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Measurements and control of the air motions within a building

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1. SYNOPSIS

There are a number of methods available concerning with distribution of air in buildings. Within control research, one can find new control algorithms which have not yet been used in practice. These new algorithms open the possibility of developing and implementing of new demand controlled ventilation systems.

In a building the internal air motions are due both to differences in temperature and pressure differences caused by the ventilation system. Therefore, one fundamental question is to what extent it's possible to control the air motions within a building using fan powered ventilation in combination with temperature control.

The aims of this paper is to report on measurements done to examine the influence of temperature differences between rooms on the air exchange through open doors in a building and to explore the use of modern control technique to minimise the temperature difference.

The result of the measurements shows that even very small (0.1-0.2°C) temperature differences between rooms cause bi-directional air flows in the doorways of a magnitude that exceed the flow rates caused by the mechanical ventilation system. Therefore it is necessary to control the temperatures in the rooms to make it possible for the ventilation system to distribute the air to those parts of the building where it is needed.

2. LIST OF SYMBOLS

$C(\Delta T)$	Coefficient
g' [m/s²] $= g\Delta T/T$	Reduced gravitation constant
g [m/s²]	Gravitation constant
Gr [-] $= g'h^3/\nu^2$	Densiometric Grashof number
ν [m²/s]	Kinematic viscosity
T_c [K]	Temperature in cold room
T_w [K]	Temperature in warm room
ΔT [K]	Tw-Tc
w [m]	Width of door way
h [m]	Height of door way
$A=hw$	Area of door way

3. INTRODUCTION

3.1 Theory

The flow in a door way can be caused by several mechanisms of which the two most important are:

- Density difference caused by temperature differences, ΔT
- Pressure differences caused by mechanical ventilation

In practice there is a combination of both. A flow driven by density difference, characterised by its reduced gravity $g'=g\Delta T/T$, through an aperture with area $A=hw$ and located in a partition wall with height H and width W can be written as:

$$q_e = f(\frac{w}{h}, \frac{w}{W}, \frac{h}{H}, Gr) \cdot A \cdot (g' \cdot h)^{1/2} \quad (1)$$

Where the first three factors are aspect ratio of the door way, contraction in width and contraction in height. Gr is the densiometric Grashof number. For a given geometry equation(1) can be cast into :

$$q_e = f(Gr) \cdot A \cdot (g' \cdot h)^{1/2} \quad (2)$$

For a fixed doorheight equation (2) implies the densiometric Grashof number is a function of the temperature (density) difference only. The presence of a temperature dependence has been observed by Kiel and Wilson (1989) and Fritsche and Lilienblum (1968).

For physically describing the flow through a door way there are two distinct models in use, both which make use of the Bernoulli equation. The orifice model makes use of the assumption that the pressure distribution is equal to that in the receiving room and the two-layer hydraulics model, Dalziel and Lane-Serff (1991), where the pressure distribution in the inflowing air is governed by its own density. In the two layer model flow separation is allowed for.

3.2 Ongoing research

To minimise energy consumption used for heating of ventilation air flow its is important that the air is distributed to the parts of a dwelling where the occupants are. To meet this demand one can make use of new control algorithms that have been developed but are not used in practice yet.

Björsell (1996) reports ongoing work on numerical simulation of air motions within a building in order to develop control algorithms for directing the ventilation air to the parts of the building where it is needed. Experimental work is carried out to develop methods to measure the air flow rates through open doors using velocity measurements in the door ways, Blomqvist, Sandberg (1996).

The aim of this paper is to continue development of experimental techniques to measure internal air movements within a multi room building using tracer gas and velocity measurements. The experimental work will develop various methods that can be used for validation of the simulation models.

4. TEST HOUSE

For the experimental work has been used a unique test house in the laboratory of the department. The house is built up to look like an ordinary Swedish apartment consisting of five rooms including hall, kitchen and bathroom (Figure 1). The height of the doors are 2.0m and the width 0.7m and 1.2m (living room door). The height of the apartment is 2.5m. The mechanical ventilation system of the house can easily be changed so it is possible to obtain any system desired.

The testroom is also equipped with computer controlled system for release of tracer gas. This makes it possible to use any type of tracer gas method. Furthermore the pressure and temperature can be recorded in each room. To be able to measure the flows through the door ways there is a computer controlled traversing unit in each door way. Each of these traversing units is equipped with 10 thermistor anemometers mounted at different heights. The anemometer was developed in house by Lundström et al. (1990) and is of the omnidirectional type. To get information about the inflowing air in each room the pressure difference compared to the ambient space was monitored during the measurements. Constant concentration tracer gas measurements have been carried out to determine the size of the incoming air flows to the different rooms including the infiltration. The result of those measurements is presented in figure 2 where the air flows are plotted as functions of the pressure difference across the building envelope.

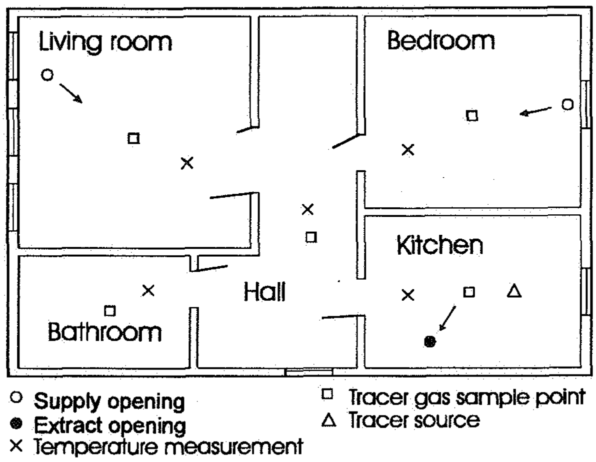

Figure 1 Test house

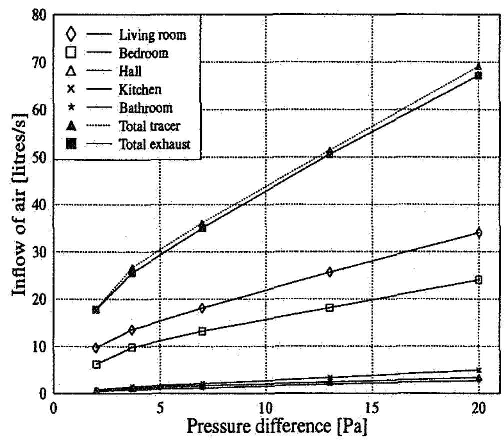

Figure 2 Measured inflow of air in each room versus pressure difference across the building envelope (doors closed).

5. EXPERIMENTAL DESIGN

5.1 Test conditions

In the test apartment was installed mechanical extract ventilation with one exhaust opening in the kitchen. The supply air was taken from the laboratory hall through two openings in the ceiling of the living room and bedroom. The exhaust air flow rate was measured by means of orifice plates, and the supply air was determined by constant concentration tracer gas measurements. To obtain a suitable temperature difference between the rooms electrically heated radiators were installed in all rooms. The electrical power of the heaters was 1000 W each. The apartment was originally equipped with ordinary commercial temperature regulators. The performance of those regulators has shown to cause temperature oscillations in the rooms. Because of the fact that even very small temperature differences between the rooms cause large bi-directional air flows in the door ways when the doors are open, it has been necessary to improve the temperature control in the test apartment in order to get steady state conditions. To solve the problem the regulators have been replaced by a computer based control system. Table 1 shows the temperature set values for the test cases and the actual measured values during the tests.

In order to measure the air flow rate through the door openings computer controlled traversing units equipped with thermistor anemometers in 10 different heights were installed in each door opening. The flow was visualised by smoke to determine the direction of the flow and the flow rate was calculated by integration over the each door aperture.

Temperature differences between hall and kitchen		
Flow rate [l/s]	Set value [°C]	Measured value [°C]
25.0	0.0	0.08
37.5	0.0	0.09
37.5	0.3	0.26
37.5	0.6	0.57
50.0	0.0	0.09
50.0	0.6	0.62

Table 1. Set values and measured values for the temperature differences for the six test cases.

To be able to trace the airflow on its way from the from the kitchen through the apartment, tracer gas was introduced in the kitchen at the triangle mark in figure 1. The concentrations were then monitored in each room at the square marks in figure 1.

At the cross marks in figure 1 the temperature was measured at four different heights by means of thermocouples connected to a data acquisition system.

5.2. Measurements

Measurements have been carried out for three different flow rates, (25, 37.5 and 50 litres/s) and for three different temperatures in the kitchen (23.0, 23.3, and 23.6°C). The temperature in the rest of the apartment has been 23.0°C.

In the door openings the air speed has been recorded in 12 (living room) resp 7 different horizontal positions in the cross section of the doors. The larger number of horizontal positions in the living room door is because of its larger width (1.2m). The values recorded are averaged over a time period of ten minutes. To determine the direction of the air movements the flow patterns have been visualised using smoke technique.

The exhaust air flow rates are measured by means of orifice plates and the supply air entering each room is measured by constant concentration tracer gas technique.

To follow the air flow patterns in the door ways tracer gas has been injected at the triangle mark in the kitchen (figure 1). The gas concentration has been measured in each room at the square marks in the same figure. The sampling points consisted of vertical tubes with holes at different heights to get an average of the concentration.

6. RESULT

6.1 Temperature and velocity

In figure 3 the result of the measurements is shown for the isothermal case. The curves show the temperature gradients in the kitchen compared to the gradient in the hall for three different extract air flow rates. In the same diagram is also shown the average air speed at the different horizontal levels. Air speed is defined as positive in the direction towards the hall. In the diagrams the upper x-axis refer to velocity and the lower x-axis refer to temperature.

In figure 4 the result is shown in the same way for the case where the temperature in the kitchen was 0.6°C higher than in the hall and the ventilation air flow rate was 50 litres/s.

6.2. Tracer gas measurements

To determine the air exchange through the kitchen door a constant tracer gas flow of 7.0 litres/h was introduced in the kitchen at the triangle mark in figure 1. To accomplish good mixing of the tracer gas a small fan is used. The tracer gas concentration was monitored at the square mark in each room until steady state conditions were reached.

Figure 5 shows the result of those measurements in the isothermal case. The curves represent the concentrations in the kitchen the hall and in the extract opening. The calculated concentration in the extract air at steady state conditions is added as a separate curve for comparison. The concentration in the extract air is calculated as the tracer gas flow rate divided by the extract air flow rate. The measured values in the extract corresponds well to the estimate. The measured average concentration in the kitchen does also correspond fairly well to the expected value which indicates that the tracer gas is mixed well into the room air.

Figure 6 shows the measurements for the case when the temperature in the kitchen is 0.6°C higher than in the hall and the extract air flow rate is 50 litres/s.

In figure 7 the result of the measurements is summarised in a bar graph which shows the steady state concentration in the hall divided by the calculated concentration in the kitchen for the six test cases.

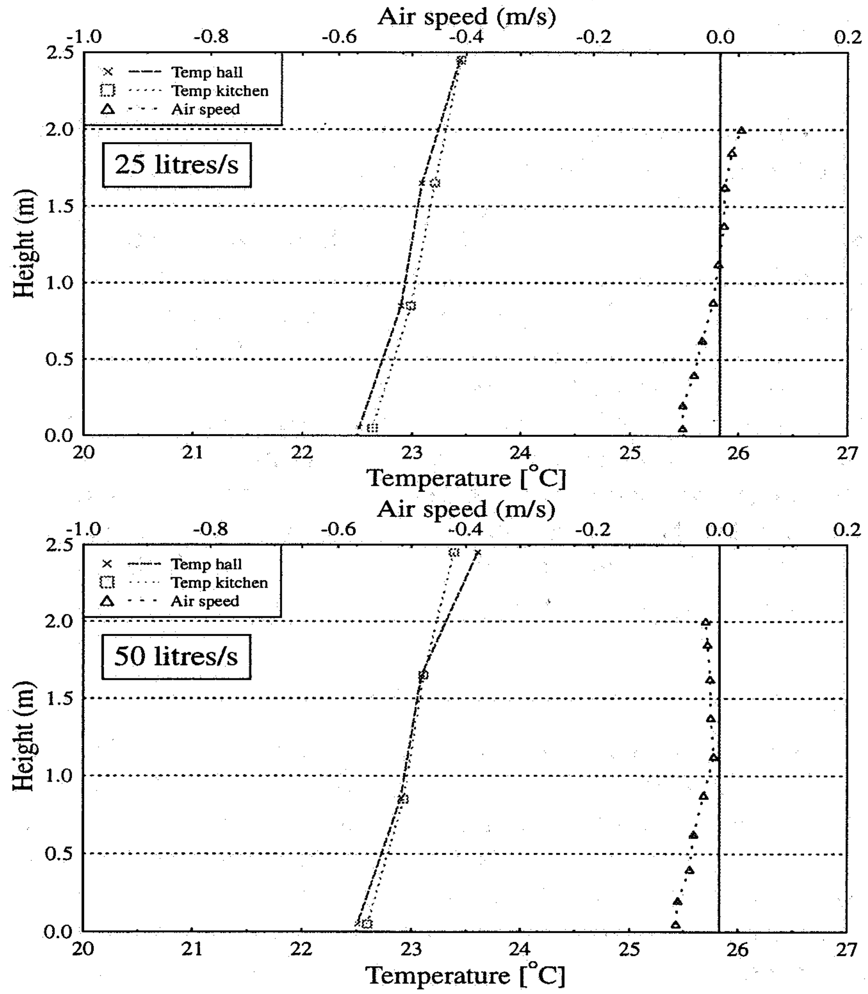

Figure 3. Air velocities and temperature differences in the kitchen door. Temperature set values are equal in kitchen and hall. Air flow rates : 25 and 50 l/s

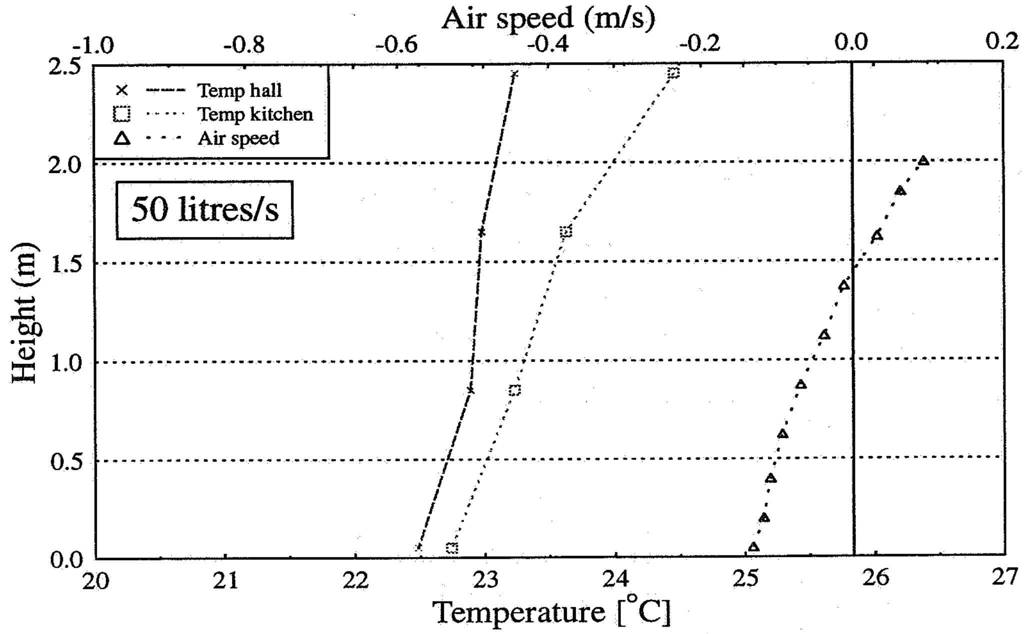

Figure 4. Air velocities and temperature differences in kitchen door. Temperature set value is 0.6°C higher in kitchen. Air flow rate : 50 l/s.

7. DISCUSSION

Using the orifice model and assuming parallel temperature distribution in the two adjacent rooms the total flow through an opening caused by temperature difference can be written as:

$$q_e = C(\Delta T)\cdot A\cdot(g'\cdot h)^{1/2} \qquad \text{(Etheridge,Sandberg)} \qquad (3)$$

Where C is an experimentally determined coefficient. When a forced flow is imposed in one direction the minimum forced flow needed to in the mean get unidirectional flow in the opening can be written as:

$$q_n = \sqrt{8}\cdot q_e \qquad \text{(Etheridge,Sandberg)} \qquad (4)$$

Figure 8 shows the air flow caused by temperature difference in the kitchen door calculated using equation(4) and the coefficient C set to 0.15. The estimated flow at a temperature difference of 0.1°C corresponds rather well with the result of the measurements shown in figure 3 where unidirectional flow has been obtained at a flow rate of 50 l/s and the actual temperature difference has been ≈0.1°C. However, the tracer gas measurements on the same case (figure 7) show that the tracer gas concentration differs from zero in the hall which indicates that the flow is not completely unidirectional. This can be explained by turbulence effects causing time dependent air flow in both directions.

It is obvious that even very small differences in temperature between rooms generates air flows which are large compared to the flows caused by the mechanical ventilation. As a comparison it can be mentioned that the Swedish building code prescribes a total forced ventilation flow

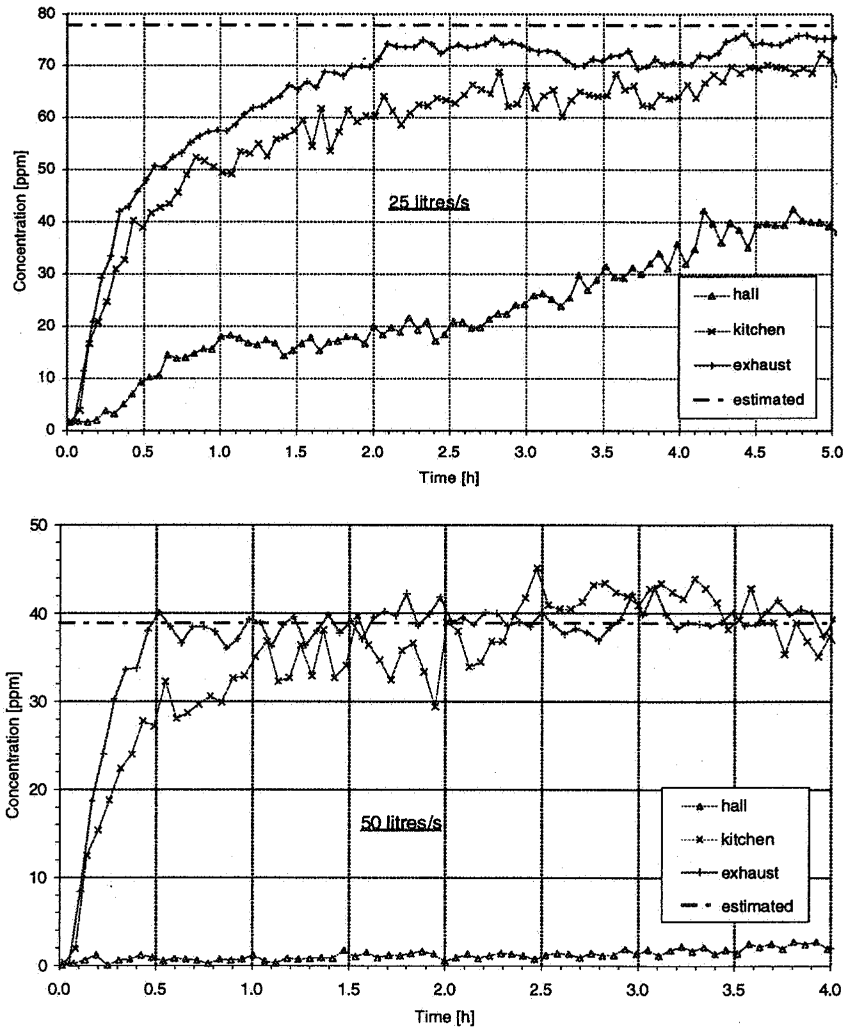

Figure 5. Spread of tracer gas from kitchen for different air flow rates. Isothermal.

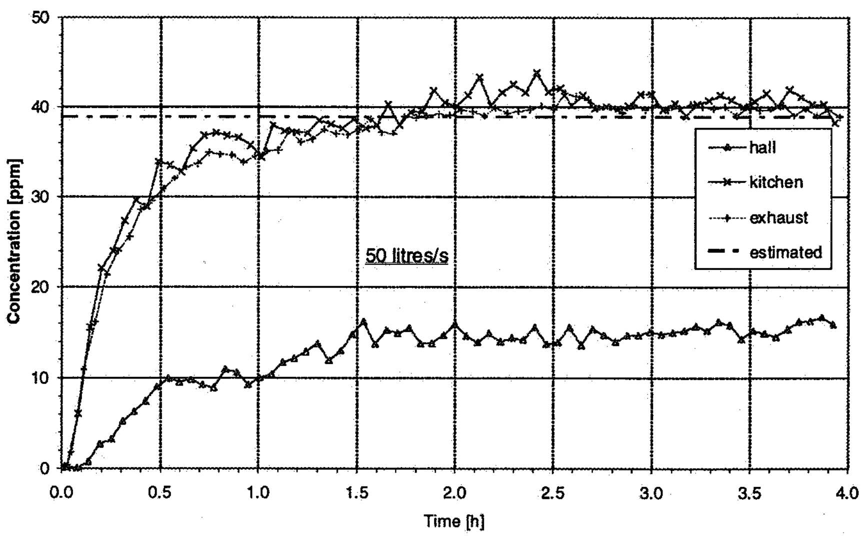

Figure 6. Spread of tracer gas from kitchen. Temperature difference = 0.6°C

rate of 25 l/s in an apartment of the same size as the test building. Usually the flow is equally distributed between kitchen and bathroom.

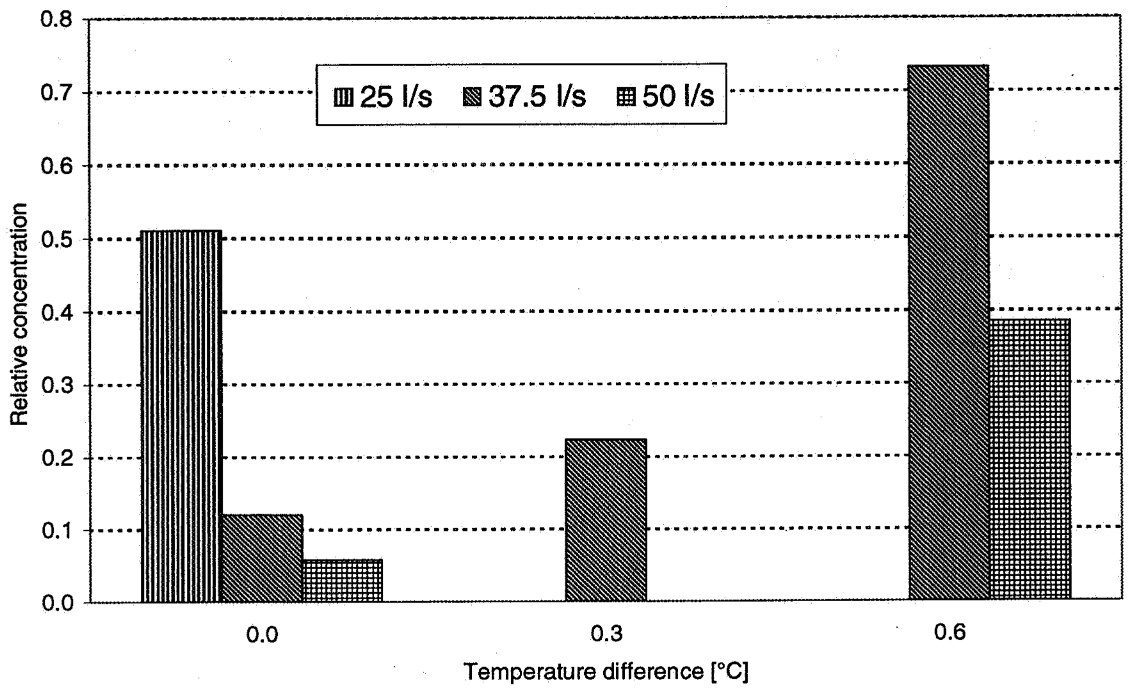

Figure 7. Summarised result of tracer gas measurements. Concentration in hall divided by concentration in kitchen at steady state conditions.

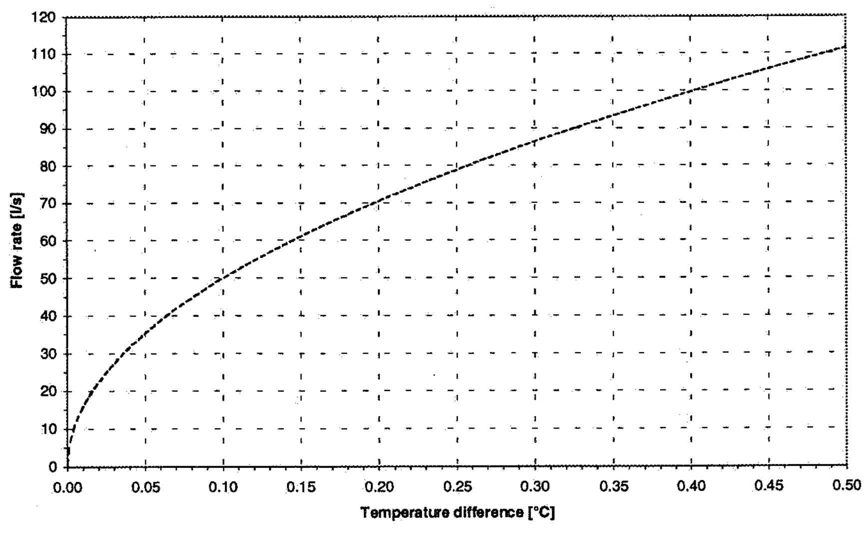

Figure 8. Estimated air flow rate through a door aperture using equation (4) (C=0.15).

8. CONCLUSIONS

The bi-directional flow caused even by very small temperature differences between adjoining rooms in a building are large compared to the ventilation flow rates. Therefore it is important to keep those differences small. Using modern computer based control technique it is possible to achieve temperature differences between rooms as small as 0.1°C.

The result of the measurements presented in this paper shows that in a door way of the size 0.7x2.0 m (WxH) it is required a ventilation flow rate of 50 l/s to get unidirectional flow in the mean when the temperature difference between the rooms is 0.1°C. This is in good accordance with the theoretical value.

The tracer gas measurements show however that even if the mean value of the flow is unidirectional turbulence can cause leakage through the door way. In the test case with 50 l/s and an actual temperature difference of 0.1°C the tracer concentration in the room nearest to the source room was 5% of the concentration in the source room.

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