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THERMAL COMFORT AND AIR DISTRIBUTION IN VENTILATED ROOMS - ENERGY SAVING CONSIDERATIONS

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1. INTRODUCTION

The creation of an acceptable thermal environment at work places in ventilated buildings is a typical fluid mechanics problem which may involve considerable energy consumption. Increased demands on comfort and increasing energy costs focus attention on the solutions and this paper deals with some new prospects.

The establishment of a micro-climate at the work place in industrial buildings in those special cases where the workers are widely spread and engaged at fixed work places is discussed in the beginning, and it is further shown how thermal comfort is created by ventilation systems with minimum energy consumption in the more general situation where all parts of the room are occupied.

2. THERMAL COMFORT AND THE CREATION OF A MICRO-CLIMATE

The most important parameters which influence man's sensation of thermal comfort are /1/: activity level (unit: met *), thermal resistance of clothing (unit: clo *), air temperature T_a, mean radiant temperature T_{mrt}, relative air velocity v, and air humidity.

The mean radiant temperature is the combined effect of solar radiation and a weighted mean of the surrounding surface temperatures /2/. Radiant spot cooling or heating is produced by a surface having a low or high temperature as shown by examples in reference /3/. The comfort limit for asymmetric radiation restricts the use of spot heating with a high temperature surface while spot cooling is possible within all practical surface temperatures (5-15 ^{o}C), see Fanger /3/ and Olesen et al /4/.

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* 1 met = 58 W/m^2, corresponding to sedentary activity.

1 clo = 0.155 $m^2\ ^{o}C/W$, corresponding to a typical European business suit.

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The principle in convective spot cooling is to create comfort by controlling locally the air velocity and possibly also the air temperature. Both the activity level and the clothing degree should be as low as possible in a warm environment. Clothing of 0.5 clo would be a minimum in many types of industrial work and fig. 1 shows the combination of ambient temperature ($T_a = T_{mrt}$) and relative velocity v which provides thermal comfort, see /1/ and /3/. Comfort conditions are partly a question of balance in heat transport from the body and the curves express how natural convection takes place below 0.1 m/s while forced convection is dominant above 0.15 m/s with a heat transmission coefficient proportional to the square root of the relative velocity /1/.

Comfort cannot be achieved by increasing the air velocity for T_a > 29-30 °C, see fig. 1, and at air temperatures above 35 °C the air velocity should not be raised, as it increases the convective heat supply to the body.

It is important to keep fluctuations at a minimum and air velocity uniform in order to avoid the sensations of draught. These conditions are obtained in the constant velocity core from a supply opening consisting of filter material and a perforated sheet having an area bigger than the cross section of the work place. It is obvious that big energy savings can be obtained with this type of spot cooling if the number of work places is limited.

3. AIR DISTRIBUTIONS IN VENTILATED ROOMS AND ASSOCIATED ENERGY CONSIDERATIONS

The air distribution which takes place in a ventilated room is a fluid mechanical phenomenon described by the boundary conditions (geometrical parameters are given in the upper sketch in fig. 2) and by the Archimedes number Ar assuming turbulent flow and high Reynolds number /5/.

$$Ar = \frac{\beta g h \, \Delta T_o}{U_o^2} \qquad (1)$$

U_o is the bulk supply velocity, ΔT_o is the air temperature difference between supply and return and β and g are coefficient of thermal expansion and gravitational acceleration respectively.

Energy saving considerations make it convenient to divide the ventilation arrangements into two different groups according to the importance of natural convection in the air distribution pattern.

3.1 SYSTEM WITH SUPPLY-JET-GOVERNED AIR DISTRIBUTION

This type of ventilation is shown in fig. 2. The momentum flow from the supply openings governs the recirculation in the whole room with only minor influence from natural convection. The supply openings are mounted so that the velocity decay in the jets takes place outside the occupied zone. A dimensioning of the system involves the calculation of the maximum air velocity in the occupied zone U_{rm}, which is especially a function of the supply opening geometry and of the parameters in equation (2) in the case of two-dimensional flow as discussed in references /6/, /7/ and /8/.

$$\frac{U_{rm}}{U_o} = \text{func}\left(\frac{h}{H}, \frac{L}{H}, Ar\right) \qquad (2)$$

U_{rm} is often kept below 0.15 m/s in rooms where sedentary work is done /9/ and fig. 1 shows that thermal comfort is only slightly dependent on lower velocities in this case and therefore not much influenced by the velocity distribution in the occupied zone. It is also possible to express the environmental quality in "Predicted Percentage of Dissatisfied" (PPD) which is a comfort index developed by Fanger /1/. An example of the use of this index in cases with U_{rm} values higher than 0.15 m/s is given in /10/.

It is important to use a separate cooling system in the case of high heat production in the room as shown in the lower sketch in fig. 2. This may be designed as an exhaust around the heat sources in industrial environments or it may be water cooling of highly loaded equipment and it may be solutions as a combination of return openings and light fixtures. A reduced load on the comfort ventilation gives a reduction in the total energy consumption and an increase in thermal comfort. Furthermore the investment in the system is reduced. The latter because removal of a high heat load by the comfort ventilation necessitates short sections (length L in fig. 2) and therefore a large number of supply openings for a given floor area as shown, for example, by Skåret /11/ and Hestad /12/.

Heating with the ventilation system in fig. 2 results in a vertical temperature gradient which may develop into stratification at a high Archimedes number. This should be avoided because it results in an ineffective air distribution in the occupied zone and because vertical temperature gradients mean high heat losses through the roof in one storey buildings. The problems are minimized if the system is designed with not too deep sections and high momentum flow from the supply openings. Fig. 3 shows an example /13/. The supply opening is placed in the left side and the heated air is normally carried down through the building by directing jets. A vertical temperature gradient builds up at some distance from the supply opening (4-5H) when the system is running without the directing jets and only an increased temperature level will maintain comfort with increased heat loss as a consequence.

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The lower sketch in fig. 3 shows that smooth temperature distribution with small vertical temperature gradients is obtained when the system is running with directing jets. This corresponds also to the more conventional system where the heated air is transported down the building in ducts with several supply openings.

3.2 SYSTEMS WITH NATURAL CONVECTION FLOW

Fig. 4 shows the principle in systems of this type which are mainly used for cooling. The primary air is supplied at low level and the air moves vertically upwards parallel with natural convection plumes from heat sources and it is removed from the room in the ceiling regions. A high load can be handled at low energy consumption because the temperature T_o in the occupied zone is low compared with the temperature in the return flow $T_o+\Delta T_o$. A vertical temperature gradient and a thermal stratification are therefore important to the efficiency of the system and they are achieved by having a high Archimedes number in all running conditions. The principles are used in heavy industry, see /14/ and /15/, but they are also used in other heavily loaded buildings such as computer centres /16/ and offices although the room height restricts use in the latter case, see /17/ and /18/.

Dimensioning of the system involves determination of the stratification height y_{st}. Fig. 4 suggests how this is achieved by supplying an amount of primary air necessary for the entrainment up to a given height and fig. 5 shows the quantitative dependence of y_{st} on convective heat loss Q_o from the source and volume flow $\dot{V}$ valid for different point and line sources in heavy industry, see Kalleberg /19/. A great stratification height y_{st} means high $\dot{V}$ and therefore a rather unstable stratification because ΔT_o and the Archimedes number become small. However the stratification should not be allowed to get too close to the supply openings by increasing the Archimedes number because the hot (and often contaminated) air may be entrained in the primary air.

4. CONCLUSIONS

High energy savings and thermal comfort can be obtained in industrial environments by the creation of a micro-climate at work places in those special cases where they are widely spaced. Radiant spot cooling and convective spot cooling may be the only solution in a particularly hot environment.

Energy savings can be achieved in air distribution systems where the supply jets govern the flow in the whole room by minimizing the vertical temperature gradient in the case of heating.

Separate cooling of heat sources by, for example, process ventilation will always decrease the total load on both comfort ventilation and process ventilation in the case of cooling with the systems.

Very high loads can be handled at low energy consumptions in systems where natural convection is a part of the air distribution. Thermal stratification creates a high temperature area outside the occupied zone giving a high temperature in the exhaust and therefore an efficient system in the case of cooling.

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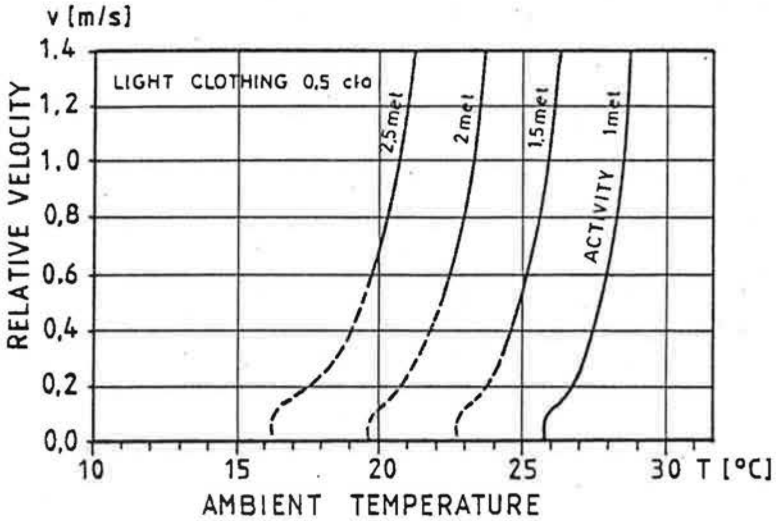

Fig. 1. Comfort diagram for air velocities in systems with convective spot cooling. The comfort lines correspond to four different activities. Dashed part of the lines represents unrealistically small relative velocities taking the activity level into consideration. From Fanger /3/.

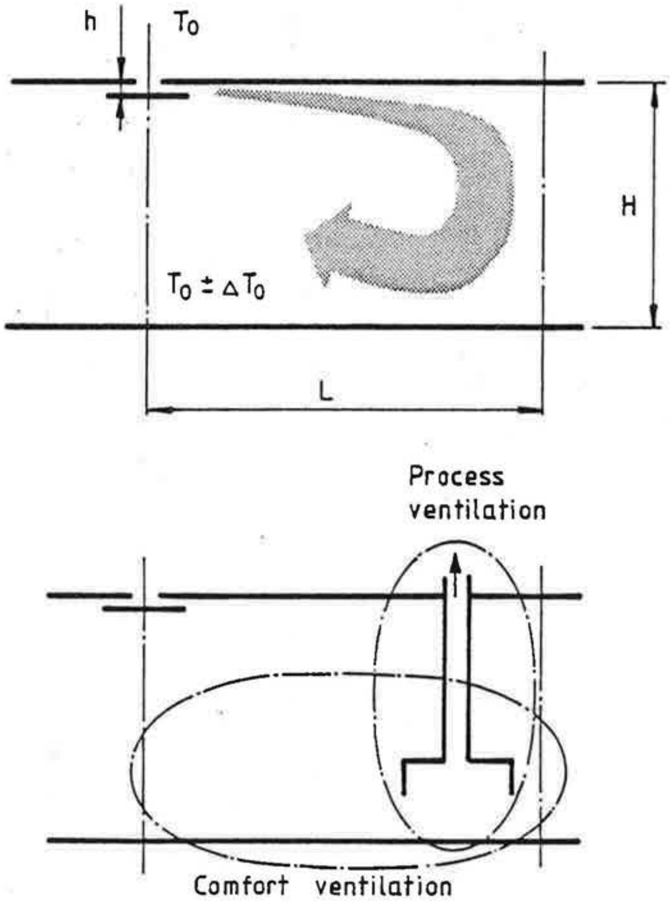

Fig. 2. Principles and geometrical parameters in supply-jet governed flow in the case of two-dimensional air movement. Process ventilation is sketched in on the lower figure.

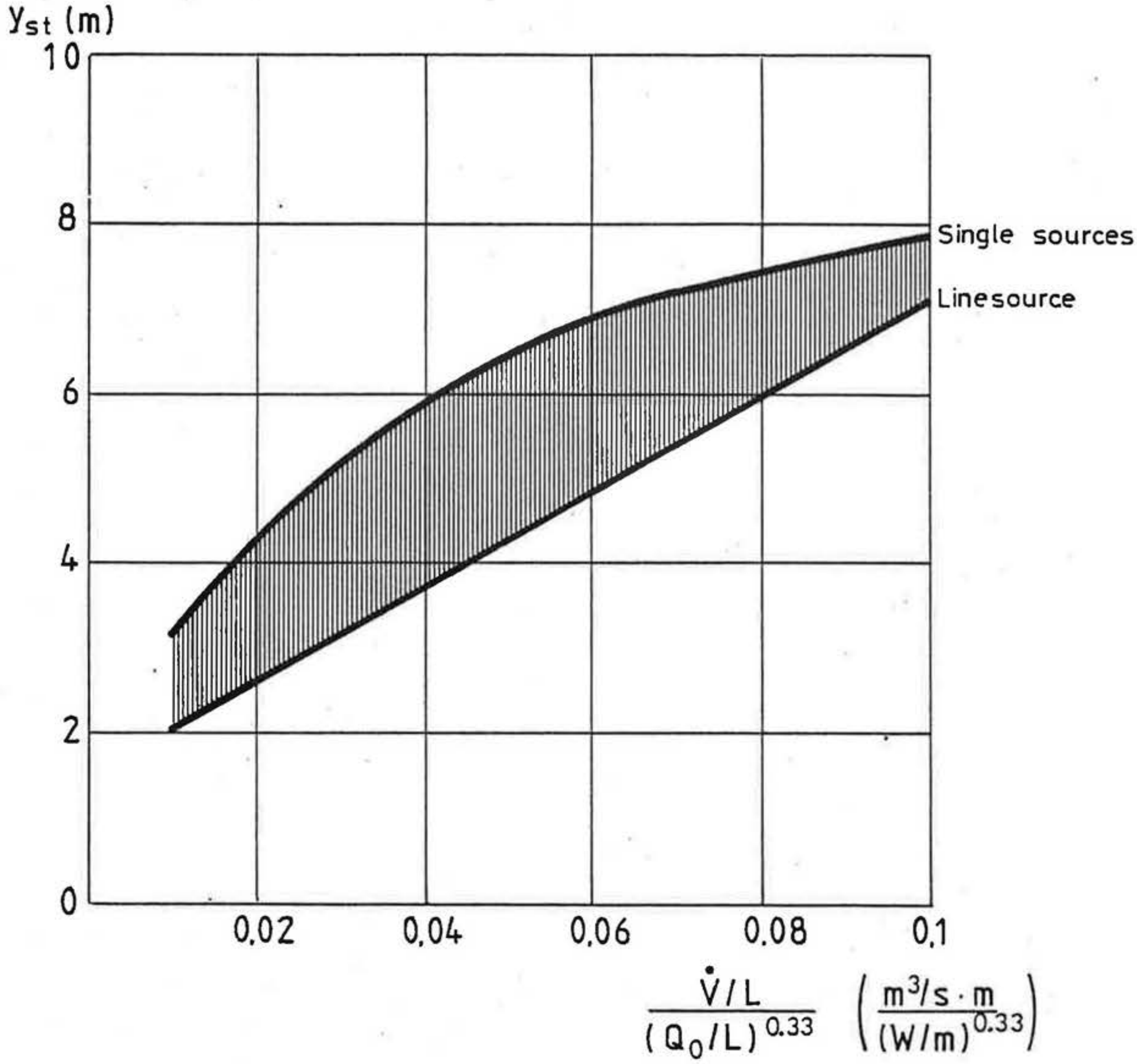

Fig. 5. Dependence of y_{st} on convective heat loss Q_0/L and volume flow $\dot{V}/L$ /19/.