CONTAMINANT DISTRIBUTION IN INDUSTRIAL AREAS WITH FORCED VENTILATION AND TWO-DIMENSIONAL FLOW

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1. INTRODUCTION

The supply jets in ventilated rooms will often create a recirculating flow as shown in a typical example in fig. 1. The wall jet from the supply opening follows the ceiling and entrains air from the occupied zone giving an air movement which involves a flow many times bigger than the supply flow, and the velocity in the wall jet will accordingly decrease to a suitable level when it reaches the occupied zone. It is obvious that contaminant from sources in the occupied zone, e.g. welding smoke, will be spread over the whole room by the ventilation system, and it is therefore important to describe the relations between the design of the air supply system, location of contaminant sources and the concentration which will be formed in different areas of the room.

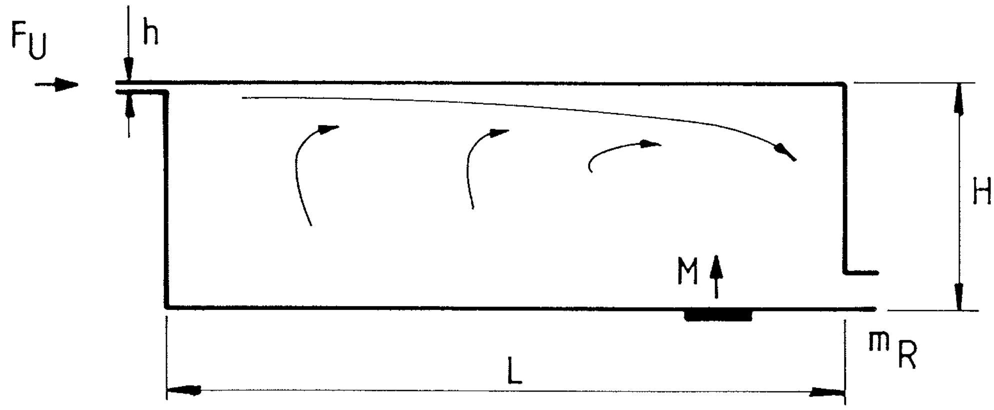

Fig. 1. Dimensions and other parameters for a room and an air distribution system with two-dimensional flow.

The results given in this article concern two-dimensional isothermal air movement. Many air supply systems create two-dimensional wall jets at some distance from the openings, and an evenly distributed contaminant source as described in section 3 may also have important practical relevance. The line sources provided in section 4 may be seldom used in practice but the results give qualitative information about the importance of the location of the source.

2. CALCULATION PROCEDURE

The concentration distribution in a room is obtained as a numerical solution of the time-averaged differential equations for flow and mass transport. This article will not go into the details of the method, see /1/ and /2/, but some comments will be made on the calculated mass transport and on the transport equation itself:

$$\frac{\partial}{\partial x}(\rho U m) + \frac{\partial}{\partial y}(\rho V m) = \frac{\partial}{\partial x}\left(\frac{\mu_{eff}}{\sigma_m}\frac{\partial m}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\mu_{eff}}{\sigma_m}\frac{\partial m}{\partial y}\right) + S_m \qquad (1)$$

where m is the mass fraction in the flow domain (mass of contaminant per unit mass of mixture). The two terms on the left hand side give the convective transport of m due to the velocities U and V in x and y direction. The two terms on the right hand side represent the local mass flux due to turbulence, and it is expressed as a "turbulent diffusion" where μ_{eff} is the effective viscosity, see /1/ and /2/, and σ_m is the turbulent Schmidt number which is equal to 0.9 in the predictions given in this paper. The last term S_m is the source term for m and it is different from zero in areas where contaminants are supplied to the flow.

It is assumed that there is no difference between the density of the contaminated gas and the air in the room in the results given in this paper. Some difference in density will not influence the results in practice (high turbulence levels, low concentrations), Oppl /3/, for example, has shown how the concentration of carbon bisulphide (CS_2) is very high in the ceiling region in a spinning mill due to natural convection in the room in spite of the relatively high density of the carbon bisulphide.

The predicted concentration distribution can either be expressed as a mass fraction of a gas or as particle or droplet number density, see Bradshaw et al /4/. In the latter case it is important that the particles or droplets are small so that the settling speed can be ignored compared with the air velocities in the room.

It is convenient to express the concentration distribution in a normalized form by division with the concentration in the return opening m_R, and this concentration is again expressed by

$$m_R = \frac{M}{F_U} \quad \text{PPM or g/m}^3 \qquad (2)$$

where F_U (m^3/s) is the fresh air supplied by the ventilation system and M (m^3/s or g/s) is the source of contaminant. An analysis of the governing parameters of the flow shows that a normalized concentration such as m/m_R can be expressed by the geometry of the supply openings and by the following equation in the case of isothermal two-dimensional flow and high Reynolds number

$$\frac{m}{m_R} = \text{func}\left(\frac{h}{H}, \frac{L}{H} \text{ and locations of source}\right) \qquad (3)$$

where h, H and L are height of supply opening , height of room and length of room respectively, see reference /1/.

3. CONCENTRATION DISTRIBUTION IN A ROOM WITH A SOURCE ALONG THE FLOOR SURFACE

Fig. 2 shows a comparison between a measured and a calculated concentration distribution in the height 0.25 H through the occupied zone. Constant contaminant flux is assumed along the whole floor surface. The measurements on fig. 2 are carried out as temperature measurements, see /1/ and the comparisons assume the analogy which exists between a weak temperature distribution and a mass fraction distribution.

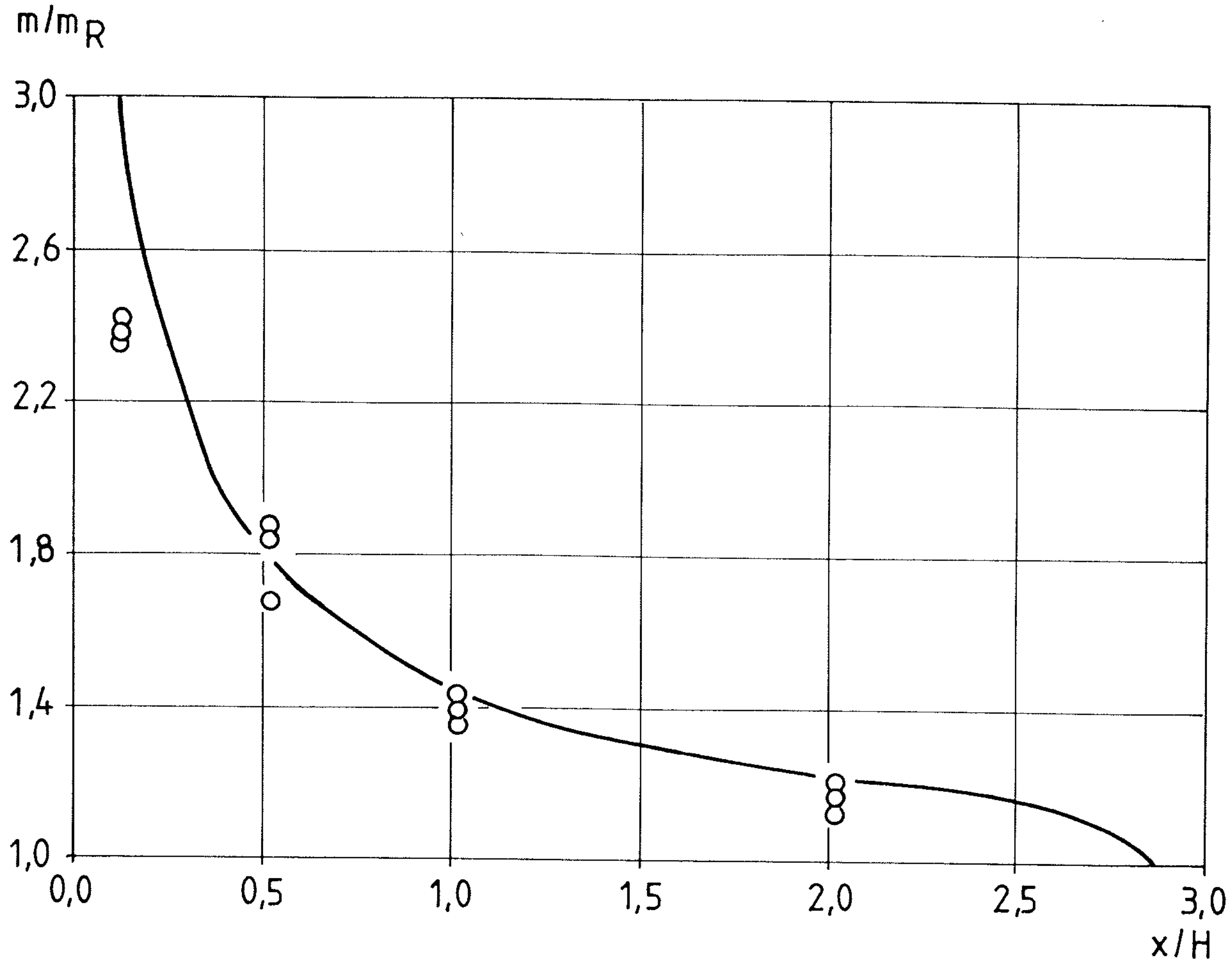

Fig. 2. Measured and calculated distribution for the height 0.25 H through the occupied zone of a room with the dimensions h/H = 0.056 and L/H = 3.0. The measurements were carried out on a weak temperature distribution, see /1/.

Fig. 3 shows the concentration distribution in a room at two different dimensions of the supply opening and it appears that a small vertical dimension of the supply opening results in the most even distribution. The reasons are that a small supply area means high entrainment in the wall jet and thus a high level of internal recirculation in the room.

The conditions in a room are often expressed by the mean ventilation efficiency ε_a which can be expressed by the following equation

$$\varepsilon_a = \frac{m_R}{m_a} \qquad (4)$$

where m_a is the mean concentration in the occupied zone. A local relative ventilation efficiency can correspondingly be expressed as

$$\varepsilon = \frac{m_R}{m} \qquad (5)$$

which is the reciprocal value of the normalized concentration distribution given in figs. 2, 3, 4 and 5. Fig. 3 expresses that the relative ventilation efficiency increases with a decrease in the height of the supply opening.

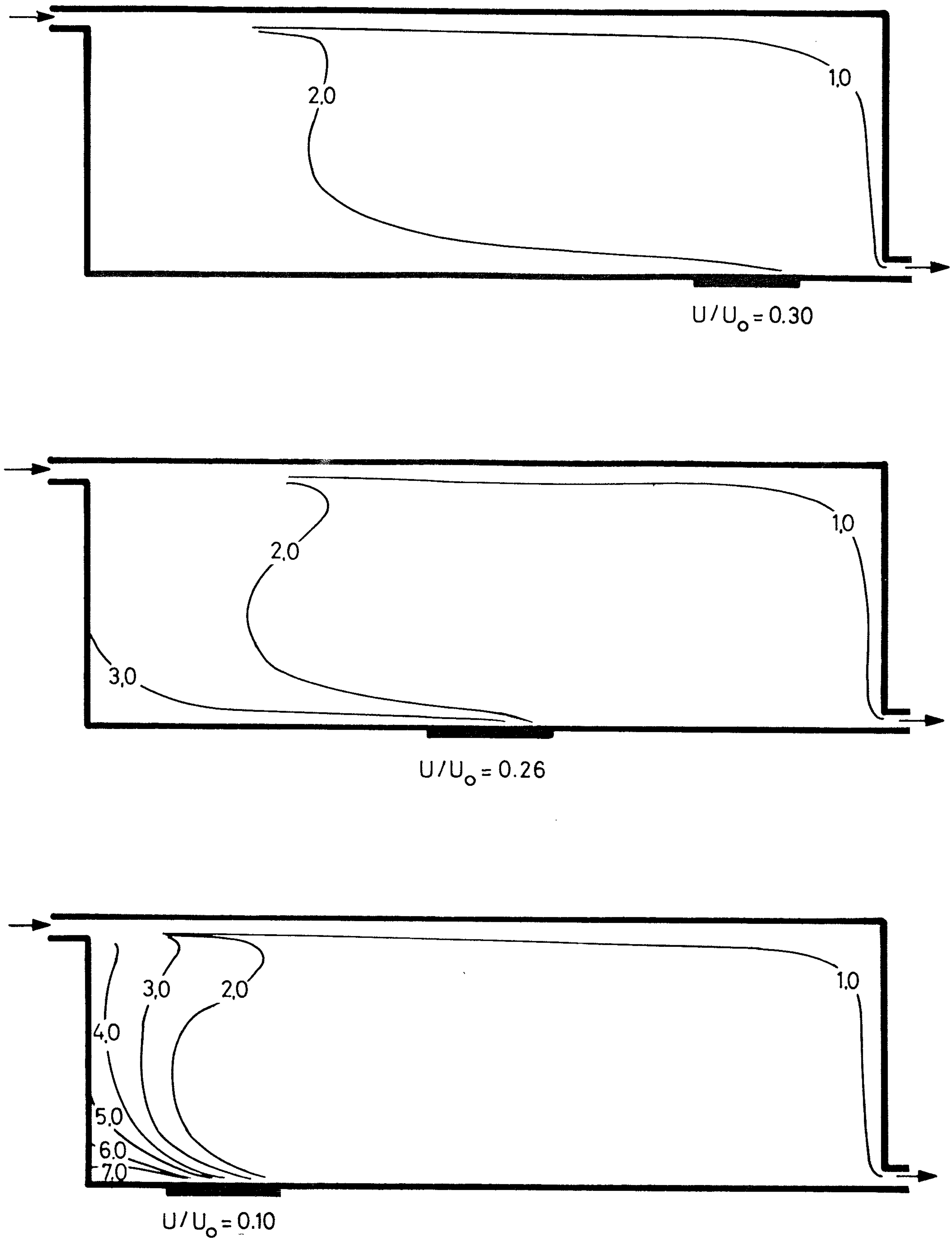

Fig. 4. Concentration distribution m/m_R in a room with two-dimensional isothermal flow at three different locations of a line source. $h/H = 0.056$ and $L/H = 3.0$.

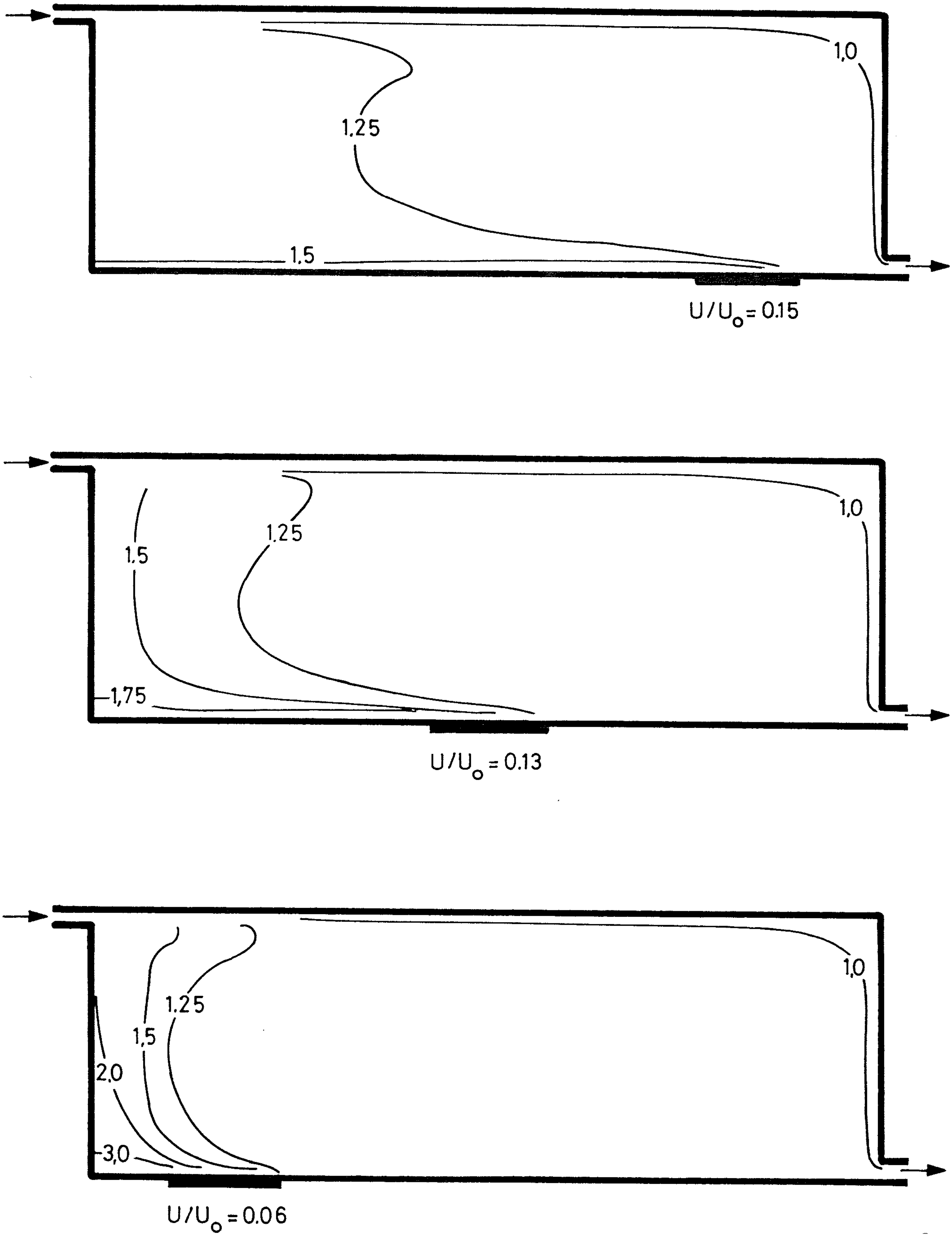

Fig. 5. Concentration distribution m/m_R in a room with two-dimensional isothermal flow at three different locations of a line source. $h/H = 0.01$ and $L/H = 3.0$.

5. SYSTEM DESIGN

The basis in the design of a system is to keep the local concentration m well below the Threshold Limit Value (TLV) everywhere in the occupied zone. Threshold Limit Values are published yearly in a number of countries, and the values adopted by American Conference and Governmental Industrial Hygienists /6/ may be mentioned as an example.

The dimensioning of the ventilation system and especially the volume flow F_U are based on formula (2) where the concentration m_R in the return opening must be far below the threshold limit value. There are several reasons for this. In the first place m_R is less than the concentration in the occupied zone as this report clearly shows, and threshold limit values are furthermore not dimensioning values but values which should not be exceeded. The difference between the concentration level in the return opening m_R and the maximum value in the occupied zone is considered by increasing F_U. A paper on arrangement of work places in the welding industry /7/ recommends multiplication of F_U by 3.0 which will also apply to other industries. Older investigations recommend multiplication factors up to 10 /8/.

It is important to use an air distribution system which gives an even concentration distribution in the occupied zone, i.e. has a high relative ventilation efficiency. But an even concentration distribution is only a part of the problem because it is also necessary to establish a low level for m_R. If a high relative ventilation efficiency is obtained using a small supply area the above mentioned requirements would work against each other because a low m_R means a high volume flow F_U and therefore a reasonably big supply area to ensure that the maximum air velocity in the occupied zone would be kept at a low level. The design of a system should be initiated by choosing a volume flow F_U which ensures that m_R is far below the threshold limit values. The supply area is then determined to obtain a velocity in the occupied zone which has the maximum allowed level.

The concentration in the occupied zone can be decreased if the maximum air velocity in the room is low by increasing the volume flow F_U from the system, preferably with fresh air though recirculating air from the system may also be used. The explanation of this is that the mixing of the room air is increased by recirculation, regardless of whether this is in the form of a high internal circulation in the room due to a small supply area or a high external circulation in the ventilation system. It is normally not allowed to recirculate contaminant room air (in Denmark) and the procedure should therefore not be used in new systems because the uniformity in concentration distribution can be obtained by limiting the supply area.

The results shown in figs. 2, 3, 4 and 5 assume small temperature differences in the room. Serious problems may arise if the system heats the room and the running conditions are such that a thermal stratification will take place in cases where the supply opening is in the upper part of the room, fig. 1. The air movement with recirculation, mixing and entrainment will take place in the upper part and stagnated air in the occupied zone will be seriously contaminated by the sources in this area.

In special cases where heat and contaminant production takes place from the same source, it may be possible to utilize the thermal stratification to separate pure and contaminant air. The supply openings should be placed in the occupied zone and the return opening in the upper parts of the room in this case. Such systems are discussed in /9/ and /10/.

If it is in any way possible, local exhaust should be used around the contaminant sources in industrial areas. Local exhausts will remove most of the produced gases, dust or aerosols, and the comfort ventilation can remove the last part as described in this paper, typically 10 to 20%. Local exhausts may therefore reduce the demand on the necessary volume flow F_U by 80 to 90%.

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REPARTITION DE CONCENTRATIONS DE PARTICULES ET DE GAZ POLLUANTS DANS DES LOCAUX INDUSTRIELS AVEC ECOULEMENT BIDIMENSIONNEL RECIRCULANT

RESUME: Il est donné des exemples de calcul sur la répartition de concentrations polluantes dans des locaux industriels ventilés. La répartition des concentrations est déterminée par la résolution des équations d'écoulement, de turbulence et de transfert des masses à l'aide d'une méthode numérique.

Il est montré comment on obtient la répartition de concentrations la plus homogène dans des locaux avec importante recirculation interne par bouche d'alimentation de dimensions réduites; il est aussi montré que l'on peut maintenir une répartition homogène en plaçant les sources polluantes dans les régions ou la vitesse de l'air est élevée.

Enfin, il est présenté une suite de méthodes pratiques pour dimensionner un systeme.