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A method of creating plug flow in ventilated rooms

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A METHOD OF CREATING PLUG FLOW IN VENTILATED ROOMS

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Introduction

The results presented here are based chiefly on measurements made in a water scale model. Additional results have been obtained with the help of computer simulations of flows in the same model. The single-room model has been chosen to be as simple as possible, and the nearest field of application in this form might be some type of "clean room" application, perhaps for industrial rooms or processes.

The Péclet number (Pe) has been used in order to make qualitative comparisons between different flow profiles. This is a dimensionless number, which can be interpreted as the ratio between the convection flow and the diffusion flow in the room being investigated. With increasing Péclet number the flow profile approaches that for plug flow.

In order to be able to transfer the results obtained here, on a model scale and with water as the flow medium, to full-scale conditions and air flow, it is possible to make use of simple uniformity laws.

Attempts in recent years to reduce energy consumption have in many cases involved a reduction in the total ventilation flow. In order to avoid a reduction of comfort in this case, it follows that the efficiency of the ventilation has to be increased.

Particular importance will attach to system solutions where the incoming air can meet demands for comfort as regards both hygiene and temperature. The efficiency achieved is often seen as a measure of uniformity. For purposes of comfort, it is necessary that neither the flow velocity nor the air temperature should exhibit over-large local variations.

Research in this field is relatively new, and the flow conditions are almost impossible to predict theoretically. In order to have any useful models it is usually necessary to carry out experiments, both small scale and full scale.

For a qualitative assessment of the flow profile produced by ventilation, it is necessary to have modern measuring equipment and well developed analytical procedures. A measure of the flow quality is given by the Péclet number. This number (Pe) can be said to constitute a measure of the axial dispersion of a trace element when it is flowing through the space under investigation.

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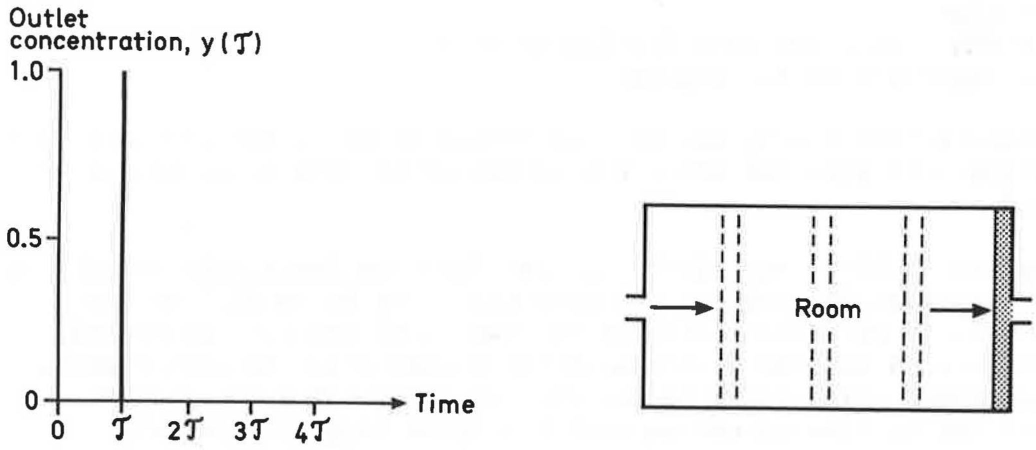
Ideal flow conditions

In order to be able to make qualitative assessments of the flow of ventilation air through an investigated control volume, e.g. a room or a hall, it is necessary to compare the flow with existing ideal models. Normally, a comparison is made with one or both of the ideal flow profiles, plug flow and complete mixing. For ventilation purposes, plug flow is in many cases preferable to a complete re-mixing.

If no mixing occurs in axial direction (the direction of plug flow) then the plug flow is ideal. The easiest way of achieving these conditions is given by the flow profile in long, narrow spaces where there is turbulent flow. In theory, plug flow consists of a series of fluid layers which extend across the entire cross-section of the flow. The layers are separated from each other by hypothetical walls which prevent axial mixing. There is no mixing between these elements of volume. This means in turn that all elements have the same residence time, defined as volume/flow (V/q), within a given control volume. The velocity profile will be even, and all the layers will be identical as regards temperature, composition and pressure. Thus the ideal case assumes and infinitely rapid radial mixing. An impulse change of the inlet concentration ceases to have any effect after the residence time.

$$t = \tau = V/q \qquad (1)$$

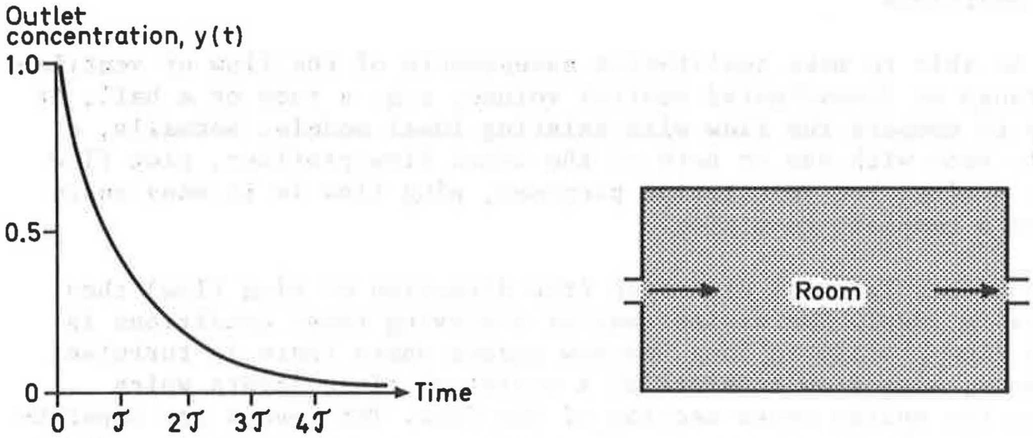
where V = total volume
q = ventilation flow



t = τ, trace element at outlet

Fig. 1. Appearance of impulse response with plug flow - outlet concentration. Time expressed in units of V/q = τ

With complete mixing, the concentration is the same everywhere. In the ideal case, a change means that all the elements are changed simultaneously and in the same way.



t>0, trace element everywhere

Fig. 2. Appearance of impulse response with complete mixing. Concentration the same everywhere in the room

The impulse response with mixing follows an exponential relationship.

$$c(t) = \frac{k}{\tau} e^{-t/\tau} \qquad (2)$$

where c(t) = outgoing trace element concentration
t = time
τ = V/q = time constant (residence time)
k = magnitude of the impulse

After a residence time $t = \tau$, any impulse change of the inlet concentration has been restored to 63%, and after $t = 4\tau$ 98% of the temporary change has been restored.

As was indicated earlier, the ideal flow profiles are impossible to achieve in practical systems. In reality, the flow can often be so diffuse that it is not even easy to determine which of the two ideal profiles described above should be used for comparison with the actual case. In this report, a method is described which makes it possible to carry out a qualitative comparison of actual flow sequences with the ideal plug flow profile.

Conditions which affect the flow

When a flow of air is being investigated, variations are often discovered in the composition, temperature, pressure and velocity of the medium. Hill (1977) divides up the deviations from ideal plug flow. Two categories are described here.

- When a flow exists, velocity gradients arise in a radial direction. As a result of this the fluid elements have different residence times. For flow through spaces where the ratio between length and width (diameter) is large, and if the flow is turbulent, then only moderate disturbances will arise as a result of velocity gradients. With a smaller ratio of length to width, and if the flow tends towards laminar flow (compare the Re number), there is a considerable risk of large deviations from the ideal velocity profile. Figure 3 shows the velocity profile with laminar and turbulent flow in a pipe. The profiles in Figure 3 are similar to those which arise with flow between parallel walls.

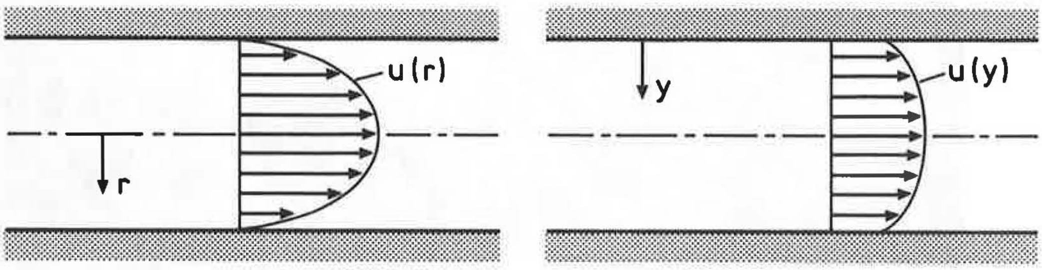


Fig. 3. Velocity profiles with laminar and turbulent flow

- In both axial and radial directions, there is an exchange of material between the fluid elements as a result of molecular diffusion and turbulent vortex diffusion. Convective mixing arises due to thermal gradients, and this in turn contributes to the exchange of material between the fluid elements. The transfer of heat from windows and walls, and convective energy transport from radiators, are common sources of disturbance.

Jet flow

Jet flow in the neighbourhood of ventilation inlets constitutes a general technical problem. The continuous stream of air easily forms jets, which rapidly penetrate the air layer in the room. These jets of air have a higher velocity than the surrounding air masses, and therefore they can easily become a source of discomfort. If the jets and the surrounding medium consist of the same fluid, as here, then the phenomenon is known as "submerged jets". The surrounding medium stabilizes this type of jet against, for example, the effect of gravity.

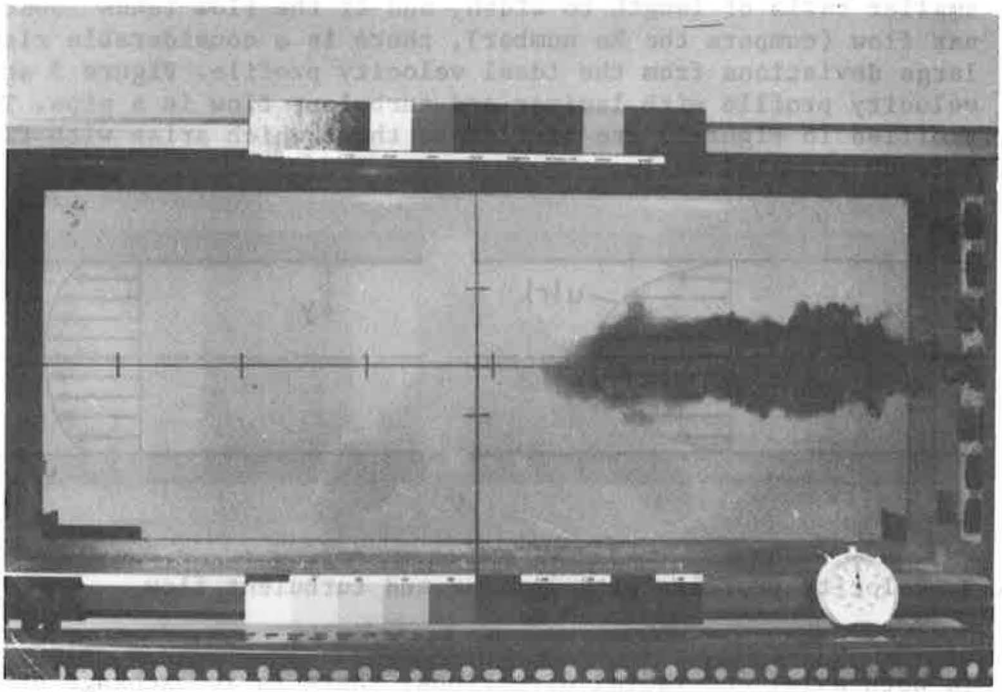


Fig. 3a. Photograph of a jet with continuous water flow in an open container. Time after injection 2 seconds, flow 7 l/min

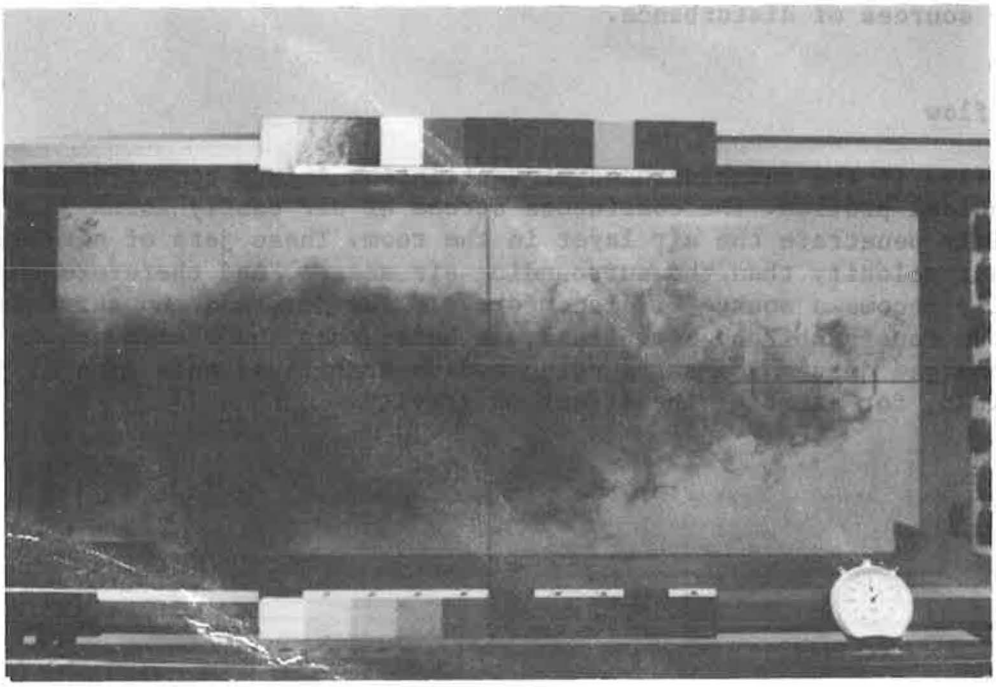


Fig. 3b. The jet impinges upon the outflow end within a period of 8 seconds. Residence time V/Q = 14.6 min

Model experiments

With the help of colour impulses, Holmberg (1978) has succeeded in photographing an incoming jet of water in an open water container in a stationary state. Corresponding conditions will apply for air. Note, however, Reynold's laws of uniformity.

There are two points which it is important to observe when trying to reduce the problems due to jet flow. In the first place, it is necessary to prevent the passage of concentrated inflow streams, and in the second place the velocity must be reduced by radial dispersion.

By directing the flow at the inlet into a vessel similar to the polygonal body shown in Figure 4, conditions are created for an effective stop to the jets. The velocity is reduced, since the diameter of the braking vessel is larger than that of the inlet. When the medium emerges it disperses efficiently against the wall.

Zhukovskii (1949) has described the flow around the body shown in Figure 4.

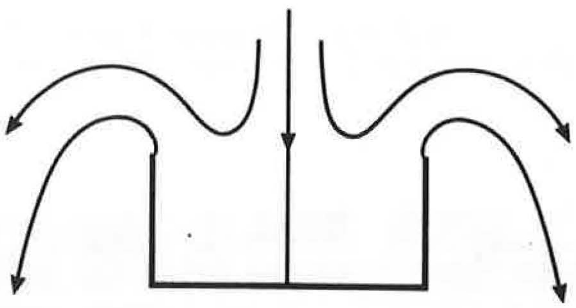


Fig. 4. A two-dimensional "jet killer"

In an attempt to verify the above argument, a dome-shaped glass vessel was placed in front of the emerging stream of water in Figure 3. The other parameters were kept constant. The results are shown in Figure 5.

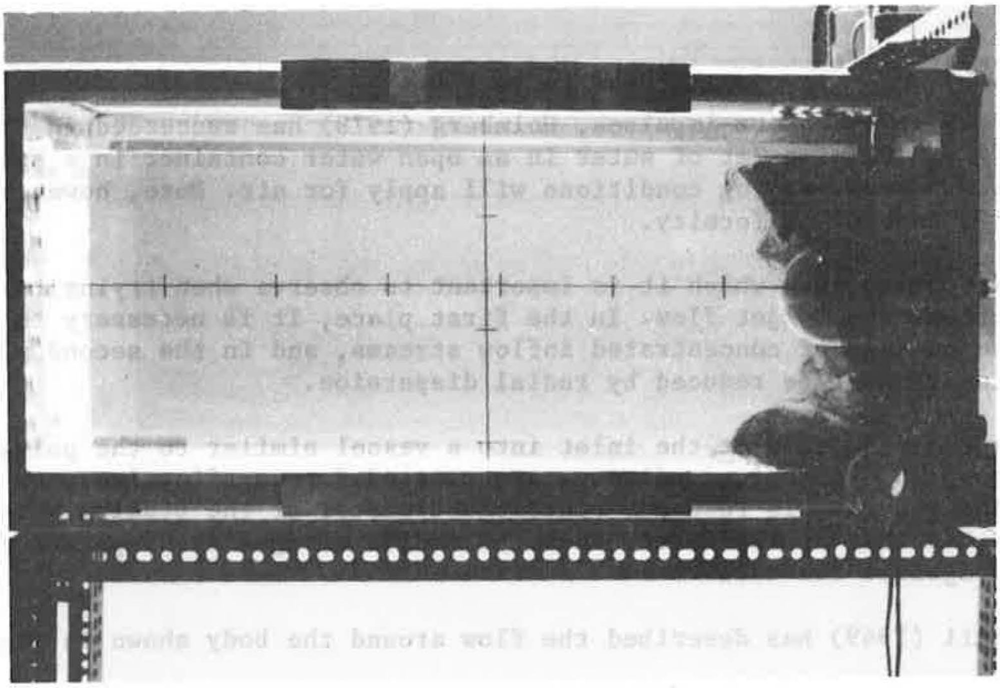


Fig. 5a. 20 seconds after injection, the impulse has left the glass vessel and is spreading out evenly from the end of the container. Flow 7 l/min

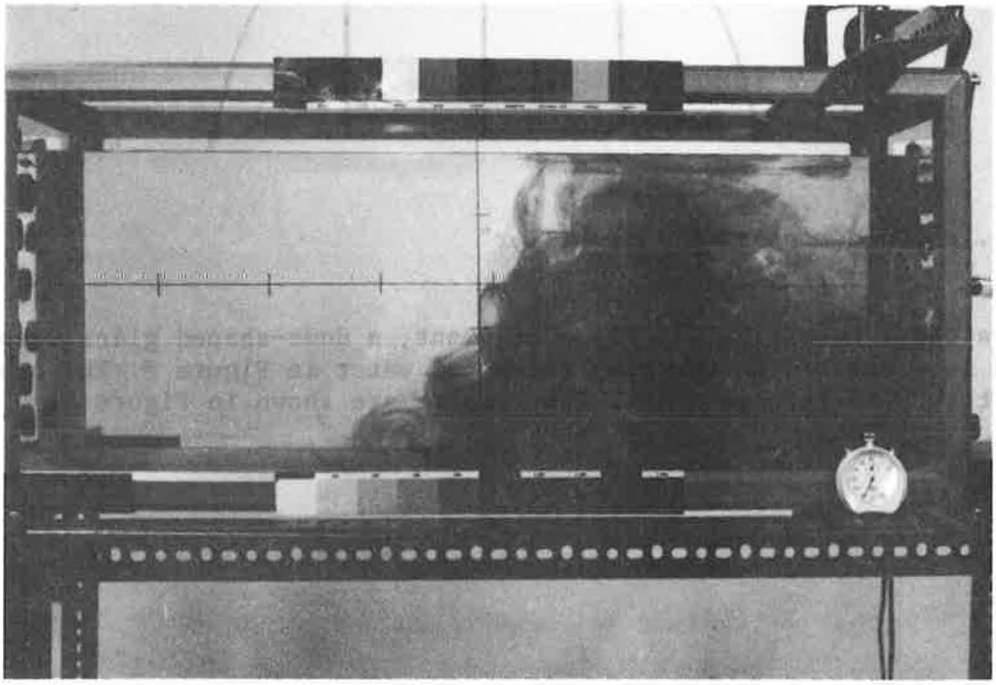
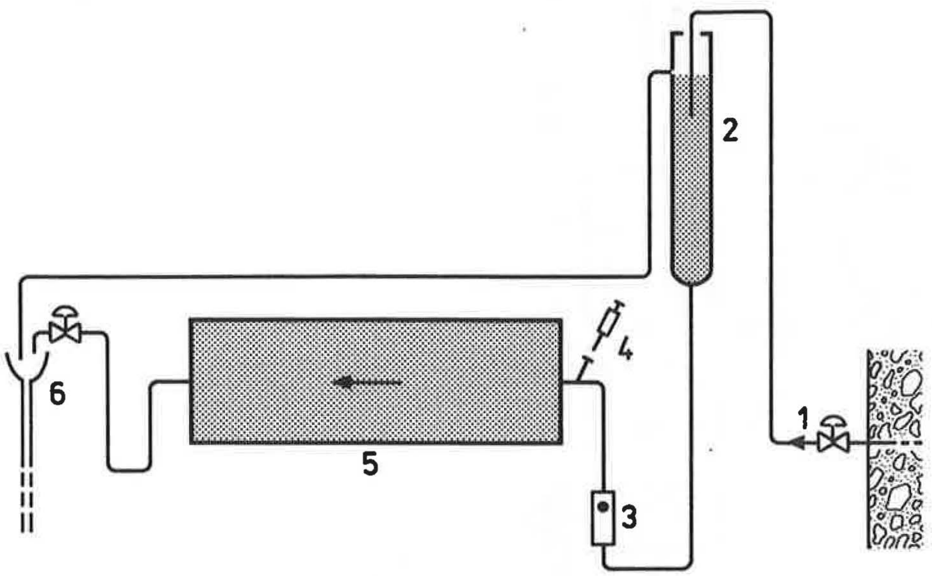


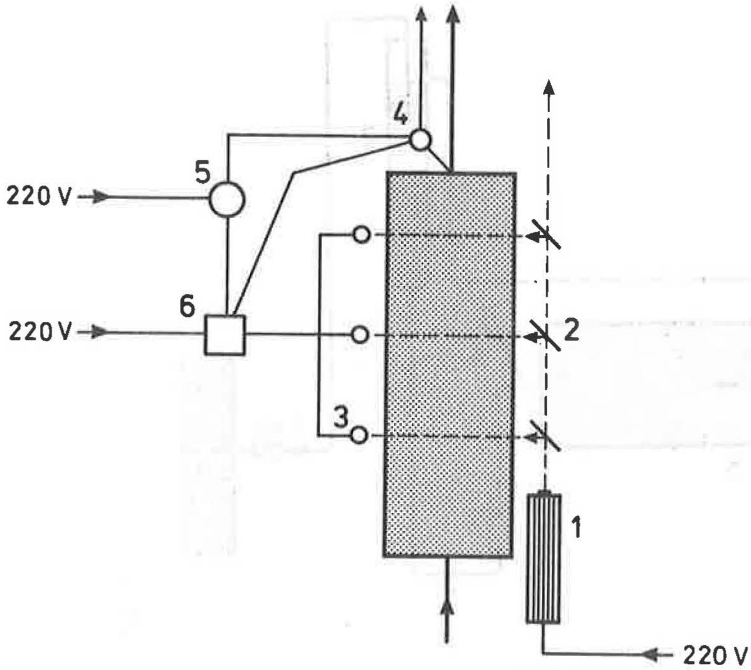
Fig. 5b. At 1 min 35 seconds, the "plug" has to a great extent broken away from the inlet wall. The flow is quiet.

The measurements were carried out in a water scale model, as shown in Figure 6. A glass column was used to provide a constant inflow pressure.



1. Valve
2. Glass column
3. Rotameter
4. Injection arrangement
5. Container (88.0 cm x 32.6 cm x 37.7 cm)
6. Outflow

Fig. 6. Test arrangement



1. Laser
2. Reflectors
3. Detectors
4. LED cell
5. Power supply
6. Datalogger

Fig. 7. Test container, peripheral equipment (seen from above)

As regards measurement equipment, in order to avoid the use of interfering sensors within the flow field under investigation it is possible to reflect (partially deflect) a laser beam. This travels axially, at 90^{o} to the phototransistor on the opposite wall, Figure 7. The same beam can be deflected at several points. Before the experiment the analog measurement range of the phototransistor should be calibrated against known trace element concentrations.

Ventilated and non-ventilated room volume

An analysis of an impulse response should here yield information about the flow profile and the residence time of particles in the control volume being investigated.

Levenspiel (1962) has given a measure of the frequency of residence times for the fluid elements within the time interval t, t + dt in the density function.

$$E(t) = \frac{c(t)}{\int_0^\infty c(t)dt} \tag{3}$$

The distribution function F(t) is defined by Levenspiel (1962) in such a way that it gives the fraction of the volume elements in the outlet flow which have a residence time between t = 0 and t = t. From (3) the following relationship can then be formulated

$$F(t) = \int_0^t E(t)dt \qquad (4)$$

Thereafter, for continuous functions Levenspiel (1962) forms an expression for the mean residence time $\bar{t}$ where the density function E(t) is included:

$$\bar{t} = \int_0^\infty t \cdot E(t)dt \qquad (5)$$

For the theoretical mean residence time $\bar{t}$, we have

$$\bar{t} = \frac{V}{q} = \tau \qquad (6)$$

For the difference between the expressions in (5) and (6) we obtain

$$\frac{V}{q} - \int_0^\infty t \cdot E(t)dt = \Delta\bar{t} \qquad (7)$$

From this expression the non-ventilated, non participating volume can be calculated according to

$$V_{st} = \Delta\bar{t} \cdot q \qquad (8)$$

From this it follows that for the ventilated, actively participating volume we obtain:

$$V_a = V - V_{st} \qquad (9)$$

Qualitative assessment of plug flow with the Péclet number

The variance is a measure of the square of the extension of the c(t) curve along the time axis. Thus the unit will be $(time)^2$. Levenspiel gives the following expression for the variance σ_t^2:

$$\sigma_t^2 = \int_0^\infty t^2 E(t)dt - \bar{t}^2 \qquad (10)$$

In order to facilitate comparisons at different residence times, it is convenient to introduce a standardized time:

$$\Theta = \frac{t}{\bar{t}} \qquad (11)$$

The standardization produces the new relationships

$$F(\Theta) = F(t) \qquad (12)$$

$$E(\Theta) = \bar{t}E(t) \qquad (13)$$

The expression in (10) is transformed to

$$\sigma_\Theta^2 = \int_0^\infty \Theta^2 E(\Theta) d\Theta - 1 \tag{14}$$

which means that

$$\sigma_\Theta^2 = \frac{\sigma_t^2}{\bar{t}^2} \tag{15}$$

The model described here (the axial dispersion model) is particularly useful for flows which deviate relatively little from plug flow. Starting from Fick's law of molecular diffusion, Levenspiel (1962) has derived a differential equation which includes a dimensionless group (D/uL). The expression, which is denoted the dispersion number, gives the axial dispersion according to

$\frac{D}{uL} \rightarrow 0$ Negligible dispersion, plug flow

$\frac{D}{uL} \rightarrow \infty$ Large dispersion, mixing

Here the apparent axial diffusion coefficient D includes all mixing phenomena in the axial direction i.e., in addition to the effects which originate in the turbulent vortex diffusion, effects such as the transfer of material in and out of stagnant zones. The mean flow velocity of the fluid is given by $u = \bar{w}$, and L denotes the total length of the volume considered.

Levenspiel (1962) gives the following relationship between the variance and the dispersion number for small dispersions

$$\sigma_\Theta^2 = 2\left(\frac{D}{uL}\right) \tag{16}$$

The definition of the Péclet number (Pe) is given for example by Lindfors (1965)

$$Pe = \frac{\bar{w}L}{D} \tag{17}$$

Equations (16) and (17) yield a relationship between Péclet number and variance

$$Pe = \frac{2}{\sigma_\Theta^2} \tag{18}$$

The expression is simplified, and can be used approximatively for Pe > 50.

If the above condition is not fulfilled, then the following is used with moderate dispersion

$$Pe = \frac{1}{\sigma_\Theta^2} + \sqrt{\frac{1}{(\sigma_\Theta^2)^2} - \frac{2}{\sigma_\Theta^2}} \tag{19}$$

If, on the other hand, $\sigma_\Theta^2 > 0.5$ then the Péclet number is obtained by iteration from the expression

$$Pe = \sqrt{\frac{2}{\sigma_\Theta^2}(Pe - 1 + e^{-Pe})} \tag{20}$$

The Péclet number gives the extent of the axial dispersion in such a way that, in practice, a large Pe means a small mixing and a flow pattern which approaches that of plug flow, while a small Pe denotes large-scale mixing and flow conditions which approach complete mixing. The Péclet number and the active volume are measures of the quality of ventilation.

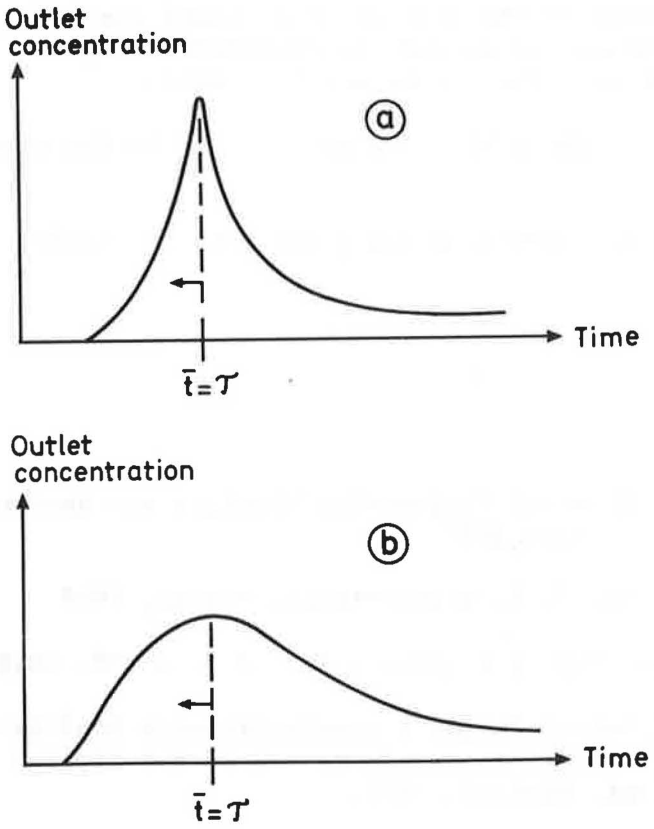


Fig. 8. Example of impulse response at outlet. In case a, the axial dispersion is less than in case b, i.e. $Pe_a > Pe_b$. The flow in (a) is the nearer to plug flow of the two cases, according to the axial dispersion model. A displacement of $\bar{t}$ in the direction of the arrow means that there will be some stagnant regions since the peak arrives too quickly.

$\bar{t} < \tau$ means $V_a < V$ since $\tau = \frac{V}{q}$

SUMMARY

When ventilation air moves through a room the flow pattern that is created normally shows similarities with both of the two ideal flow patterns, i.e. complete mixing and plug flow.

For ventilation purposes the plug flow pattern is of great interest but the technical implementation requires that disturbing fluid jets should be avoided.

In this paper a simple one-room model has been investigated experimentally. Tracer dye concentrations have been measured photometrically with a helium-neon laser as light source.

By altering in the entrace conditions of the experimental vessel the velocity of the incoming fluid could be decreased and its direction changed. The incoming water was thus spread over the entire entrance wall.

This led to a flow profile normal to the wall which was similar to the plug flow profile.

A qualitative measure of the plug flow attained was given with calculated Péclet numbers.

References

(1) Hill, C.G. An Introduction to Chemical Engineering Kinetics and Reactor Design, John Wiley & Sons, Inc., New York 1977

(2) Zhukovskii, N.E. Collected Works, 2, 3, Yostekhizdat, Moskva, 1949

(3) Bryan, G.H. och Jones, R. Proc. Roy. soc. Lond., Ser. A 91 A 630, 1918

(4) Holmberg, S. Försök att uppnå kolvströmning i bassängliknande behållare (Attempts to achieve plug flow in pool-like containers). Work for diploma at Inst. för tekn. kemi, Åbo Akademi, Finland, 1978.

(5) Lindfors, L.-E. Lectures on Non-ideal reactor systems, course 202175, Åbo Akademi, Finland, 1976.

(6) Levenspiel, O. Chemical Reaction Engineering, J. Wiley & Sons, Inc., New York, 1962

(7) Lindfors, L.-E. PhD work at Inst. för tekn. kemi, Åbo Akademi, Finland, 1965.

Appendix

$c(t)$

↓

$$E(t) = \frac{c(t)}{\int_0^\infty c(t)\,dt}$$

↓

$$\bar{t} = \int_0^\infty t \cdot E(t)\,dt$$

↓

$$\bar{t} = \bar{t}_a$$

↓

$$V_a = \dot{V} \cdot \bar{t}_a$$

↓

$$\sigma_t^2 = \int_0^\infty t^2 E(t)\,dt - \bar{t}^2$$

↓

$$\sigma_\Theta^2 = \frac{\sigma_t^2}{\bar{t}^2}$$

↓

$$\sigma_\Theta^2 \leq 0.0392$$ — yes → $$Pe = \frac{2}{\sigma_\Theta^2}$$

↓ no

$$Pe = \frac{1}{\sigma_\Theta^2} + \sqrt{\frac{1}{(\sigma_\Theta^2)^2} - \frac{2}{\sigma_\Theta^2}}$$

↓

$$\sigma_\Theta^2 > 0.5$$

↓

Pe = initial value

↓

Iteration:

$$Pe = \sqrt{\frac{2}{\sigma_\Theta^2}\,(Pe - 1 + e^{-Pe})}$$

↓

cf.

↓

Pe

Diagram showing calculation sequency