necessary to use air locks to prevent transmission of infection within the building.

6.2 Air movements through horizontal openings

Air flow pattern in horizontal openings due to buoyancy forces is more complex than for the case of vertical openings. The appendix (Paper VI) reports on scale model tests showing that the flow resistance is about three times larger than for a vertical opening with the same geometrical and thermal conditions. This is in accordance with other works (Epstein 1988, Davis 1995). The potential for air and heat distribution is therefore substantially less in a horizontal opening than in a vertical.

The tests reported on in Paper VI also include measurements where a simplified staircase is attached to the horizontal partition wall close to the opening. The measurements for that case show that the flow rate through the opening increased by 13% under influence of the “staircase”. Blay’s (1998) full scale measurements, however, showed a decrease in flow rate of 30% when a staircase was present. The explanation was probably that the geometry of the two models used in the experiments was different, both with respect to the shape of the “staircase” and its location in the model.
6.3 Gravity currents

Systems using ventilation by displacement take advantage of cool gravity currents. In this work a new field of application for gravity currents has been pointed out when warm gravity currents are used for combined heating and ventilation. The ability to pass obstacles and the fact that the gravity currents are self regulating to a certain extent are two properties that are useful in this application. Entrainment of fluid from the ambient is small, which the distinct upper bound of the current indicates (see Fig 5.30 a-e).

6.4 Distribution of heat and ventilation air

Thermal forces can be used to distribute both ventilation air and heat within a building as reported in Paper VII of this work. Heat is distributed as a warm gravity current from a central space in a building through openings at different levels or through open doors. Within each room gravity currents will distribute the heat to the parts of the room where the need is greatest. This may be an attractive alternative when converting buildings equipped with electric radiators to other forms of heating because of the high cost of a conventional hydronic system.
7. Conclusions

The work reported in this thesis clearly indicates that buoyancy forces are important for heat transport and the distribution of ventilation air within buildings. The central conclusions of this work may be summarized as follows:

- **Vertical openings**
  Buoyancy-driven air flow in internal vertical openings can distribute considerable amounts of air and thereby thermal energy within a building. These air movements are also important for the spread of contaminants.

- **Transition from bi-directional to unidirectional flow**
  Air movements are typically bi-directional in doorways separating rooms with different temperatures and large airflow rates will normally be required to inhibit this bi-directional air exchange.

- **Horizontal openings**
  The flow resistance of horizontal openings is greater than that of vertical openings, therefore the potential of heat transport by air movement in horizontal openings is less.

- **Gravity currents**
  Thermally-driven air movements, called gravity currents, have transport characteristics that are well suited for the distribution of cool or warm air within rooms.

- **Unconventional conversion of heating system**
  Thermal forces can be used to advantage for heat transport and the distribution of ventilation air within buildings in connection with the conversion of direct electric heating systems to, for instance, systems utilizing hot water distributed by district heating.
8. Future work

This work points out that it is difficult to obtain unidirectional flow in doorways unless we do not use very large forced flow rate. However, it should be useful to further explore the conditions required to obtain unidirectional flow in doorways. This could be done in a more extensive study where geometry, pressure, temperatures and forced flow rates were varied and the flow rate through the opening measured. The impact of door openings (transient course of events) on contaminant spread is also interesting to evaluate. Application examples where direction of flow can be of great importance are hospitals, kitchens and industries.

When converting direct electric heating to district heating using the unconventional method described in Paper VII, the heating and ventilation of kitchen and bathroom may cause problems because we do not want recirculation air from those sources. Therefore the heating of kitchens and bathrooms needs to be examined further. Even if the laboratory tests show that the unconventional conversion may work in practice, it would be desirable to test the system in a real building during an entire heating season. This test should also include a solution for the problem connected with heating of the bathroom and kitchen.

Besides physical experiments, future work can include numerical modelling of the mechanisms that influence heat transfer and air transport within buildings. Exploration of how the properties of gravity currents can be useful within buildings is another example of a topic for future work.
9. Summary of papers

**PAPER I** To what extent can the air movements within a building be controlled with mechanical ventilation?

There are a number of methods for air distribution in buildings. In the field of control and regulation technology, new methods are being developed which are not yet used in practice. These methods open new opportunities for developing systems for need-controlled ventilation. The internal air movements in a building are controlled by temperature and pressure differences created by the mechanical ventilation system. An interesting question is whether it is possible to control these air movements by means of fan-controlled ventilation. The intent of this work is to develop methods for studying air movements in a multi-room apartment. Experiments have been conducted to measure airflow in door openings by means of air velocity gauges and air distribution with various trace gas methods. These methods may then be used for validation of simulation models of the multi-zone model type within the field of air distribution.

**PAPER II** Measurement and control of the air movements within a building

This work constitutes a continuation of the previous paper and discusses airflow in both directions in a door opening at various temperature differentials between the rooms separated by the door. Because it is already known that small temperature differences give rise to large airflows in the door opening, a major part of the work has been devoted to improving temperature regulation in the test apartment used for the experiments. The results of the measurements show that in order to be able to control the airflow between rooms by controlling ventilation, the required temperature differences are very small (0.1°C). With greater temperature differences, the thermally driven airflows in the door openings become so large that they greatly exceed the prescribed ventilation airflows.

**PAPER III** Transition from bidirectional to unidirectional flow in a doorway

The airflow in door openings is controlled by pressure differentials caused by the mechanical ventilation system and density differences dependent on temperature differences between the rooms. If no forced flow arises and both rooms that are separated by the door have different temperatures, the air in the door opening can flow in both directions. If air is supplied to one room and removed from the other, with sufficiently great forced flow the air will flow in only one direction in the door — unidirectional flow. In this paper air velocity measurements in a door opening with various temperature differentials and exhaust flows are reported. An expression for how large a forced airflow is required to achieve unidirectional flow in a door opening for various temperature differentials between the rooms has been developed.

**PAPER IV** Spread of density currents within a multi-room building

During the cold season of the year complaints from residents about draughts in residences are commonly heard. These draught problems are caused by the replacement air which is taken directly from outside via air vents near the windows. In order to reduce the thermal comfort problems, it should be possible to supply air in spaces where the residents are not sedentary.
for extended periods, which is then distributed to other parts of the residence by means of so-called density currents. To investigate the fundamental conditions for such air supply and distribution, trace gas measurements have been conducted in a test apartment. The air was supplied and removed to the rooms via slots above and below the doors. The results of the measurements show that air distribution in this manner is possible if the slots are least about 10 cm high.

Studies of fundamental characteristics of two-dimensional density currents has also been done both at full scale in air and on a model scale with water as the working fluid. An expression for how the buoyancy flux in a two-dimensional density current in air dissipates with distance from the intake device when the current has warmed up is reported.

PAPER V  A note on air movements through horizontal openings in buildings

This paper reports on an experimental study of the possibilities of using buoyancy forces to distribute air and heat through horizontal openings. The experiments have been carried out in a scale model with water as the operating fluid. The result of the study shows that a staircase below a horizontal opening will increase the fluid exchange through the opening slightly.

PAPER VI  Air movements through horizontal openings in buildings – a model study

A building contains a number of large openings like doors and staircases. When the temperature of the spaces connected by these openings differs, the difference in density will cause air movements through them. Horizontal air movements through vertical openings in buildings like doors and windows are well investigated while studies of air movements through horizontal openings like stairwells are less frequent and therefore this work focuses on this case. The paper reports on an experimental study of the possibility of using buoyancy forces to distribute air and heat through horizontal openings. The experiments have been carried out in a scale model with water as the operating fluid. The result of the study shows that the flow rate through a horizontal opening is roughly half of the flow rate through a vertical opening for the same conditions, probably caused by the more complex flow pattern in the horizontal opening. A staircase below the horizontal opening will guide the flow somewhat and will cause a small increase of the fluid exchange through the opening.

PAPER VII  Conversion of electric heating in buildings – an unconventional alternative

To decrease the electric energy used for heating buildings it has become desirable to convert direct electrical heating to other heat sources. This paper reports on a study of the possibility of using an unconventional method for conversion to avoid installing an expensive hydronic system. The conversion method combines the ventilation and heating systems and uses air instead of water for distribution of heat within the building, taking advantage of thermal forces and the special properties of gravity currents. Full-scale tests have been carried out in a test apartment inside a laboratory hall where the conditions could be controlled. Temperatures and efficiency of ventilation have been measured to ensure that the demands with respect to thermal climate and air exchange were fulfilled. The results show that it is possible to use the method for heating and ventilation when converting the heating system, but further work has to be done to develop a detailed solution that works in practice.
10. References


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