DISPLACEMENT VENTILATION FORMING AT DIFFERENT AIR FLOW RATES

Z. Trzeciakiewicz, Z. Popiołek, S. Mierzwiński
Department of Heating, Ventilating and Dust Removal Technology
Silesian University of Technology, Gliwice, Pl.

ABSTRACT

The paper presents the results of the tests of two-zone airflow pattern forming in a room with displacement ventilation where various heat sources and various airflow rates were tested. The position of the interface layer between the zones was determined experimentally – on the basis of tracer gas concentration measurement and on the way of calculation - on the basis of the plume model above a point heat source complemented with experiment. The following heat sources were used: a plume simulator, a desk lamp, a computer, a round plate and a human body. Quasi-laminar diffusers supplied the air. The test results show that in order to define the interface position in displacement ventilation where real extensive heat sources are used, it is possible to apply the experimentally completed model of plume above a point heat source.

INTRODUCTION

The air pattern in the case of classical displacement ventilation – according to the "filling box with a plume" model – is characterised by two horizontal flow zones occurring in the room. The lower one is the zone of the air inflow into the plume and the upper one - of the air circulation and mixing [1]. The zones have different flow characteristics. In the interface occurring between the zones a step increase in thermal stratification and in the concentration of contamination can be observed.

The interface is placed at the elevation where the air volume flux in the plume is equal to the supply airflow rate. Beginning from this elevation, the plume entrains the air only from the circulation zone, and the momentum is used for the air circulation induction and air mixing in the upper zone. The two-zone air flow pattern under the real conditions of displacement ventilation is affected by 4 factors: *plumes, supply air flows, thermal conditions* and *room geometry*. The plumes contribute thermal buoyancy forces, supply air flows determine the interface position by their flow rate, the room thermal

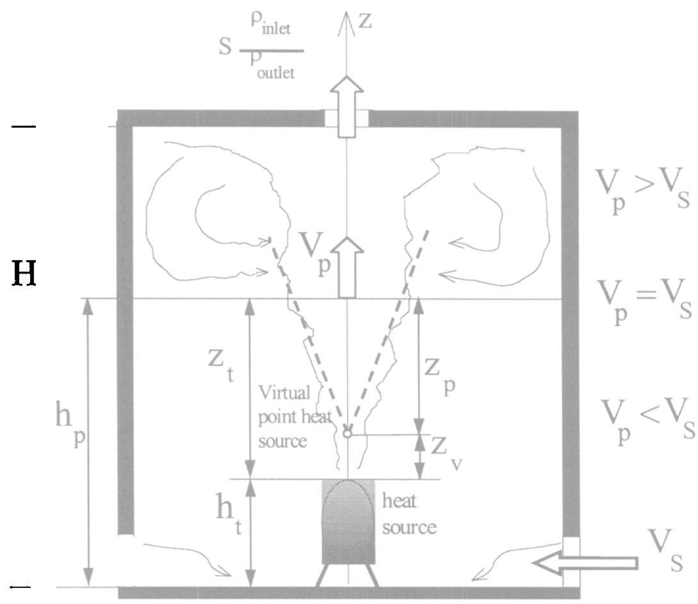

Fig.1 Two zone air flow pattern in displacement ventilation

conditions and its geometry form the air temperature distribution and, in this way, may affect the plume flow rate and the interface position. Although the above factors may be changed independently, together they all form the picture of displacement ventilation.

THE AIM AND METHOD OF THE TESTS

The aims of the tests were:

- Verification of the possibility to apply the method of the plume air volume flux calculation above a heat source, suggested by Popiołek et al.[2], to predict the flow rate of plumes above various heat sources under displacement ventilation conditions;
- Verification of the accuracy of the interface position predicting when the above mentioned method is applied under displacement ventilation conditions when real heat sources and different air supply rates are considered.

The method of the plume predicting [2], consists in introducing experimentally defined values of parameters k_V and z_V to the well known model of plume above a point heat source.

$$V_p = k_V\, Q_z^{1/3} z^{5/3} = k_V\, Q_z^{1/3} (z_t - z_V)^{5/3} \qquad (1)$$

where: Q_z – the enthalpy excess in the plume
k_V – the flow rate coefficient
z_t – the distance between the cross-section considered and the top of the heat source, see Fig. 1.

The enthalpy flux in plume, Q_z, may be determined from the heat source balance. Since under displacement ventilation conditions the plume develops in the environment of significant thermal stratification, large amount of the source heat exchanged on the way of natural convection, Q_c, is used to "heat" the air entrained by the plume up to the ambient temperature at the elevation considered. [3]. The enthalpy excess at the elevation "z" may be calculated from the relation

$$Q_z = Q_c - \rho c_p \int_0^z V_p S dz \qquad (2)$$

where $S=dt_\infty/dz$ is the stratification factor. From Eq.2, using Eq.1, Q_c, of the source may be evaluated when the plume enthalpy excess Q_z is known from the measurement at the elevation z. It is also possible to evaluate Q_z when Q_c is known.

$$Q_c = Q_z + \frac{3}{7} Q_z^{1/3} \rho\, c_p\, k_V\, S\, z^{7/3} \qquad (3)$$

Since $Q_z=f(Q_c)$ is an implicit function it is necessary to use the "search result" or "solver" procedure (EXCEL). The flow rate coefficient, k_V, and the origin distance, z_V, are determined individually for each heat source. It is worth determining these parameters on the basis of velocity and temperature excess distributions in the zone of fully – developed turbulent plume where $R_t \approx R_w = 0.15 \div 0.20$m. (elevation above the origin about 1.4 m.). It is recommended to determine the origin distance from the relation $z_V = z_1 - 7.75R_{t1}$ [2].

The interface position was analysed by two methods:

- By calculation in the way based on the "filling box with a plume" model, complemented with a method of the plume air volume flux predicting. This method consists in the assumption that the elevation where the plume flow rate gets equal to the supply air flow rate $V_{p.}=V_S$ corresponds to the interface position. The elevation value can be obtained from Eq.1 assuming the plume rate $V_{p.} = V_S$

$$h_{p.} = h_t + z_V + k_V^{-3/5} Q_z^{-1/5} V_V^{3/5} \quad (4)$$

- Experimentally, on the basis of the measurement of tracer gas vertical distribution, assuming that the interface position was at the elevation h_{50}, where a 50% increase in the tracer gas concentration occurred in the plume surroundings.

RESULTS OF THE TESTS

Twenty-five measurement series were carried out, differing in the kind and power of the heat source, its position, the number of ventilating air changes and the way in which the air was supplied. The tests were done in a room the dimensions of which were 3×3×3 m. The air was supplied through two quasi-laminar diffusers placed in two opposite corners of the room and it was removed through a ceiling diffuser. The amount of the air removed corresponded to 1÷7 - air room volumes per hour. It was possible to determine the vertical air temperature distribution in the plume surroundings by stationary thermocouple systems. Movable measurement systems made it possible to measure the air temperature and velocity distributions in the plume as well as the tracer gas distribution at any level outside the plume. The tracer gas was introduced to the plume just above the heat source.
The following heat sources of various shapes and powers were used:
- Heat sources of simple shapes such as the plume simulator [4], the power of which was 250 and 490 W (which made it also possible to generate plumes of different Archimedes numbers) and a round plate of the power of 600 W.
- Heat sources of complex shapes such as a desk lamp, a computer with a monitor and a human body.

The power of these heat sources changed from 80 to 600 W (up to 66 W/m^2). The top of each source was placed at the height of 0.5 ÷1.3m above the floor level.

Fig. 2 shows the results of the interface elevation tests, determined on the basis of the vertical tracer gas concentration distributions measured in the plume surroundings as well as vertical temperature simplex distributions in the plume surroundings $(t_\infty - t_{inlet})/(t_{outlet} - t_{inlet})$. The flow rate coefficient k_V, and the origin distance z_V, was determined individually for each source. In order

Table1 The values of k_v i z_v determined for the plumes tested

HEAT SOURCES	n	S	Qc	$Q_{z=1.4m}$	k_V	z_V
	h^{-1}	K/m	W	W	-	m
plume simulator 250W	1	2	245	170	0.0056	0.12
plume simulator 490W	1	3	445	307	0.0060	0.26
computer with a monitor	1	1.8	57	22.5	0.0055	-0.49
desk lamp 100W	1	0.9	37	20	0.0068	0.2
round plate 600W	1	2	187	120	0.0061	0.16
human body	1	1	32	15	0.0055	-0.56

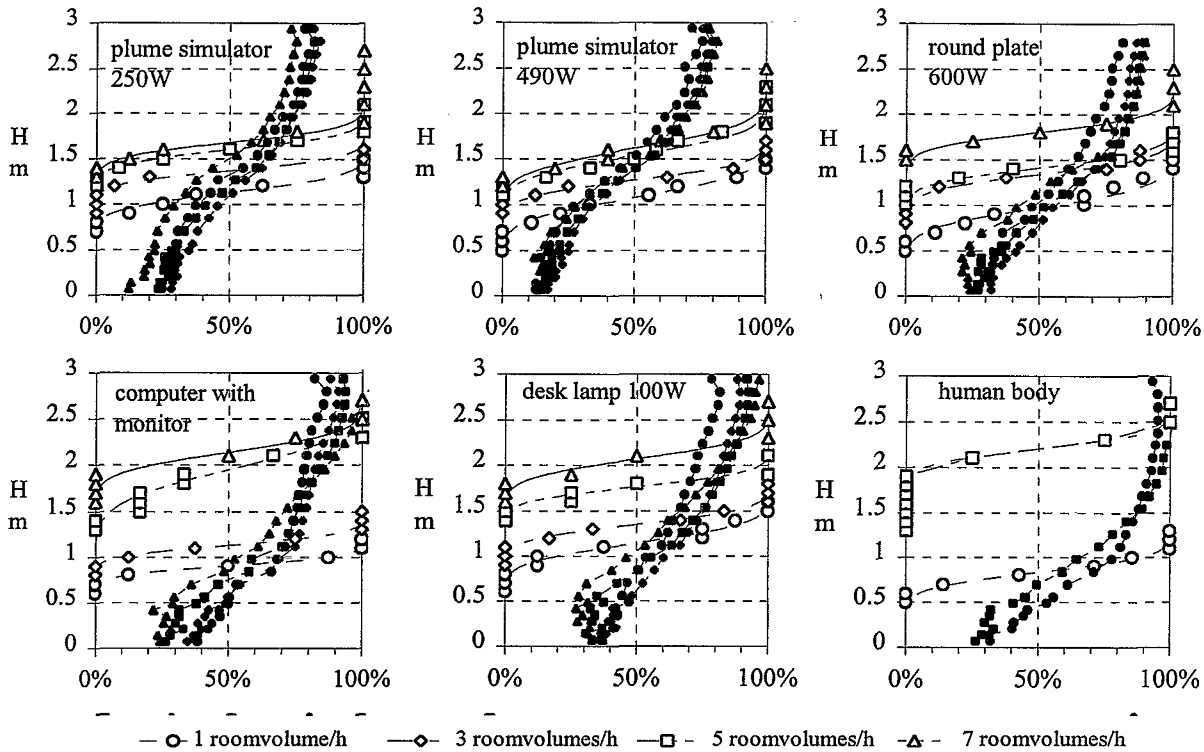

Fig. 2 Results of vertical distribution measurements of tracer gas concentration (markers empty) and simplex of air temperature in the plume surroundings (filled markers) in the room with displacement ventilation.

to determine these parameters the series corresponding to the smallest number of changes were selected i.e. 1 room volume/h = 0.0075 m^3/s since in these cases stratification value in the plume surroundings was the lowest.

Having assumed the plume enthalpy excess equal $Q_{z=1.4\ m.}$, the entrainment coefficient k_V, was calculated on the way of computer optimisation by minimising $\Sigma(V_{calculated} - V_{measured})^2$. The values of parameters determined for the plumes tested are presented in Table 1. Fig. 3 shows the error of the air volume flux calculation for the plumes tested $(V_{calculated} - V_{measured})/V_{measured}$, according to the method suggested. The mean value of error is 1% but the mean of the absolute value of error is 12%. These values may increase for some heat sources by about 10% if the mean value k_V=0.006 is assumed.

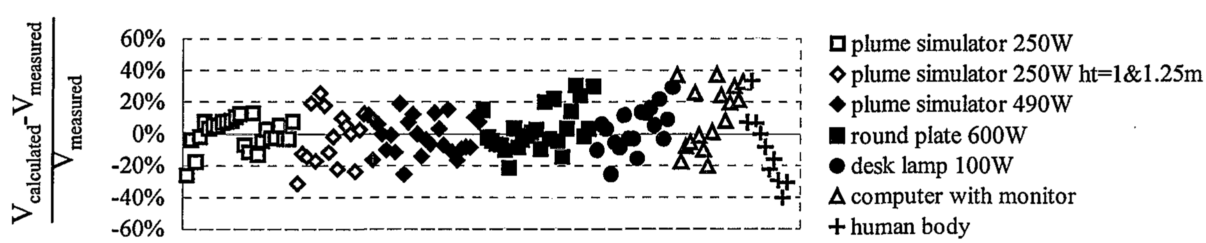

Fig.3 Errors of the air volume flux calculation in plumes, according to the method suggested.

Fig.4 shows the relation between the predicted interface elevation hp, calculated from Eq.4 and the elevation h_{50}, determined from vertical distribution of the tracer gas concentration.

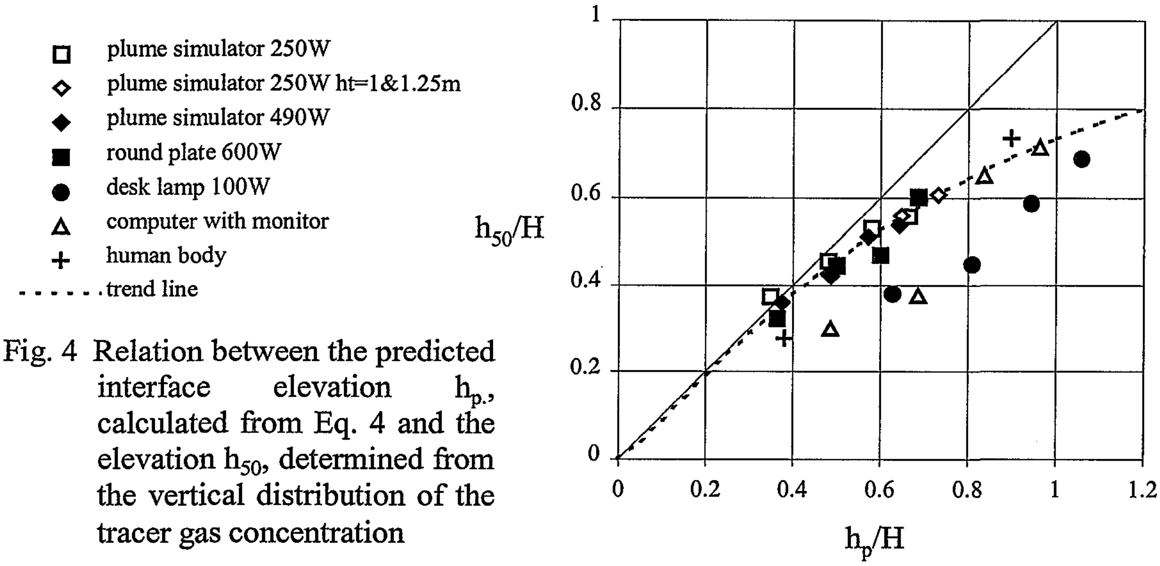

Fig. 4 Relation between the predicted interface elevation h_p., calculated from Eq. 4 and the elevation h_{50}, determined from the vertical distribution of the tracer gas concentration

DISCUSSION OF THE TEST RESULTS

Having analysed the results, the following remarks can be emerge:

- The elevation of the interface and its thickness may be precisely determined from the vertical distribution of the tracer gas concentration
- It is not possible to determine the interface elevation on the basis of vertical distribution of the air temperature in a room since the temperature increase in the real conditions of displacement ventilation does not have clear step changes.
- When a heat source geometry is simple and thus the plume generation is not disturbed significantly (plume simulator, round plate) the interface elevation, h_p., calculated from Eq. 4 coincides with to the value determined experimentally, h_{50}, up to the level of 60% of the room height. At higher levels a discrepancy between h_{50} and h_p. occurs and it gradually increases when the air change number is increased.
- The discrepancy between the value determined experimentally, h_{50} and the value calculated, h_p., may appear in relation with the phenomena which are physically comprised in h_{50} and are not considered when h_p. calculating. These phenomena may be the dynamic effect of the ceiling on the plume (the plume impact on the ceiling) and the short circuit in the outflow–inflow. These phenomena could not be identified in the tests
- When extensive heat sources of complex shapes and very irregular conditions of the convective heat transfer (desk lamp) were used, h_{50} and h_p. were not consistent within the whole range of the ventilating air change. When the geometry of the extensive heat sources was less complicated (computer, man) the values of h_{50} and h_p. got closer at high numbers of air changes. In the case of the lamp and computer it was observed that the experimental elevation h_{50} was sometimes found below the heat source top. This phenomenon could be caused, among others, by disturbances which, in the case of the computer, occurred in the plume due to the internal cooling fan and in the case of the lamp – due to the desk presence which contributed to the plume development deformation.

- Stratification, depending on the room heat loss may vary and even increase when the number of changes increases. In the test room where heat loss was observed (k=0.7 W/m^{2}K) stratification depended mainly on the heat source type and power. It slightly increased when the number of room volumes increased. For the plume simulator of the power of 250 W, at 1÷7- room volumes/h, stratification was 2.0÷2.4 K/m. It resulted from varying heat loss of the test room when the number of room volumes changed. At the given power of the heat source in the room with displacement ventilation, certain mean air temperature is established. At small number of room volumes the effect of the ventilating cold air on the room temperature decrease is small. The elevation of the inflow zone is low and the room heat loss is the highest (190 W at 1 air change). The higher the number of air changes is, the lager room volume is filled with the cold air. This causes further reduction in the mean temperature in the room and thus the heat loss decreases (-33 W at 7 room volumes/h).
- No changes in k_V value were observed in the plumes tested at different numbers of air changes. There is no need to correct this value at different stratification. Stratification should be taken into account by introducing the enthalpy excess to Eq.1 according to Eq.3.

CONCLUSIONS

1. The tests proved that the two–zone air flow pattern in real rooms with displacement ventilation developed in the conditions similar to those presented in the "filling box with a plume" model.
2. The present method, based on the model of plume above a point heat source, may be used to predict the interface elevation in displacement ventilation with sufficiently good results in the case of extensive heat sources but only when they do not introduce significant disturbances in the plume generation process.

ACKNOWLEDGEMENT

The research were carried out within the Research Project No T07G 03 911 financed by the Polish State Committee for Scientific Research (KBN) in 1996-1999.

KEY WORDS

Ventilation, Convection, Displacement ventilation, Tracer gas

REFERENCES

1. Sandberg M. Lindstrom S. A model for ventilation by displacement, Proc. ROOMVENT'87, Sess.3 Stocholm 1987
2. Popiołek Z., Trzeciakiewicz Z., Mierzwiński S. Improvement of a Plume Volume Flux Calculation Method, Proc. 6th International Conference on Air Distribution in Rooms, ROOMVENT'98, Stockholm, Sweden
3. Popiołek Z.; Problems of testing and mathematical modelling of plumes above human body and other extensive heat sources, A4-serien nr 54, Inst. for Uppvarmnings och Ventilationsteknik, Royal Institute of Technology, Stockholm 1981
4. Mierzwiński S., Popiołek Z., Trzeciakiewicz Z. Experiments on Two-zone Air Flow Forming in Displacement Ventilation, Proc. ROOMVENT'96, Vol.3. Yokohama, Japan, 1996.