THE MIXING OF AIR BETWEEN ADJACENT ROOMS IN DWELLINGS

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ABSTRACT

Calculating contaminant concentrations in dwellings using the multi-chamber theory implies some method of evaluating the air exchange through the doorways. The development and main features of an analytical method applicable to this purpose are presented. The parameters of the method are evaluated by tracer gas measurements in a system containing two chambers. The results are analyzed and their usefulness estimated.

INTRODUCTION

The main goal in developing the ventilation of buildings is usually to find a solution which achieves good air quality in the whole ventilated space in all situations and with reasonable energy costs. It is therefore essential to know how different factors affect the contaminant concentration histories in the system. The movement of the air, particles and other contaminants in a dwelling containing several rooms is a complicated phenomenon. Nevertheless, the concentrations can be evaluated using the well-known multi-chamber theory [1]. Calculations using this theory imply a knowledge of the quantities describing the system in question. Several factors influence the concentration histories. The mixing of air between adjacent rooms, which is described by the air flows through the doorways, is one such factor.

The purpose of this study is twofold. First, to choose a method for evaluating the air flows through doorways, to be able to calculate concentration histories using the multi-chamber theory. Second, to find out the features of this method when applied to conditions existing in dwellings. In principle there are several possibilities to evaluate the air flows between adjacent rooms. In the case of an existing system the air velocities in the doorways can be measured and the flow rates integrated. Methods using one or several tracer gases can also be used. With the same amount of work the quantities of primary interest, the concentration histories can, however, be measured direct without any need for further calculations. It might in this context thus be more natural to evaluate the flows by calculation, either using numerical fluid dynamical methods or analytical approaches. The numerical methods do not usually correspond with the multi-chamber theory as regards the assumptions made and the information included in the results. Hence, the best alternative seems to be the analytical approach.

THE MOVEMENT OF AIR THROUGH THE DOORWAY

The analytical calculation of the air exchange through a doorway implies some simplifying approximations. Brown and Solvason [2] considered a system of two chambers separated by a vertical partition. The fluid in the system was able to move from one chamber to the other through a rectangular opening of height H and width W. The first approximation was to assume uniform temperatures T_1 and T_2 and uniform densities ρ_1 and ρ_2 in the chambers. The system was closed, which means that there was no connection between the system and its environment. Thus the pressure difference between the two chambers at level z is

$$\Delta p(z) = g(\rho_2 - \rho_1)z, \qquad (1)$$

where g is the acceleration due to gravity. The zero level of the vertical coordinate is determined in a natural manner by the conservation of mass. Because there is no net flow, the flow rate from chamber 1 to chamber 2 is equal to the flow rate from chamber 2 to chamber 1. To achieve such a situation the pressure difference in the opening must be symmetrical, Fig.1a. Further, if the flow through the opening is assumed to be ideal and the fluid is assumed to be a perfect gas, the velocity at level z becomes

$$v(z) = \left(2g\frac{\Theta}{T}z\right)^{\frac{1}{2}}, \qquad (2)$$

Θ being the difference in gas temperatures between the chambers and T being the mean gas temperature in the whole system. The volume flow rates through the opening are calculated by integrating the velocities over the appropriate area. Thus, for example in the case of Fig.1a the flow rate through the lower part of the opening turns out to be

$$Q_1 = CW \int_{-H/2}^{0} v(z)dz. \tag{3}$$

The coefficient of discharge was added to allow for the real frictional nature of the flow. The integration of Eqn.(3) yields

$$Q_1 = \frac{1}{3} CWH \left(\frac{aH}{2}\right)^{\frac{1}{2}}, \tag{4}$$

where $a = 2g\Theta/T$. The flow rate Q_2 in the opposite direction through the upper part of the opening is in this case equal to Q_1.

Shaw and Whyte [3] developed the theory further for hospital hygiene purposes. They considered an open system by adding a net air flow to the previous case. The principle of pressure summation thus gives for the pressure difference in the doorway

$$\Delta p(z) = g(\rho_2 - \rho_1)z + p_x, \tag{5}$$

p_x being the pressure difference due to the ventilation system or some other external source and producing the net flow rate Q_x, Fig.1b. By applying the Bernoulli equation both to the total flow and to the net flow separately, the velocity in the doorway becomes

$$v(z) = (az + v_x^2)^{\frac{1}{2}}, \tag{6}$$

where v_x is the mean velocity in the doorway corresponding to the net flow rate. Now the flow rates in opposite directions are no longer equal. The outflow Q_2 having the same flow direction as the net flow and the inflow Q_1 flowing in the opposite direction are

$$Q_1 = CW \int_{-H/2}^{z_0} v(z)dz, \tag{7}$$

$$Q_2 = CW \int_{z_0}^{H/2} v(z)dz. \tag{8}$$

The bound of integration z_0 is called the neutral level and its position changes depending on the temperature difference and the net flow rate. When the neutral level is between $-H/2 \leq z_0 \leq H/2$, the integration of Eqns.(7) and (8) yields

$$Q_1 = \frac{1}{3} CWH \left(\frac{aH}{2}\right)^{\frac{1}{2}} \left(1 - \frac{2v_x^2}{aH}\right)^{\frac{3}{2}}, \tag{9}$$

$$Q_2 = \frac{1}{3} CWH \left(\frac{aH}{2}\right)^{\frac{1}{2}} \left(1 + \frac{2v_x^2}{aH}\right)^{\frac{3}{2}}. \tag{10}$$

Increasing the net flow rate decreases the inflow. When the neutral level reaches the value $z_0 = -H/2$, the inflow is equal to zero and the outflow is equal to the net flow rate. Shaw and Whyte made an extensive series of measurements to verify this theory. They did, however, have some slight difficulty in explaining the results related to small, 0...2 K temperature differences. They found a solution by setting the coefficient of discharge as a function of the temperature difference Θ and the velocity v_x.

Lidwell [4] criticized the above presentation severely. His own solution was to use a turbulence pressure term $\pm p_u$ operating equally in opposite directions. This way the movement of air in the doorway could be explained, when there was no temperature difference or net flow. The pressure difference between the rooms is now

$$\Delta p(z) = g(\rho_2 - \rho_1)z + p_x \pm p_u. \tag{11}$$

Due to the nature of the turbulence pressure, there are two flow velocities

$$v^+(z) = (az + 2(p_x + p_u)/\rho)^{\frac{1}{2}} \tag{12}$$

$$v^-(z) = (az + 2(p_x - p_u)/\rho)^{\frac{1}{2}} \tag{13}$$

and also two neutral levels z_0^+ and z_0^-, Fig.1c. The inflow and outflow are each divided into two components. For example, in the case in Fig.1c the inflow is

$$Q_1^+ = \frac{1}{2} CW \int_{-H/2}^{z_0^+} v^+(z)dz \tag{14}$$

$$Q_1^- = \frac{1}{2} CW \int_{-H/2}^{z_0^-} v^+(z)dz \tag{15}$$

and after the integration the components are

$$Q_1^+ = \frac{1}{6} C W H \left(\frac{aH}{2}\right)^{\frac{1}{2}} \left(1 - \frac{4(p_x + p_u)}{\rho a H}\right)^{\frac{3}{2}} \tag{16}$$

$$Q_1^- = \frac{1}{6} C W H \left(\frac{aH}{2}\right)^{\frac{1}{2}} \left(1 - \frac{4(p_x - p_u)}{\rho a H}\right)^{\frac{3}{2}} . \tag{17}$$

The final value for the inflow is the sum of the positive and negative components above. The outflow, having the same flow direction as the net flow, is calculated in an analogous way. Further, the Bernoulli equation applied separately to the net flow leads to inconsistencies between the net flow rate, the outflow and the inflow. Therefore the values for the flow rates are calculated by simply choosing for the pressure difference p_x a value such that the equation

$$Q_x = Q_2 - Q_1 \tag{18}$$

becomes valid. Depending on the position of the neutral levels, the temperature difference and the mutual values of the pressure differences, the outflow and inflow are calculated using equations of different kinds.

A METHOD FOR EVALUATING THE PARAMETERS C AND p_u

The temperature difference between adjacent rooms in dwellings rarely exeeds two or three degrees centigrade when the door is open. Similarly, the mean velocity corresponding to the net flow rate through the doorway usually varies from a few centimetres per second to only a few millimeters per second. From this point of view the measurements made e.g. by Shaw and Whyte [3] contain relatively little relevant information. For this reason it was decided to seek values for the coefficient of discharge C and the turbulence pressure p_u in conditions usually existing in dwellings. Because the final goal was to combine the previous method with the multi-chamber theory to calculate contaminant concentrations in systems containing several rooms, it was natural to choose a tracer gas measurement method. After trying a few alternatives, a stationary two-chamber method was chosen. This method is based on tracer gas measurements in a system containing two chambers, Fig.2. Using external equipment a net flow rate Q_x is forced through the doorway from chamber 1 to chamber 2. A constant release rate $\dot{m}_2$ of tracer gas is injected into chamber 2, where the concentration is assumed to have a uniform value C_2. The inflow Q_1 also transports tracer gas into chamber 1, achieving a uniform concentration C_1. The conservation of mass for chamber 1 yields

$$V_1 \frac{dC_1}{dt} = -Q_2 C_1 + Q_1 C_2, \qquad (19)$$

where V_1 is the volume of chamber 1 and t is time. In a stationary situation the time derivative of the concentration C_1 is equal to zero and Eqn.(19) becomes

$$\frac{Q_1}{Q_2} = \frac{C_1}{C_2}. \qquad (20)$$

Hence only two quantities, the concentrations C_1 and C_2 need to be measured to evaluate the ratio of the flow rates Q_1 and Q_2. On the other hand, according to the theory on the mixing of air between adjacent rooms, the ratio of the flow rates is a function of the coefficient of discharge and the turbulence pressure

$$\frac{Q_1}{Q_2} = f(C, p_u). \qquad (21)$$

To solve the parameters C and p_u at least two values measured in identical conditions are needed for the ratio C_1/C_2. If there are more than two values available, it is possible to choose for the parameters values which produce the best agreement between the measured and calculated concentrations.

MEASUREMENTS

Measurements to evaluate the parameters C and p_u were performed in the laboratory of the National Swedish Institute for Building Research. A test house containing five rooms and having a floor area of $70.2m^2$ and a total volume of $175.7m^3$ was available, Fig.3. By closing and sealing the doors to the hall, the kitchen and the bedroom were separated from the other rooms to form a system of two chambers. The supply air into this system came through two air inlets located above the bedroom window. The exhaust air was extracted from the kitchen. The temperature difference between the rooms was achieved using radiators located beneath the window in both rooms. The tracer gas, a mixture of He and N_2O, was injected at a constant release rate through rotameters into the kitchen. To make the concentration distribution as uniform as possible, the gas was injected at sixty points by means of perforated tubes. The air temperatures were measured at the center point in each room. The concentrations were monitored at three different levels in the center of each room and at two levels by the doorway. The net flow rate through the doorway, which was equal to the supply flow rate to the bedroom, was measured separately before and after every parameter measurement using the constant concentration method [5].

As was previously mentioned, to solve the values of the coefficient of discharge and the turbulence pressure at least two pairs of concentration values are needed in a stationary situation. This was done by changing the release rate of the tracer gas twice during a twelve-hour run. In this way three concentration levels were achieved during each measurement situation and the values of the parameters could be based on three pairs of concentration values. Fig.4 shows the concentration histories of two such measurements. During run TC13 the temperature difference Θ was relatively large. The 2.03 m high doorway was only 0.12 m wide. As a consequence the mean velocity v_x corresponding to the net flow rate was rather high. The flow in the doorway was steady and clear-cut. Because the temperature in the kitchen was higher than in the bedroom, the air flowed from the kitchen to the bedroom through the upper part of the doorway and back through the lower part. The highest concentrations were, as expected, in the kithcen. The existence of a concentration difference between the upper and lower part of the kitchen is clear. This was due to the air flow from the bedroom. A similar difference also existed in the bedroom. Thus, the assumed uniform concentration difference was not valid in practice. The concentration distribution can naturally be made uniform by mechanical mixing e.g. by using fans. This was also tried while developing the injection technique. The system was, however, extremely sensitive and the use of any kind of fan was out of the question, because this immediately affected the air flow through the doorway. Hence the uneven concentration distribution must be accepted and the effects must be compensated in the calculation procedures. Instead of a stationary situation a quasi-stationary situation must likewise be accepted in practice. During run TC17 both the temperature difference and the mean velocity were small because the door between the rooms was wide open. The flow was no longer as steady. The temperature in the kitchen was still higher and the flow directions were in principle the same as during the previous example. The fluctuations in the concentrations were then stronger because of the smaller heating power and as a consequence of the poorer thermal mixing. According to visual observations, if both the temperature difference and the mean velocity were small, the velocity distribution in the doorway was indeterminate and unstable. Nevertheless, measurements using tracer gas can be performed also under such conditions.

To evaluate values for the coefficient of discharge and the turbulence pressure, more than twenty runs similar to those presented in Fig.4 were made. The temperature difference between the center points of the rooms varied between $\Theta = 0...3$ K. The specific flow rate of the system was about $0.5(m^3/h)/m^3$. By keeping the net flow rate through the doorway constant and by changing the position of the door, three different values for the mean velocity were achieved in the range v_x=0.75...4.5 cm/s. The concentration of each chamber was calculated as a mean value of all three measuring points during one hour before the change in the tracer gas release rate. In this way three concentration values for both chambers could be derived from each run. Using Eqns.(20) and (21) a combination of values for the parameters was chosen such that the best agreement between measured and calculated concentrations was achieved according to the criterion of least squares. These calculations were performed using a digital computer.

THE PARAMETERS

The values of the parameters vs. the temperature difference are presented in Fig.5. Each level of velocity v_x has a symbol of its own. The first impression is that the scatter of the results is quite large. The coefficient of discharge does, however, seem to be a function of both the temperature difference and the mean velocity and it can be presented by means of an exponential function

$$C(\Theta, v_x) = 3.7v_x + 6.4v_x e^{-\Theta} - 0.90e^{-\Theta} + 0.96, \tag{22}$$

where the unit of measurement for the temperature difference is [K] and the unit of measurement for the mean velocity is [m/s]. On the other hand, no correlation can be found between the previous arguments and the turbulence pressure. The influence of the turbulence pressure on the values of the flow rates is of importance only when Θ and v_x are both small. For this reason and for the lack of correlation, a constant value p_u=30 mPa was chosen for calculation purposes.

In seeking an explanation for the large scatter of the results, the effects of the theory itself spring to mind first. The analytical model contains several approximations which are compensated by choosing suitable values for the parameters. However, many factors affecting the air exchange through the doorway are not included in the theory. Futher, the method for deriving the parameters causes scatter particularly in the values of p_u, because the coefficient of discharge has a stronger influence on the calculation result. Errors in the measurements do of course also affect the results. The influence of variations in the air humidity was especially clear as no compensation was used.

DISCUSSION

The aim of the coefficient of discharge is to take into account the effects of the real frictional flow compared with the ideal flow. In physical terms this coefficient should always be smaller than unity. The tracer gas measurement method did, however, also give values larger than unity. This can of course be explained by errors in measurement because the excess is only small. Another reason may be, that the evaluation of the parameters was based not only on the theory for calculating the air flows through the doorway but also on the multi-chamber theory. In this context complete mixing was assumed, this in itself being in harmony with the assumption of uniform temperature, though it may affect the values of the parameters. The position of the door may also influence the coefficient of discharge, but it hardly explains why the theoretical maximum value was exeeded.

The turbulence pressure is a residual term aiming to explain the air movement through the doorway which cannot be explained by the other factors included in the theory. The air inside a dwelling is always moving. There is no need for a temperature difference between some specified points in the rooms or a net flow rate to achieve air movement through the doorway. Warm and cold surfaces create convective flows which make the whole air mass move. The impulse of the supply air also has an effect on the movement of air in the room. Such phenomena are of no minor importance, especially when the temperature difference and the mean velocity correponding to the net flow rate are small. At larger temperature difference values the turbulence pressure has practically no influence on the calculated flow rates.

Despite of their apparently uncertain values, the parameters have proved to be quite useful. By combining the multi-chamber theory with the method for calculating the air flows through a doorway, a computer program [6] was developed to calculate concentration histories in dwellings. The measured concentration histories in a system of five rooms could in most cases be described satisfactorily by means of the calculation program. The program must, however, be used with care. It can be applied only to conditions usually existing in dwellings. In addition, all the chambers must be horizontally adjacent. For vertical flows it should be possible to make corresponding parameter evaluations than for horizontal flows already has been done. In this way the usefulness of the calculation procedure could be further increased.

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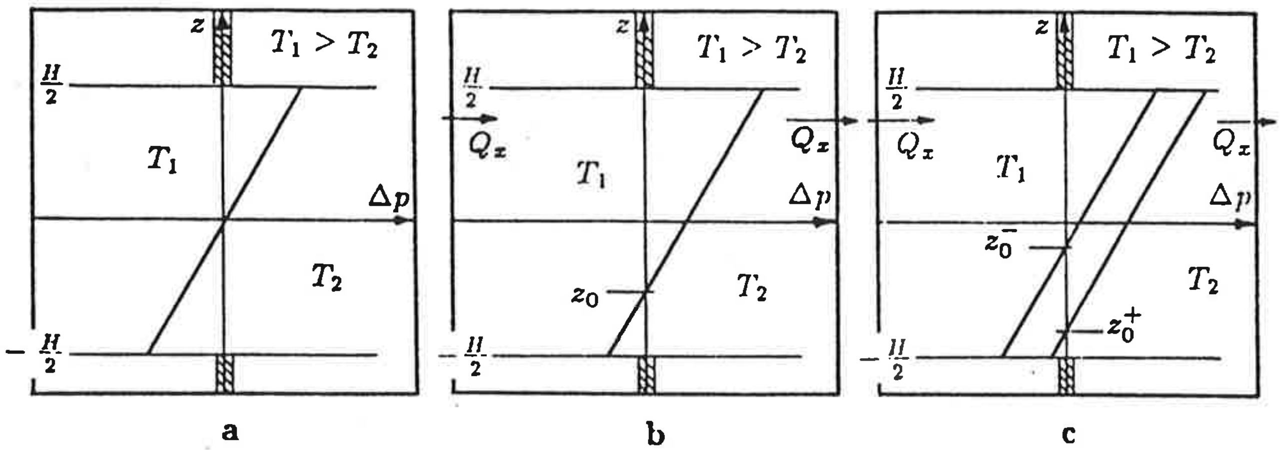


Fig.1 Pressure difference between adjacent chambers

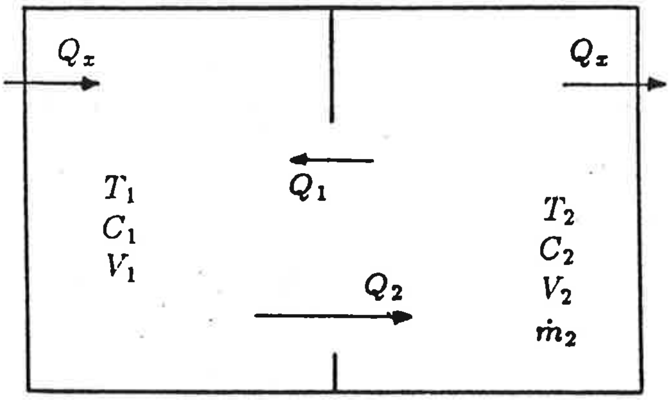


Fig.2 A system of two chambers

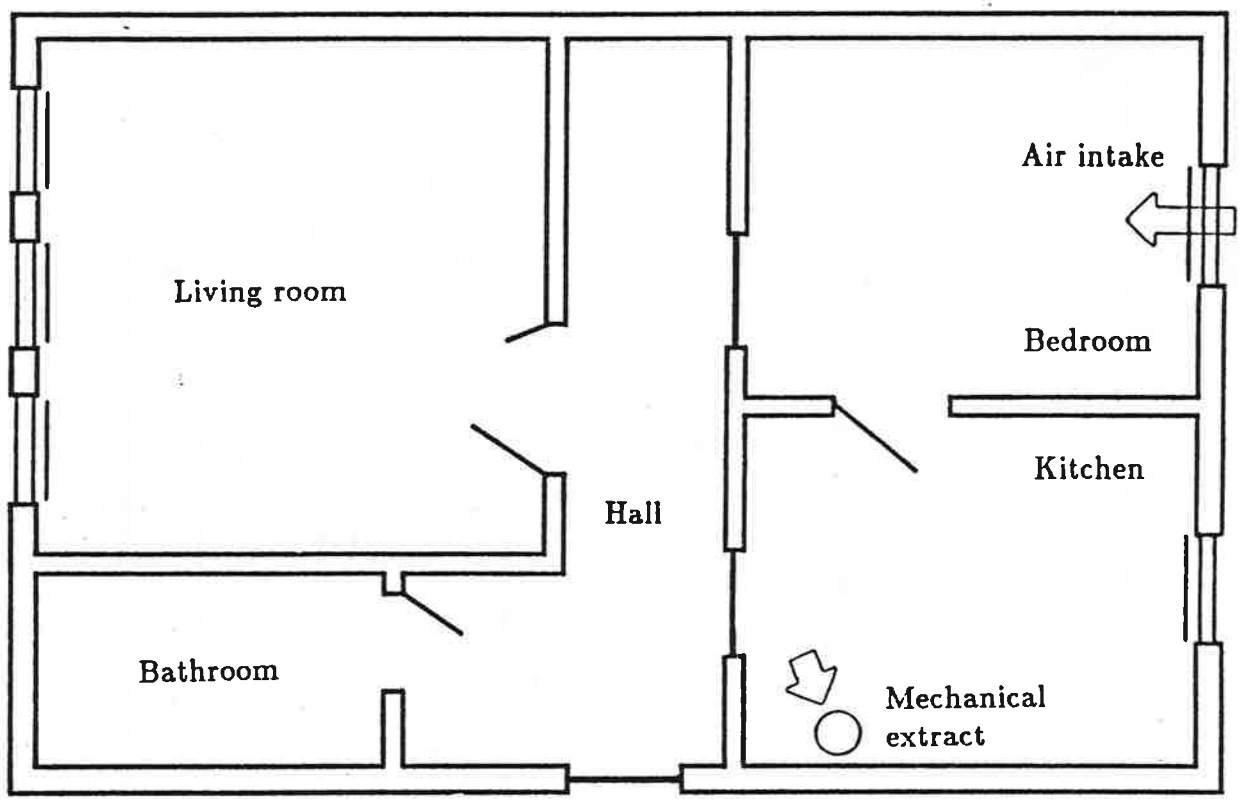
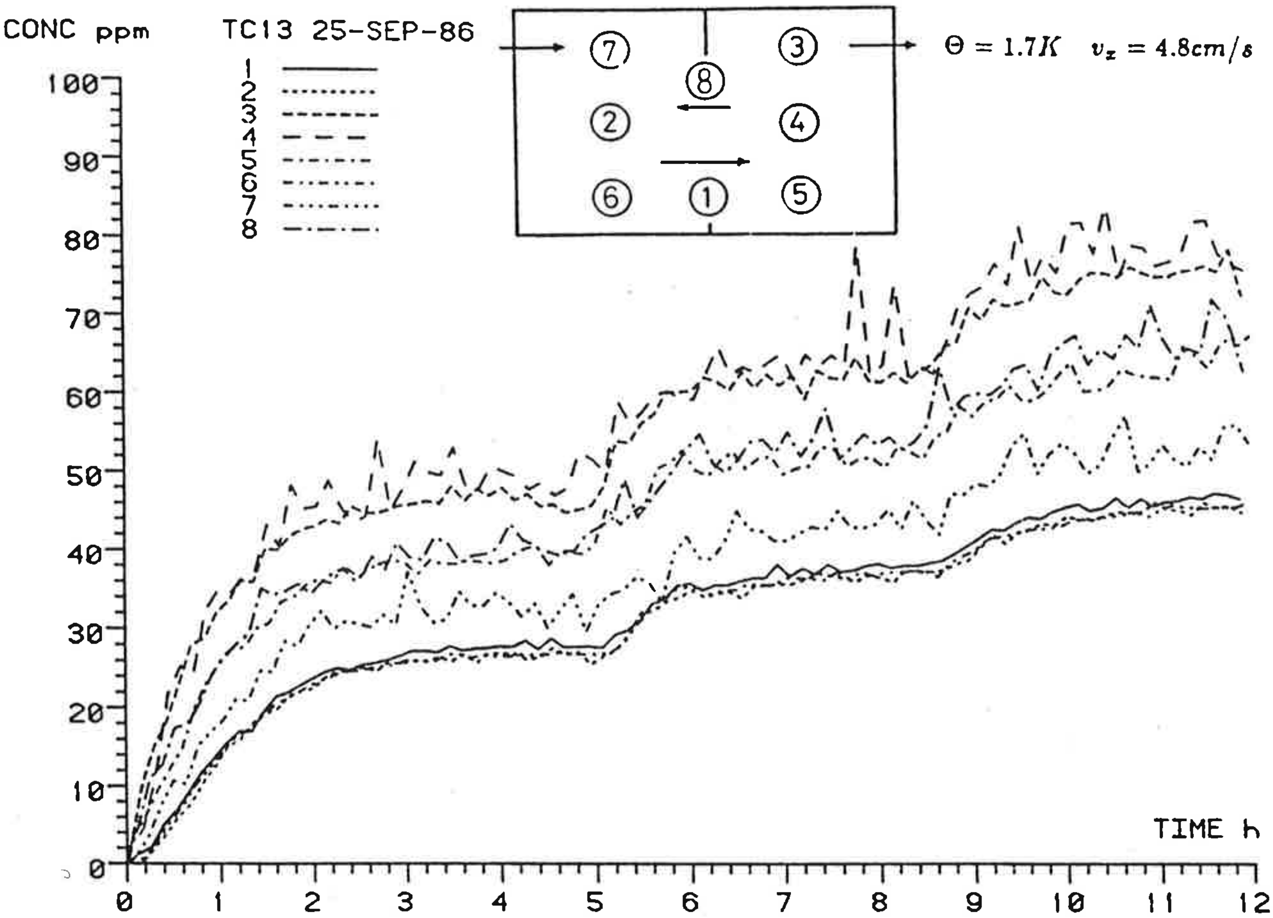


Fig.3 The test house of The National Swedish Institute for Building Research



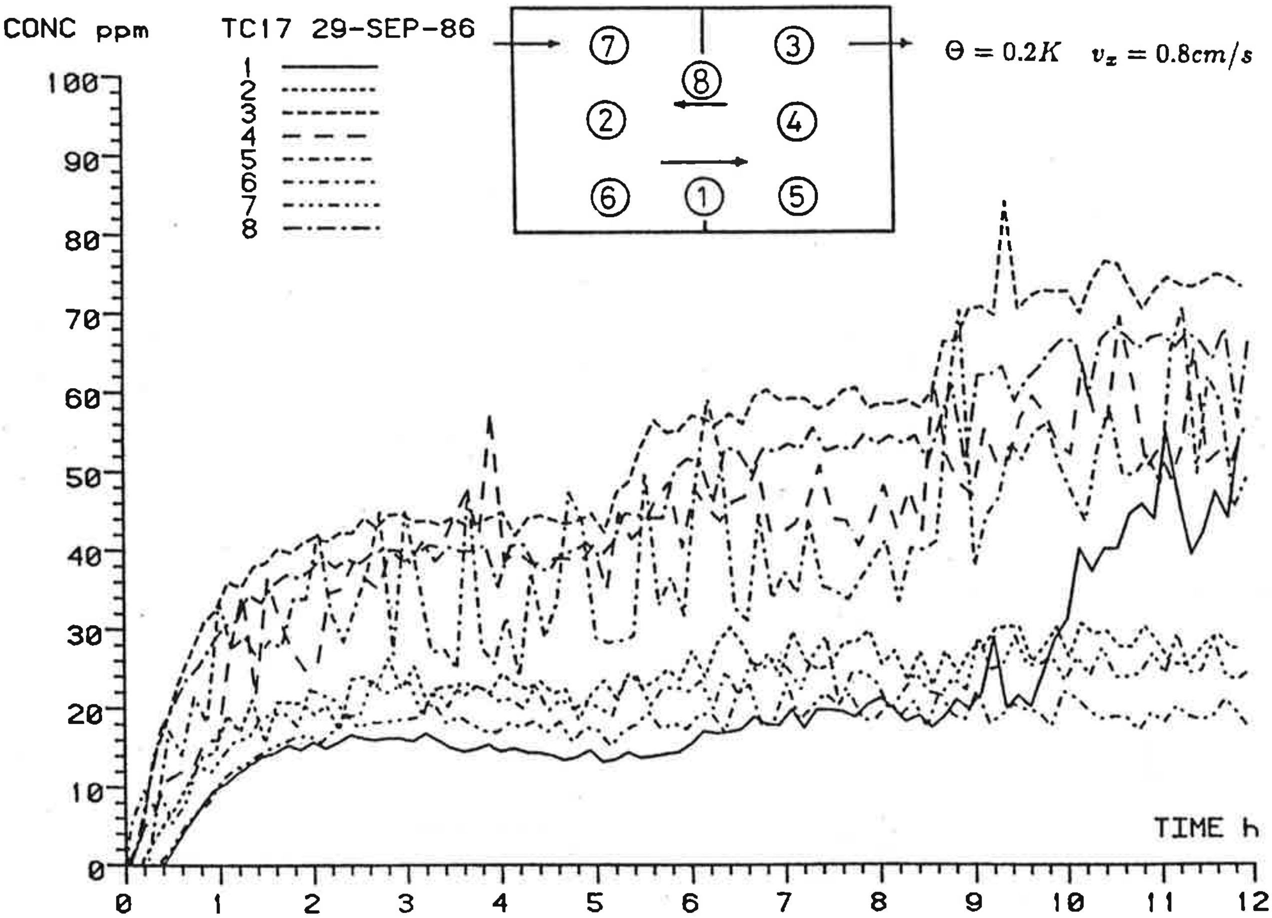


Fig.4 Two examples of concentration histories. The stationary two-chamber method

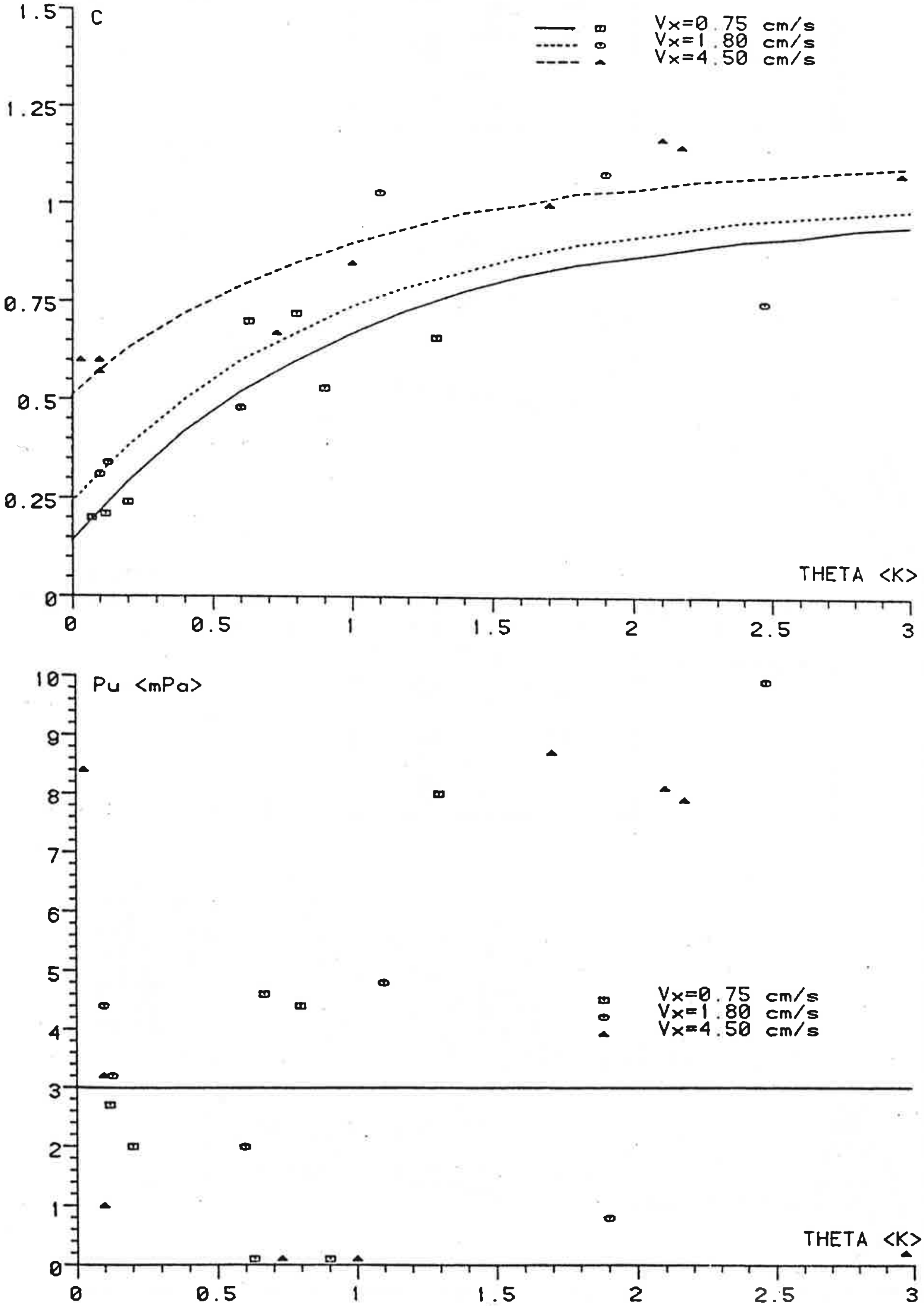


Fig.5 The coefficient of discharge and the turbulence pressure vs. temperature difference