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ROOM VENTILATION WITH DESIGNED VERTICAL AIR TEMPERATURE STRATIFICATION

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SUMMARY

The designing of ventilation systems in such a way that the natural tendency of the air for temperature stratification would be stabilized allows one to improve considerably the effectiveness of air exchange. A mathematical model of air exchange in ventilated rooms with vertical air temperature stratification from the concentrated heat sources creating stable convective flows is described in this paper.

A vertical air temperature stratification system is compared with a conventional mixing-type system for a computer operator's room and for a workshop where heat generating equipment is evenly distributed across the floor.

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INTRODUCTION

In ventilated rooms with sources of heat and gas emissions there is a tendency for uneven vertical air temperatures and gas concentration distributions. Most of the ventilation systems disturb the natural pattern in the development of convective flows above the heat sources and cause an intensive mixing of the room air with supplied air jets, which results in a rather even distribution of the parameters in the room.

The design of ventilation systems so, that the natural tendency of the air for vertical temperature stratification wouldn't be suppressed but, on contrary, would be stabilized allows one to improve considerably the effectiveness of air exchange.

he principle of applying the phenomenon of temperature stratification to natural ventilation of hot industrial premises were proposed by I.A. Shepelev [5] and developed by him later in cooperation with one of the authors of the present paper [6]. At present, ventilation systems with temperature stratification set-ups are widely used, particularly in Scandinavian countries. Special air diffusers for such systems are produced by many companies in these countries, which have gained experience in their application. The problems concerning the principles of operation and design of temperature stratification systems have been described by P. Jackman [1], M. Sandberg [2], E. Scaret [3], O. Seppanen [4], Ma Renmin [10], H. Mathisen [11], etc. This paper presents a mathematical model and analyses of air exchange in ventilated rooms with heat sources which include vertical air temperature stratification.

METHOD DESCRIPTION

In the systems with vertical air temperature stratification, air is supplied into the lower zone of the room at low initial velocity and is extracted from the upper zone. Let us consider a probable pattern of heat and air flow distribution in the room. The heat sources give up heat by convection (q_{conv}) and radiation (q_{rad}). Convective heat warms up the air adjacent to the source; this air moves upwards into the upper zone with the convective flow. Radiant heat warms up the colder surfaces of the room which become secondary heat sources.

The convective flows above the sources increase the volume due to the inflowing masses of ambient air. If the volume of the supplied air within the height of the occupied zone is enough for the development of convective flows and the supplied air velocity is low enough to prevent the blow away of convective flows, there is no circulation of the upper zone air into the lower zone. At the level where the flows of supplied air and the convective flows are equal to each other temperature stratification occurs: a so-called "heat cushion" is formed above this level with comparatively uniform air temperature higher than that in the lower zone.

Convective flows serve as natural channels by which convective heat is transferred from the lower zone to the upper zone. Secondary heat sources are formed on the surfaces in the room which are heated as a result of heat radiation from the primary sources. Radiant heat exchange takes place between the heated surfaces, which results in the redistribution of heat flows. As a rule [8], the intensity of heating the air by secondary sources is low and no stable upward flows are formed above them. The heat is transferred to the air in the lower zone.

If the primary heat sources in the room are not intense enough or if their surface area is evenly distributed through the room, e.s., a heated floor or spectators sitting close to each other in a theater hall, no stable convective flows are formed. The convective heat from the sources is assimilated by the supplied air in the occupied zone, which, while flooding the lower zone is being heated due to the convective heat and is forced out into the upper zone by the colder supplied air. In this case the level of stratification is determined by the height of the air diffuser which must be at least equal to the height of the occupied zone.

The basic principle of the described system operation is to minimize the vertical mixing of the air. Stable convective flows are the factors stabilizing temperature stratification, whereas turbulence generated in the room by supplied air jets and convective flows acts as destructive factors. The intensity of turbulent exchange in rooms with temperature stratification is, however, much smaller than in mixing type ventilation due to a lower velocity of air supply and its partial suppression by gravitational forces.

The design of air stratification systems involves the determination of the conditions required for stabilizing the stratification at a pre-set level and finding the value of the air exchange rate required to provide the desired air parameters in the occupied zone and the conditions of air supply.

The method of zone-by-zone heat balances, suggested by Shilkrot [8] can be used for such calculations. According to this method , the room is divided into separate zones within which the values of the characteristic parameters such as temperatures or concentrations are assumed to be equal or their distribution known. The values of the parameters in each zone are calculated by solving a system of equations for material and heat balance which are set up for each zone.

Following the pattern of heat and flow distribution in the case with strong heating sources, four zones are selected in the room: the air of the occupied zone (1) - below the stratification level and the air of the upper zone (2) - above the stratification level; the room surfaces in the lower zone (3) and in the upper zone (4).

$$F_{l.z.}\alpha_{conv.l.z.}(\tau_{l.z.} - t_{l.z.}) + F_{turb}\alpha_{turb}(t_{u.z.} - t_{l.z.}) + C_p G_o (t_o - t_{l.z.}) = 0$$

$$F_{u.z.}\alpha_{conv.u.z.}(\tau_{u.z.} - t_{u.z.}) + F_{turb}\alpha_{turb}(t_{l.z.} - t_{u.z.}) + C_p(G_o - G_{exh})(t_{l.z.} - t_{u.z.}) + q_{conv} = 0$$

$$F_{l.z.}\alpha_{conv.l.z.}(t_{l.z.} - \tau_{l.z.}) + F_{rad}\alpha_{rad}(\tau_{u.z.} - \tau_{l.z.}) + F_{l.z.}K'(t_{out} - \tau_{l.z.}) + q_{rad.l.z.} = 0$$

$$F_{u.z.}\alpha_{conv.u.z.}(t_{u.z.} - \tau_{u.z.}) + F_{rad}\alpha_{rad}(\tau_{l.z.} - \tau_{u.z.}) + F_{u.z.}K_{u.z.}(t_{out} - \tau_{u.z.}) + q_{rad.u.z.} = 0$$

The equations for the heat balance are supplemented by the following conditions:

(1) Temperature stratification level should be above the occupied zone:

For rooms with strong heating sources

$$G_o - G_{exh} \geq G_{conv.l.z.}$$

For rooms with weak heating sources distributed throughout the room

$$h_o \geq h_{l.z.}.$$

(2) Turbulent exchange between the zones shouldn't disturb temperature stratification:

$$Ri \geq Ri_{crit},$$

where

$$Ri = \frac{g}{t+273}\frac{\partial t}{\partial h}\left(\frac{\partial V}{\partial h}\right)^2$$

(3) Supplied air flow shouldn't blow away convective flows:

$$V_o \le V_{o\,crit};$$

(4) Desired air temperature $t_{o.z.}$ and air motion $V_{o.z.}$ within occupied zone:

$$t_{o.z.min} \le t_{l.z.} \le t_{o.z.max}$$

$$V_{o.z.} \le V_{o.z.\,max}.$$

The results of numerical simulation have shown [9] that the radiant heat exchange in a room plays an important part in forming air temperature distribution in lower and upper zones. The role of turbulent heat exchange between the zones does not become significant with the increase of air exchange rate, but decreases rapidly when the difference between the temperatures in the upper and lower zones increases due to suppression of turbulence by gravitational forces. With the value of Ri $\ge$ 5 the effect of turbulent heat exchange can be ignored. The use of the local exhaust systems reduces the effectiveness of air exchange by the general ventilation system; if the amount of air exhausted by local ventilation systems from the lower zone exceeds 50% of the total air exchange, the need for a displacement ventilation system is questionable.

Comfort conditions in the occupied zone are as a rule met if the initial temperature difference of the supplied air doesn't exceed $\Delta t_o = 5°C$. The velocity of the supplied air $V_o < 0.7$ m/s ensures the condition that the convective flows are not disturbed if the distance between the air diffusers and the source exceed 2 m. In some cases the design value of the air exchange rate is found from the condition of providing the pre-set stratification level rather than determined by the temperature difference limit of supplied air into the occupied zone. This tendency increases with an increase in the number of heat sources.

The results of using the above mathematical model to design systems with vertical temperature stratification systems were compared with those of laboratory and field experiments and have proved to be in a good agreement.

COMPARISON WITH CONVENTIONAL SYSTEMS

Let us consider some design solutions for vertical temperature stratification systems.

Computer operator's room with an area of 6 x 6 m^2 and a height of 3 m is occupied by 12 operators and 12 displays. The heat gain is 5760 W from the displays and 972 W from the operators. Also there is input from insolation equal to 1300 W. The required air temperature in the occupied zone is 22°C; air velocity must not exceed 0.2 m/s. The results of calculations for a vertical temperature stratification system are presented in Table 1.

TABLE 1

Parameters of the Vertical Temperature Stratification System for Computer Operator's Room

q_o	q_{conv}	$q_{rad.l.z}$	$q_{rad\ u.z}$	$h_{o.z}$	G_o	Ri	U_o	$t_{l.z}$	$t_{u.z}$	t_o	K_t
W	W	W	W	m	kg/h	-	m/s	°C	°C	°C	-
8000	3450	1430	3120	1.8	6160	7	0.16	22	25.2	20.5	3.1

The air exchange rate G_o has been found from the condition of providing temperature stratification at a height of 1.8 m. The air temperature difference of 3.2°C between the occupied zone and the upper zone ensures stability of stratification and allows one to ignore the turbulent exchange ($Ri > Ri_{crit} = 5$). Efficiency of air exchange $K_t = 3.1$. Air is supplied into the occupied zone by four half cylinder perforated panels 1 m in diameter and 1.5 m in height, placed at the walls. Air flow through each diffuser is 1540 kg/h. To ensure stable convective flows, air diffusers should be located at a distance exceeding 1.5 m from the heat sources.

In a conventional mixing ventilation system to be used in the operator's room air can be supplied through ceiling mounted air diffusers ($K_t = 1$). The air exchange rate at the initial temperature difference $t_{o.z} - t_o = 3.5$°C, would be 8230 kg/h. The use of temperature stratification in this case allows one to reduce the air exchange rate by 35% and is obviously expedient.

In a workshop with an area of 36 x 24 m² and a height of 6 m, heatgenerating equipment ($Q_{eq} = 20600$ W) is distributed evenly across the floor space. There are local exhausts, evacuating $G_{exh} = 1400$ kg/h air from the lower zone. The required air temperature in the occupied zone is $t_{l.z} = 25°$ and air velocity must not exceed 0.4 m/s. The results of calculations for vertical temperature stratification system are presented in Table 2.

TABLE 2

Parameters of the Vertical Temperature Stratification System for the Workshop

q_o	q_{conv}	q_{eq}	$h_{o.z}$	G_o	Ri	U_o	$t_{l.z}$	$t_{u.z}$	t_o	K_t
W	W	W	m	kg/h	-	m/s	°C	°C	°C	-
21600	10300	20600	2.0	13150	1	0.25	25	26	20	1.2

Air is supplied into the occupied zone by two cylindrical perforated panels 1 m in diameter and 2 m height installed in the occupied zone: 6575 kg/h by each air diffuser. The value of the Richardson number (**Ri** = 1) in this case is below the critical value. A slight air temperature difference between the occupied zone and the upper zone doesn't ensure stable stratification in the room. The effectiveness of air exchange (K_t= 1.2) is low. In this example temperature stratification has no advantage over the mixing-type systems.

CONCLUSIONS

Air temperature stratification systems allows designers to improve effectiveness of air change by general ventilation in rooms with stable convective flows. Radiant heat exchange in a room plays an important part in forming air temperature distribution in lower and upper zones. The role of turbulent heat exchange between the zones can be ignored when the value of Ri $\geq$ 5. Local exhaust systems reduce the effectiveness of temperature stratification systems; if the amount of air exhausted by local ventilation systems from the lower zone exceeds 50% of the total air exchange, the need for a temperature stratification system is questionable. Mathematical model based on zone-by-zone heat balances can adequately describe the process of heat exchange in rooms and allows one to perform the calculations needed for designing ventilation systems with vertical temperature stratification and to optimize their operation regimes.

NOMENCLATURE

α_{conv}, α_{rad}, α_{turb} = coefficients of convective, radiant and turbulent heat exchange correspondingly, W/m² °C;

$F_{l.z.}$, $F_{u.z.}$, F_{turb} = area of the surface of heat exchange in lower zone, upper zone and between the zones correspondingly, m²;

$h_{l.z.}$ = height of the lower zone, m;

$\tau_{l.z.}$, $\tau_{u.z.}$ = surface temperature in the lower and upper zones correspondingly, °C;

$t_{l.z.}$, $t_{u.z.}$, t_{out}, t_o = temperature of the surfaces in the lower and upper zones, outside and supplied air correspondingly, °C;

$K'_{l.z.}$, $K'_{u.z.}$ = incomplete heat exchange coefficient for room obstructions in the lower and upper zones correspondingly, W/m²°C;

G_o, G_{exh}, $G_{conv\ l.z.}$ = the amount of supplied and exhausted air in the lower zone and air in convective flow in the lower zone, kg/h;

q_{rad}, q_{conv} = radiant and convective heat flows, W.

V_o = velocity of the supplied air, m/s;

$K_t = \frac{t_{uz} - t_o}{t_{1z} - t_o}$ = efficiency of air exchange coefficient.

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