\# 6065

International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

# TESTING AND MODELLING OF THERMAL PLUMES IN ROOMS

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## ABSTRACT

Thermal plumes, even weak ones, are essential factors causing air movement in rooms. Recently, convective flows have become of particular interest owing to displacement ventilation. Referring to ventilation processes predicting the paper discusses experimentally acquired knowledge of plumes characteristics as well as the experimentally improved integral method for calculation. The method makes it possible to simulate a plume over a heat source of any shape, also in the environment with stratification and to analyze and optimize numerically the measurement results in different conditions. Mutual relations between the plume model and buoyant ventilation modelling are mentioned. Attention is paid to the choice of methods for air flow pattern predicting in spaces with heat sources.

**KEYWORDS** Plume, Room Airflows, Integral Method, Experiment

## 1. INTRODUCTION

In the air flow pattern in ventilated rooms, flows related to thermal convection occur very often and in different forms. Their parameter fields are sensitive to disturbances, difficult to identify and to predict.

Thermal plumes in rooms are generated by heat sources that significantly differ in power, shape and size. These may be industrial furnaces, burners, heaters, computers, lamps, people etc. The plumes develop either in aerodynamically neutral environment or in environment that deforms their buoyant forces and mechanically limits their evolution. Figure 1 present some characteristic examples of relating a thermal plume with room ventilation process, namely:

a. Plume over a heat source in a relatively large space
b. Plume that initiates air circulation and air exchange in a confined space
c. Plume deformed by aerodynamical mixing and lateral flows.

Due to the variety of parameters of heat sources and of plume surroundings it is difficult to predict covective flows and air flow patterns in rooms. The possibilities to overcome those difficulties ought to be coupled with the tools for ventilating flows testing and calculating.

In relation to ventilation processes predicting, one may assume that the variety of parameters of a heat source above all induces experimental identification and analysis of such the phenomena. Prediction syntheses of the required flow patterns ought to be sensibly divided into physical-mathematical simulations, making use of dimensional analysis and into numerical simulations, based on turbulence models.

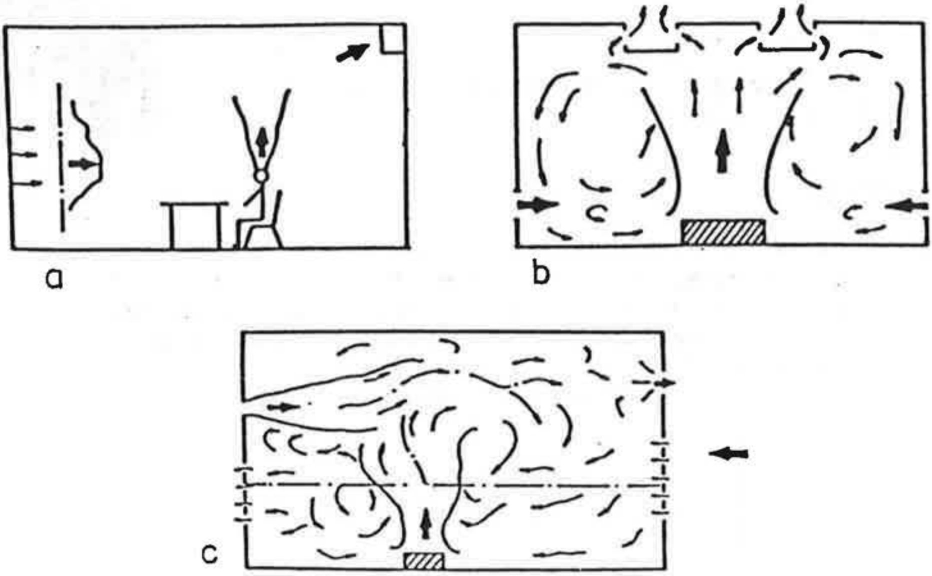

Figure 1. Participation cases of plumes in ventilation processes
a. Plume in a relatively large space
b. Plume initiates air circulation and exchange
c. Plume aerodynamically deformed

Physical simulations are necessary in many cases when ventilation processes are predicted, in particular, in cases of large enclosures with geometrically and technologically complex problems and where thermal plumes are essential element of air flow patterns.

Integral methods for thermal plume calculation stem and are well related to experiment. Their improvement makes it possible to simplify significantly the share of experiment in effective prediction of air flow in rooms.

Experimental tests of thermal plumes have some special conditions that are worth discussing.

Taking the above into account the three aspects of the problem of thermal plumes coded in the title of the paper:

testing - modelling - in rooms

are referred mainly to tests of the process of fluid entrainment by plume and spreading process of the plume in room conditions, to the improvement of the integral methods for plumes calculation and to their application in prediction of selected cases of displacement ventilation.

## 2.1 PLUME IN AN ENVIRONMENT OF INFINITE EXTENT

The way in which an axisymmetrical free plume is formed in neutral i.e. stagnant and of infinite extent environment is shown in Figure 2. The following characteristic stages of its development may be separated:

I. Flow in the boundary layer region where convective boundary flows mix and form a plume; laminar motion changes into turbulent, distributions of parameters are not explicitly determined.
II. Self-similarity of the mean motion region; the plume becomes turbulent and axisymmetrical, the plume spreads non-linearly.
III. Complete self-similarity flow region; the flow turbulence is fully developed, the plume spreads linearly.

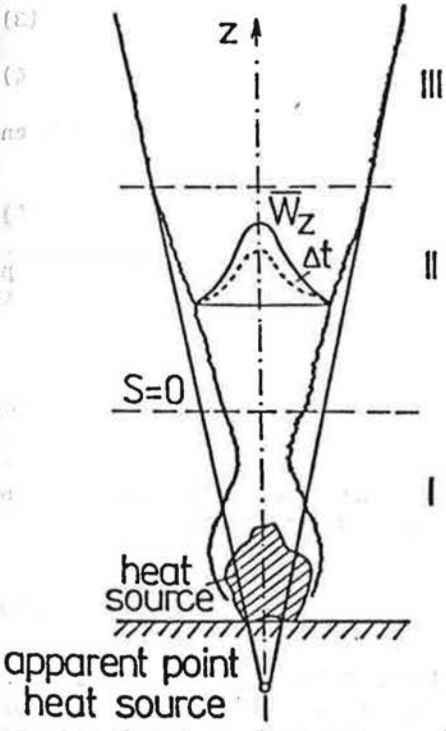

Figure 2. Flow region in the plume above a heated body

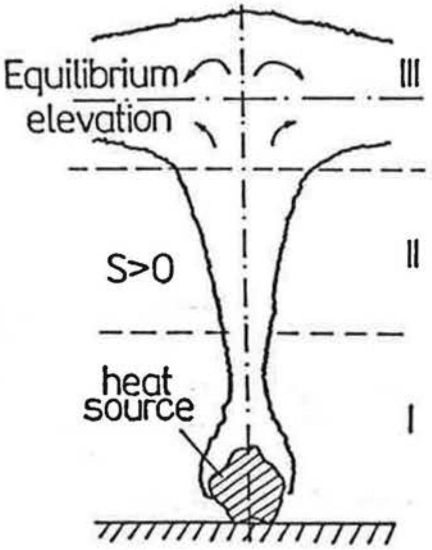

Figure 3. Flow region in the plume in the case with thermal stratification of the ambient air

A conserved quantity in plume is thermal buoyancy flux $B_0$ or enthalpy excess $Q_0$. The initial value of thermal buoyancy and the shape of the heat source are of decisive influence on the plume spread and on the way in which it is formed.

In enclosures, plumes over weak heat sources seldom reach the III stage of development. However, calculation models refer just to the flow self similarity region.

### 2.1. Model of plume over a point heat source

The model of plume over a point heat source has been known for a long time and it is often applied in calculations related to ventilation. According to the assumptions:

- velocity and temperature distributions are Gaussian error curves:

$$\bar{w}_z/\bar{w}_{zm} = \exp(-r/R_w)^2 = \exp\left[-m(r/z)\right]^2 \tag{1}$$

$$\bar{\Delta t}/\bar{\Delta t}_m = \exp(-r/R_t)^2 = \exp\left[-p(r/z)\right]^2 \tag{2}$$

- plume spreads linearly with the height:

$$R_w = m^{-0,5}\ z \tag{3}$$

$$R_t = p^{-0,5}\ z \tag{4}$$

In the above equations parameters m and p are given constant values and therefore the ratio of the profile widths is constant, too:

$$\lambda = R_t/R_w = (m/p)^{0,5} = \text{const} \tag{5}$$

- the ratio of buoyant forces to inertial forces does not change since the momentum is produced by buoyant force, constant along the length, thus:

$$Ar = Ar_o = \frac{\beta g \bar{\Delta t}_m R_w}{\bar{w}_{zm}^2} = \frac{2p}{3m^{3/2}} = \text{const} \tag{6}$$

- the plume fluid consists of that which has been entrained from the environment thus the equation of volume conservation:

$$\frac{d}{dz}\left(\bar{w}_{zm}\ R_w^2\right) = 2\alpha \bar{w}_{zm}\ R_w \tag{7}$$

where $\alpha$ is an entrainment constant corresponding to the entrainment hypothesis introduced by Sir Geoffrey Taylor in 1949. Turner (1986) determines $\alpha$ as the ratio of the entrainment velocity at which external fluid flows into turbulent flow across its boundary to the axial mean velocity of the plume, $\bar{w}_{zm}$.

Therefore, the parameters of the self-similar axisymmetrical plume depend on the source power Q and on the height z, the location of the considered cross-section over the source. For the axial values of the parameters the following relations are acquired:

$$\bar{w}_{zm} = k_w\ Q^{1/3}\ z^{-1/3} \tag{8}$$

$$\bar{\Delta t}_m = k_t\ Q^{2/3}\ z^{-5/3} \tag{9}$$

where coefficients $k_w$ i $k_t$ are closely related to parameters m and p.

## 2.2. Plume in a stably stratified environment of infinite extent

In rooms with heat sources there is also thermal stratification of air. Depending on the actual air flow pattern stratification with different air temperature density gradients may occur. In tests made by Koefed (1991), Mund (1991) Fitzner (1989) and Mierzwiński (1980) air temperature gradients observed in rooms varied within the limits 0.3 - 1.5 K/m which corresponds to dimensionless stratification values S = 0.01-0.1 according to the formula:

$$S = s\, R_{wo}/\bar{\Delta t}_{mo} \qquad (10)$$

Figure 3 illustrates the way in which a plume spreads and the characteristic stages of its development in a stratified environment:

I. Initial stage, similar to region I when S=0, but stratification affects the plume forming.
II. Mean motion self-similarity zone; significant effect of stratification.
III. Density equilibrium zone; buoyant forces and inflow velocity disappear, the plume reaches its maximum height where the air flows away in horizonal direction.

An analytical description of the process can be formulated having assumed that similarity of velocity and temperature profiles exists at all elevations. The enthalpy conservation equation is as follows:

$$\frac{d}{dz}\left(\bar{\Delta t}_m\, \bar{w}_{zm}\, R^2 \frac{\lambda^2}{\lambda^2 + 1}\right) = \bar{w}_{zm} R_w^2\, \frac{dt_e}{dz} \qquad (11)$$

where $dt_e/dz$ is a vertical change of the ambient temperature related to stratification (Baines and Turner 1969). The analysis of equilibrium elevation is presented when are presented results of plume calculations by means of integral method.

## 2.3. Process of fluid entrainment in a plume

Turbulent diffusion of momentum and heat in a plume model is characterized by coefficients m and p of velocity and temperature distributions. Archimedes number $Ar_p$ and the ratio of profile widths $\lambda_p$ are related to the coefficients m and p as follows:

$$m = \frac{4}{9}\, Ar_p^{-2}\, \lambda_p^{-4} \qquad (12)$$

$$p = \frac{4}{9}\, Ar_p^{-2}\, \lambda_p^{-6} \qquad (13)$$

In results the entrainment coefficient for a plume is:

$$\alpha_p = \frac{5}{6}\, m^{-0.5} \qquad (14)$$

Similarly, the entrainment coefficient for a jet is:

$$\alpha_j = 0.5\ m_j^{-0.5} \tag{15}$$

The values of parameters m and p has not been determined with sufficient accuracy yet. After Rouse m = 96, p = 71, after George m = 55, p = 65, after Shepieliev m = 74, p = 59 (Popiołek 1981). Hence the inaccuracy of calculation and the necessity of additional explanation.

Popiołek (1987), on the basis of analysis of closing equations given by Fox and Seban and Behnia, derived relations that should refer to the values characterizing turbulent diffusion of momentum in plumes and in forced plumes:

$$\alpha_j = \frac{3}{4}\ Ar_p\ \lambda_p^2\ \frac{3 - \lambda_p^2}{1 + \lambda_p^2} \tag{16}$$

$$Pr_t = \frac{(3 - \lambda_p^2)\ (2 + \lambda_p^2)}{5\lambda_p^2\ (1 + \lambda_p^2\ )} \tag{17}$$

However, in the above equations only the value of the entrainment coefficient of jet is sufficiently well known; it is defined as close to $\alpha_j = 0.057$.

From Fox's formula (Fox 1970) the entrainment factor $\alpha_p$ of a plume may be expressed as follows:

$$\alpha_p = \alpha_j + \left( 2 - \frac{3}{1 + \lambda_p^2} \right) Ar\ \lambda_p^2 \tag{18}$$

From Equation 18 it is apparent that the entrainment process for a plume is more intensive than for a jet generated by a point momentum source.

$$\alpha_p = \alpha_j + f(Ar_p,\ \lambda_p) \tag{19}$$

According to Fisher et al. (Turner 1986) experimentally determined value $\alpha_p$ is 0.083.

Given relations regarding the entrainment process in a plume or a jet result from the similarity arguments which assume linear spread of both radii with height. In practice, different turbulence structure is observed. Turbulent plume develops in the air in a form of large-scale vortices. Therefore its shape is not as determined as jet shape and the entrainment and mixing processes are different, too.

The value of turbulent Prandtl number in Equation 17 depend on flow turbulence structure. When large-scale so called "empty" vortices are observed in flow, $Pr_t$ is less than 0.5. When small vortices prevail, $Pr_t$ is greater than 0.5.

## 3. INTEGRAL METHOD FOR PLUME MODELLING

Experience of many researchers proves that it is practically impossible to work out methods that would enable to calculate plume parameters beginning just above the heat source. In practice, calculations may be carried out only for the mean motion self-similarity zone (stage II). Moreover in calculations one ought to take into account the effect of the generating conditions as well as of the ambient air properties conditions on the entrainment process in plume.

To this purpose it is necessary to determine experimentally at what elevation above the source that region occurs and what parameters values are at its beginning. From measurements of temperature and velocity distributions one may calculate the boundary value of Archimedes number $Ar_o$, the ratio of profiles $\lambda_o$, the enthalpy flux $Q_o$ and the boundary width of velocity profile $R_{wo}$. Knowing those parameters and having information about the ambient air stratification S, one may calculate further development of convective flow using the present integral method.

### 3.1. Experimental-mathematical integral method

The improved integral method (Popiołek 1984, 1987) is similar to the integral method used for vertical buoyant jets. The difference consists in application of Gaussian profiles instead of flat ones at the beginning of turbulent flow region. The method introduces also a different form of the second closing equation describing the changeability of profile widths.

The presented integral method for plume calculation consists of the following equations:

- Equation of mass conservation

$$\frac{d}{dz}\left(\bar{w}_{zm}\, R_w^2\right) = 2\alpha\, \bar{w}_{zm}\, R_w \tag{20}$$

- Equation of vertical momentum conservation

$$\frac{d}{dz}\left(\bar{w}_{zm}\, R_w^2\right) = 2\, \beta\, g\, \overline{\Delta t}_m\, R_w^2\, \lambda^2 \tag{21}$$

- Equation of energy conservation

$$\frac{d}{dz}\left[\frac{\lambda^2}{(1+\lambda^2)}\, \overline{\Delta t}_m\, \bar{w}_{zm}\, R_w^2\right] = -\,\frac{dt_e}{dz}\, \bar{w}_{zm}\, R_w^2 \tag{22}$$

- Closing equation i.e. Fox's formula describing the changeability of the entrainment coefficient according to the Equation 18 and 16.

- Second closing equation, describing the changeability of the ratio of the profiles widths:

$$\frac{d}{dz}\left[\overline{\Delta t}_m \frac{\lambda^2+1}{\lambda^2+2}\right] + \left[2 - \frac{(\lambda^2+1)^2}{\lambda^2(\lambda^2+2)}\right]\frac{dt_e}{dz} + \frac{\overline{\Delta t}_m}{R_w}\,\frac{\lambda^2+1}{\lambda}\,\gamma = 0 \qquad (23)$$

where factor $\gamma$ characterizing turbulent diffusion of heat is:

$$\gamma = \frac{5}{2}\,Ar_p\,\frac{\lambda_p^3}{\lambda_p^2+2} \qquad (24)$$

In order to describe temperature distribution in the plume surroundings the following equation is applied:

$$t_e = t_{eo} + \overline{\Delta t}_{mo}\,S\left(\frac{z}{R_{wo}}\right) \qquad (25)$$

### 3.2. Verification of the method

Figure 4 presents the results of plume calculation in the mean motion self-similarity zone (line) compared with experiment tests results (points). The measurements were carried out in a flow over a horizontal plate of diameter 0.5 m and thickness 0.07 m, heated to about 200°C. Apparently there is good agreement between the calculation and measurement results.

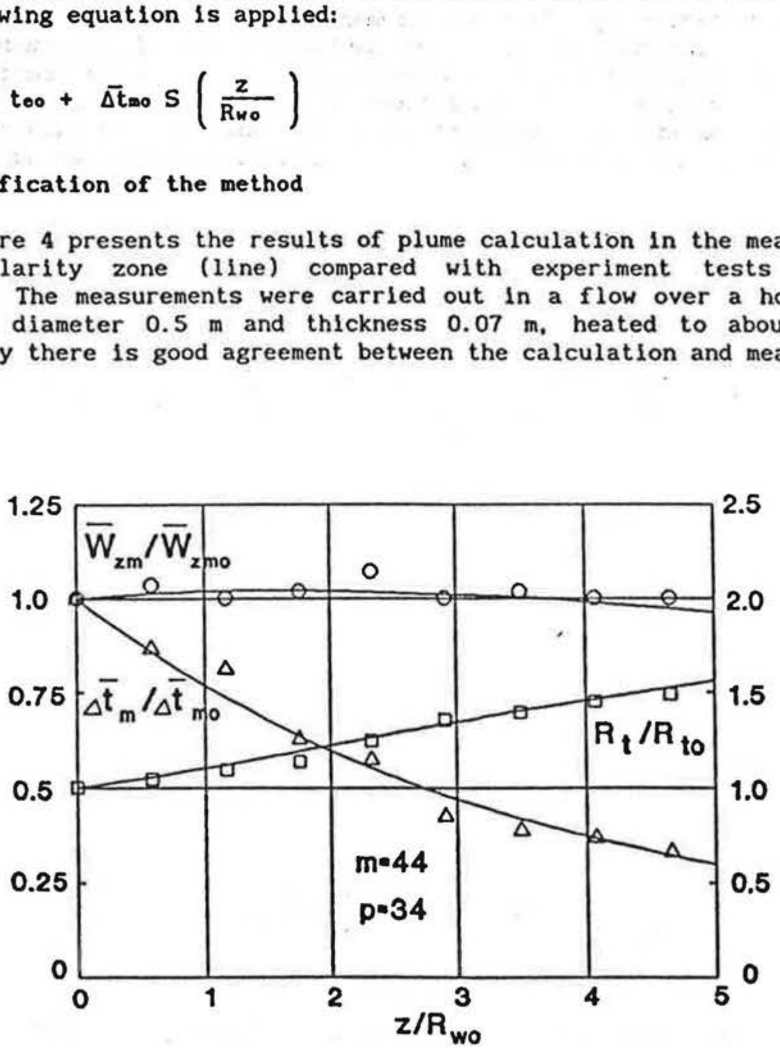

Figure 4. Plume parameters above the heated plate: 50 cm in diameter, $Q_o$=400 W. Points: experimental results, solid lines: calculation by the integral method with m = 44 and p = 34

The calculation results when the model of plume above a point heat source is applied significantly differ from the measurement results.

## 3.3. Application of the method

It might be interesting to apply the improved integral method in:

- optimization analysis of experiment results of plume tests in different conditions
- analysis of plume parameters distribution in the environment with and without stratification.

**Experiment analysis.** Formerly, Popiołek and Mierzwiński (1984) analysed test results by various authors regarding turbulent diffusion in plumes and located those results on a so called "map" of characteristic values. The map, shown in Figure 5 was made with the use of the Equation 12, 13, 16 and 17. It shows that the experimental data obtained so for by George, Szepieliew, Abramovitch, Rouse and Popiołek are divergent.

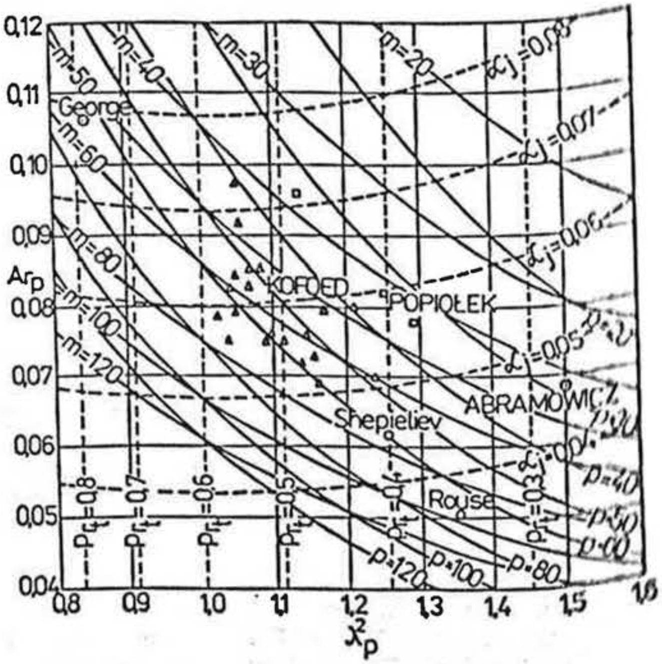

Figure 5. Map of self-similar plume characteristic parameters Ar$_p$ and $\lambda_p^2$ equivalent to m, p, Pr$_t$ and $\alpha_j$. In the map data of George, Rouse, Shepielov, Kofoed and Popiołek are marked

In order to explain the problem new extensive experimental data on plumes presented by Nielsen and Kofoed (1988) and by Kofoed (1991) was also analysed. By means of computer optimization the results of measurements of separate plumes were averaged and the data for the integral method were made more precise. Then, the relations between momentum diffusion parameters and boundary parameters in different plumes were analysed.

Experimental data included the following ranges of plume parameters:

$Q_o = 15 - 400W$, $Re_o = 7000 - 15000$,

$Ar_o = 0.07 - 0.15$, $S = 0 - 0.014$.

In the tested range of values of plume parameters the value of $\lambda_p^2$ (and thus also $Pr_t$ number) practically was independent of m, $Ar_o$ and S, but it slightly decreased when $Re_o$ got higher.

The average value $\lambda_p^2$ was about 1.1, ranging from 1.05 to 1.25 where as the averaged value of velocity distribution parameter m changed from about 70 to about 40. It was observed that:

- m increased when $Q_o$, $Re_o$ and S increased
- m decreased when $Ar_o$ value got higher and when ventilating air exchange increased in the room where the plume spread.

It is interesting how velocity profile width (at quasi-constant ratio $\lambda_p^2$) will depend on the choking degree of the air flow to the plume. At full choking (when only recirculation was maintained) the value m was 62±4 and at full, free supply (without recirculation) m reached the value of about 40. Hence, after Equation 14 the value of the entrainment coefficient $\alpha_p$ may change under these conditions from about 0.13 to 0.1.

It is worth mentioning that according to Equation 14 the value of m is about 100 at $\alpha_p = 0.083$ determined experimentally by Fischer (Turner 1986). Presumably those tests refereed to the environment with stratification. Turner (1986) mentioned also that the value $\alpha_p = 0.083$ was based on much less precise data then in the case when $\alpha_j = 0.05$ for a jet.

**Analysis of parameters distribution in the plume.** Calculation results of temperature and velocity vertical distribution in the plume axis in self-similarity of mean motion zone for the case without stratification, S = 0, are shown in Figure 6.

Velocity and temperature changes strongly depend on Archimedes number $Ar_o$ at the beginning of the zone. Whereas the other analysis shows that the boundary value of the ratio of profiles widths $\lambda_o$ is of less influence on velocity changes and of quite little influence on temperature excess.

Stratification affects all plume parameters making their values lower, however, its strongest effect is observed on the temperature excess in the plume axis and on the temperature profile width. Figure 7 presents distributions of local Archimedes number Ar and enthalpy flux Q for various values of stratification coefficient S. It is apparent that even stratification of $S = 10^{-4}$ already effects significantly on parameters distributions in plumes.

The effect of stratification is revealed no sooner than at certain distance from the initial cross-section. The distance can be defined on the basis of enthalpy changes. Figure 8 shows the distance where enthalpy is less by 10%. Practically, for distances shorter than $z_{Q=0.9}/R_{wo}$ the effect of stratification is negligible. The distance can be calculated with sufficient accuracy from the relation:

$$\frac{z_{Q=0.9}}{R_{wo}} = \frac{1}{20\,S + 0.5\,\sqrt[3]{S}} \qquad (26)$$

Figure 9 shows the distance where enthalpy flux decreases to zero and where horizontal flow away of fluid begins.

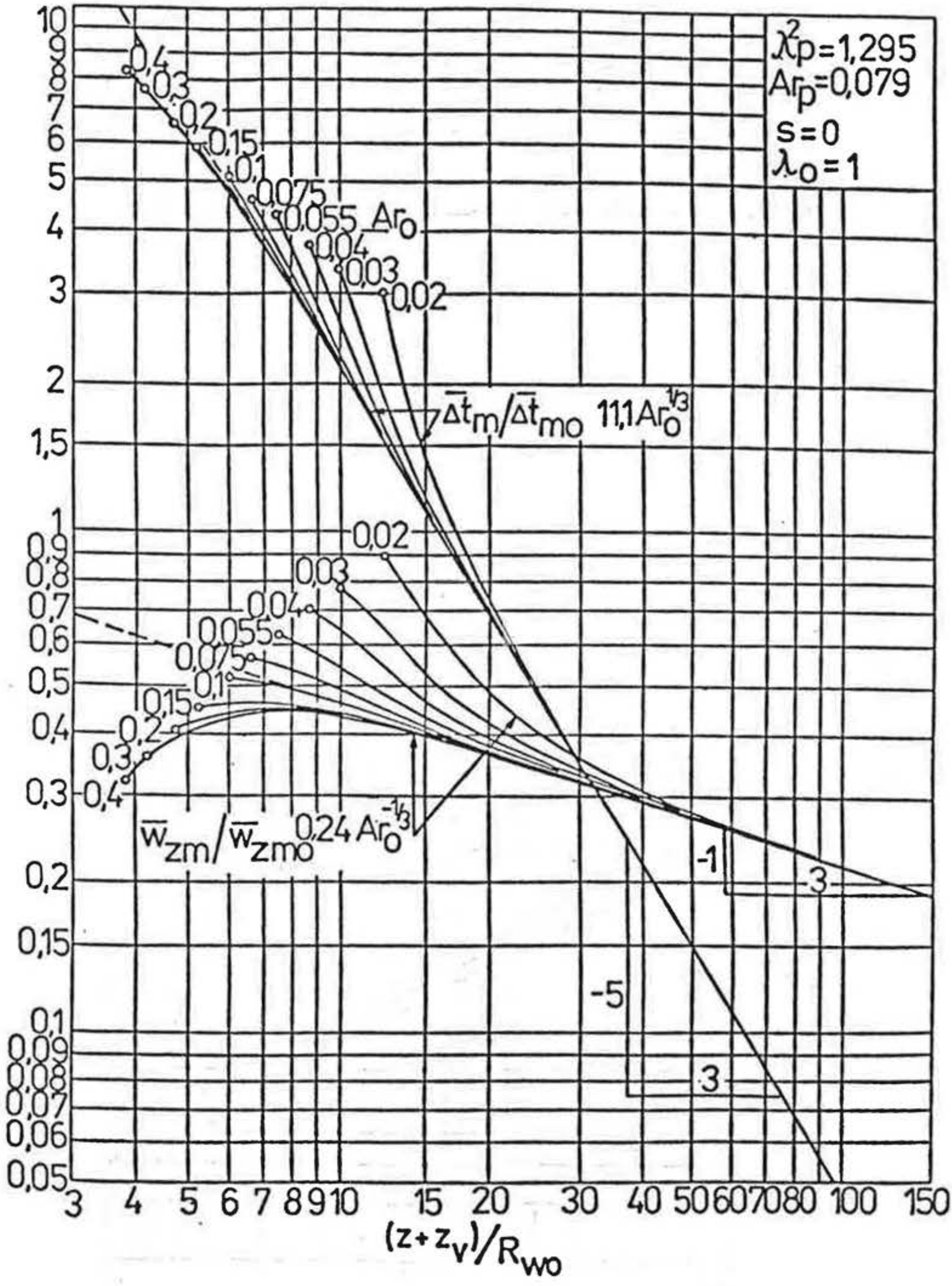

Figure 6. Normalized dimensionless velocity and temperature excess in the plume axis as a function of the distance from the virtual point heat source for different boundary $Ar_o$ numbers

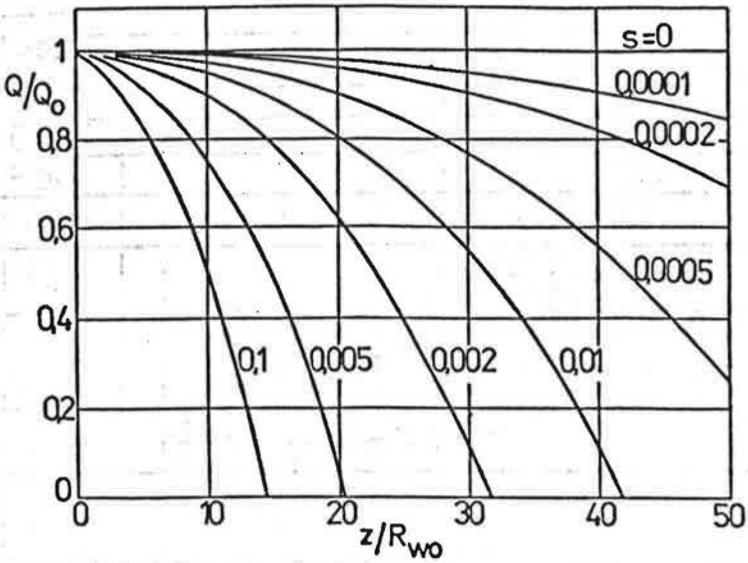

Figure 7. Enthalpy flux in plume in the case with stratification

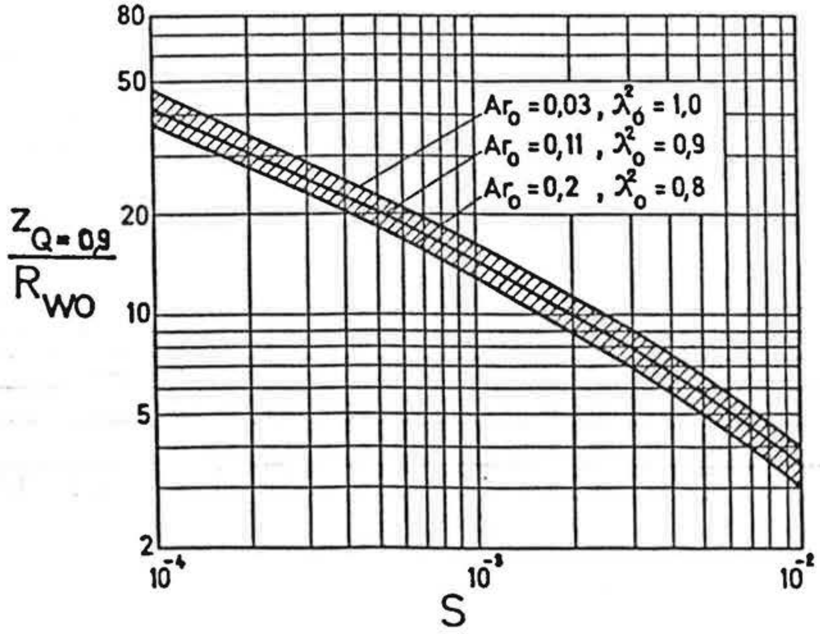

Figure 8. Elevation above which the influence of stratification on the plume cannot be neglected

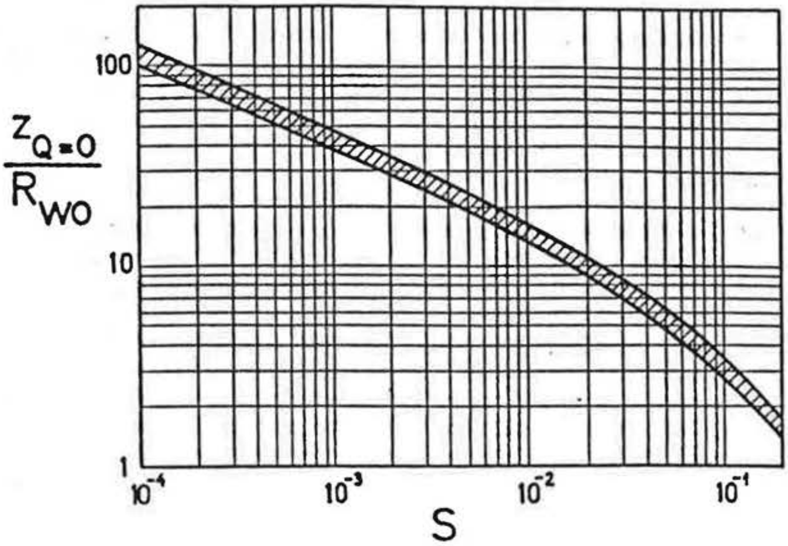

Figure 9. Elevation at which the enthalpy flux in plume decreases to zero, the negative buoyancy zone of plume begins and the fluid flows out horizontally

That distance can be calculated from the relation:

$$\frac{z_{Q=0}}{R_{wo}} = \frac{1}{2.5\,S + 0.2\,\sqrt[3]{S}} \tag{27}$$

The integral method in the form presented formerly becomes unreliable close to the maximum elevation since in this region velocity distributions and moreover temperature distributions significantly differ from the Gaussian curve. When limiting the ratio of profiles width $\lambda$ to certain value e.g. $\lambda^2=0,5$ in calculations one may determine the maximum elevation $z_{w=0}$ above the height $z_{Q=0}$. The maximum elevation $z_{w=0}/R_{wo}$ is up to 3 times higher that $z_{Q=0}/R_{wo}$. It is worth mentioning that the maximum plume elevation defined in this way is in conformance with the results acquired by Fox.

## 4. PROBLEMS OF EXPERIMENTS ON THERMAL PLUMES

### 4.1. Measurements of temperature and velocity distributions

Experimental tests of plumes are found difficult and laborious, mainly because of small values of measured parameters, unstable flow and erratic lateral movements. At temperature profile measurements, the required thermometer accuracy should be of the order of 0.01 K which is difficult to achieve. Moreover, the thermometer sensor ought to have the adequate time constant due to the instability of the flow.

Measurement of velocity profiles creates ever more difficulties. Velocity is usually much lower than 1 m/s whereas flows are of very intensive turbulence and are not isothermal. Only a laser anemometer is suitable for measurements of such the flows unreservedly. Vibration anemometer (such as DISA LVA) has similar qualities but its range is limited to 0.3 m/s.

In turbulent flows it is necessary to select the averaging time according to the scale of the actual vortices so as to get the required accuracy of estimators of the mean values of parameters. One must know frequency spectrum function or autocorrelation function of velocity fluctuations. The accuracy of mean velocity measurements in plumes was discussed by Popiołek (1981).

It is also worth mentioning that the accuracy of calculation of the volume, momentum and enthalpy fluxes in the plume does depend on the accuracy of temperature and velocity measurements within the whole region where the density values of the fluxes are the highest but not in the plume axis only. Such the regions in an axisymmetrical plume occur within the range of 1.7 $R_w$ for volum flux and of 1.2 $R_w$ for enthalpy flux.

In the tests of the plume above a sitting man particular consideration was given to the scatter of mean velocity measurement results. The scatter, was 3 ÷ 4 times wider than one should have expected on the basis of the statistical analysis of the measurement errors. Similar phenomenon was observed also above other heat sources. It appeared that the reason was the large scale instability of the flow in plume consisting in the plume axis wandering.

Figure 10 (Popiołek and Mierzwiński, 1984) shows some examples of plume axis wandering observed in a plume above a heated sphere of diameter 0.7 m. The plume axis was deflected from the vertical by about 0.25 $R_t$ and it slowly changed its position within the range of also about 0.25 $R_t$. Correction of the measurement results, taking into account the actual plume axis position, made it possible to reduce the scatter to 3÷5%.

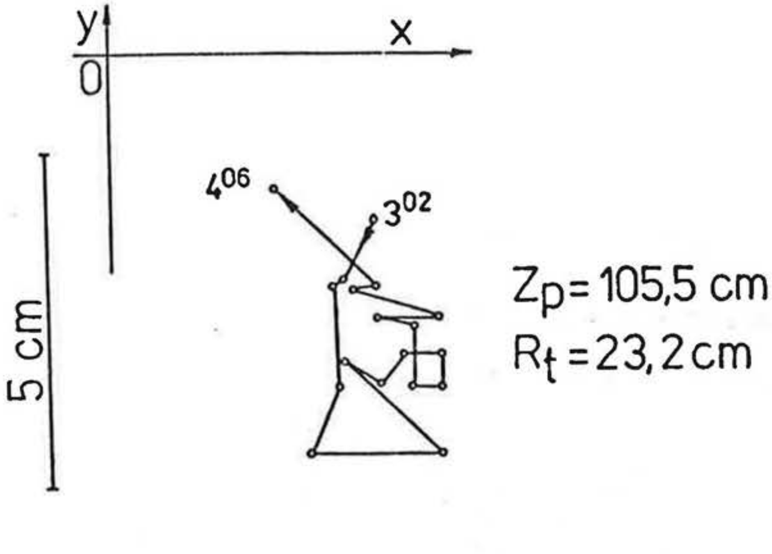

Figure 10. Plume axis wandering

The phenomenon of deflection from the vertical and wandering of the plume axis was observed also by H. Homma. Popiołek (1981) proved that the phenomenon is strongly affected by the actual conditions in the plume surroundings.

The actual position of the plume axis may be determined by means of a simultaneous measurement of parameters in many points, it is subsequently possible to calculate actual radial distances of the sensors from the plume axis (Popiołek 1987).

### 4.2. Aerodynamical properties of plume above the human body

Figure 11 pictorially presents the flow regions and mean temperature and velocity distributions in a plume above a sitting man. Up to the height of about 0.5÷0.7m above the head the shape of the plume evolves and the cross-stream profiles of velocity and temperature gradually change. It can be said that beyond that level a zone of self-similarity of mean motion occurs, the plume is axisymmetrical, while the cross-stream profiles of the parameters already are of quasi-Gaussian shape (Mierzwiński and Popiołek 1983). Figure 11 presents also vertical distribution of temperature excess and velocity in the plume axis. Figure 12 represents the results of velocity measurements in the cross-section of the plume at the height of 0.75 m above the head.

It is worth mentioning that eddy viscosity of the plume is only 100-300 times greater than molecular viscosity of the air. In the conditions of measurements the product of Gr.Pr numbers reaches the value of $2\cdot10^7$ for the head and $3\cdot10^8$ for the trunk. Then, the investigated phenomena occur in the range of boundary conditions o turbulent motion development.

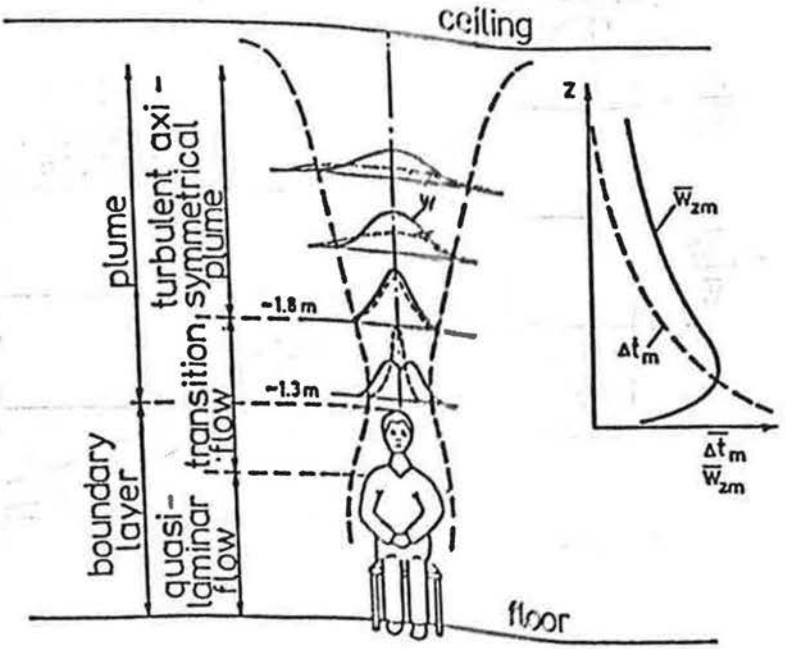

Figure 11. Flow region and parameters distribution in plumes above human body

The investigated plume displays the following average aerodynamic properties at the height of about 0.75m above human head, with room temperature of 19÷23°C:

| | |
|---|---|
| axial velocity | $\bar{w}_{zm} = 0.17 \div 24$ m/s |
| overtemperature in the axis | $\overline{\Delta t}_m = 0.7 \div 1.0$ K |
| velocity profile width | $R_w = 0.24 \div 0.33$ m |
| temperature profile width | $R_t = 0.20 \div 0.27$ m |
| profile widths ratio $R_t/R_w$ | $\lambda = 0.7 \div 1.05$ |
| Reynolds number | $Re = 3400 \div 6500$ |
| Archimedes number | $Ar = 0.13 \div 0.3$ |
| enthalpy flux /excess/ | $Q = 13 \div 30$ W |
| flow rate | $V = 0.03 \div 0.08$ $m^3/s$ |
| momentum flux | $I = (4 \div 9) \cdot 10^{-3} kg/s^2$ |
| kinetic energy flux | $E = 0.5 \div 1.2$ mW |
| eddy viscosity | $\epsilon_m = (20 \div 50) \cdot 10^{-4}$ $m^2/s$ |

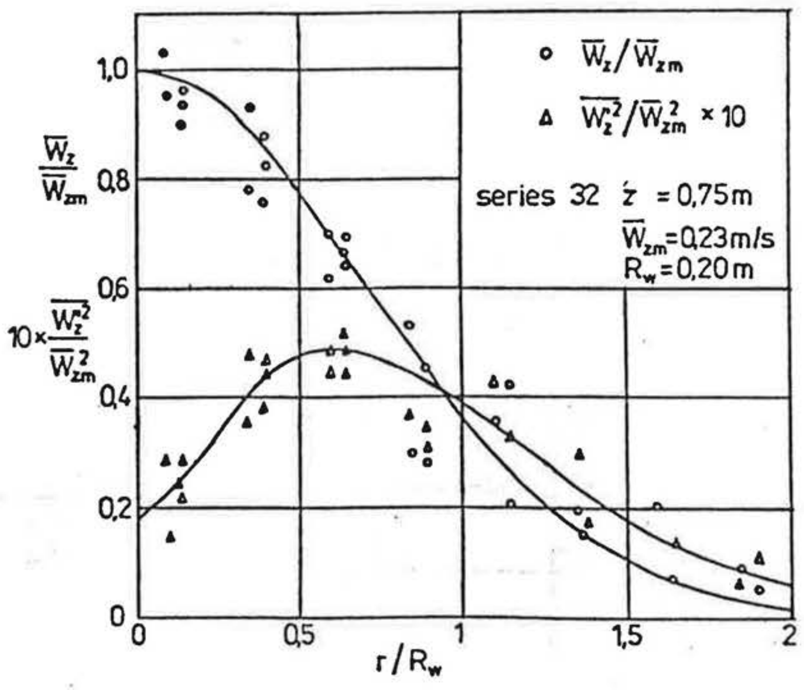

Figure 12. Radial distribution of mean velocity and velocity longitudinal fluctuations in a plume above human body

## 4.3. Methods for direct measuremnt of valume flux of the plume

In the case of room ventilation it is sometimes necessary to determine the flow rate in plumes without going into details of their shapes and distributions of their parameters. Then, the volume flux may be measured directly by mean of simplified methods.

**Zero method.** The method was used for thermal plumes by, among others, Fitzner (1989) and Kofoed (1991). The method consists in equalizing the amount of air exhausted by a hood placed above the heat source to the volume flux of the plume at the level of the hood inlet. The equalization degree is evaluated by visualization of the flow. Several practical remarks regarding the method can be found in Kofoed's work.

**Stratification method.** The method (Sandberg and Lindstrom 1987) refers to displacement ventilation principles. According to the two-stage model the smoke introduced into the plume recirculates in the upper zone and after some time the flow pattern gets stabilized. The interface position changes according to the changes of the air flux supplied to the room. In this way one can determine the flow rate in the plume at different heights above the heat source.

## 4.4. Laboratory stands for plume tests

**Stand for plume tests in stagnant environment.** It is necessary to construct a special chamber to create conditions in which the environment will not dynamically influence the plume development and where it can be assumed that the tested plume spreads freely as in a calm environment. Such a chamber was constructed by Popiołek (1987). The chamber dimensions: 3.4x3.4x3.8; its walls made of foil. Inside the chamber there was no circulation of the air which flew from the bottom and was entrained by the plume. The vertical velocity of the air motion in the plume surroundings was negligible (about 3.5%) when compared to the velocity in the plume axis owing to the proportion of the chamber height to its sides. The vertical velocity of the air at a level can be calculated on the basis of the parameters of the PPHS.

**Plume simulator.** In real conditions of ventilated rooms as well as in laboratories it is difficult to get a free plume comprising the III stage of the flow self-similarity.

The constructed plumes simulator (Popiołek 1987) generates a forced plume but it gives the possibility to select the plume initial parameters in such a way that even at short distance, e.g. about 1 m, a pure buoyant region can be observed.

The PPHS model was verified by determination of the standard deviation of the pole distance z for separate cross-sections of the plume where the temperature excess profiles were tested. Simulator also may be applied to generate self-similar plumes over extensive heat sources in physical scale models of ventilation processes.

## 5. PLUMES IN VENTILATED ROOMS

### 5.1. Plume in an enclosure

In an enclosure thermal plume evokes circulation and thermal stratification of the ambient air, at the cost of its buoyant forces, as well as the air transport from supply to outlet openings. In this way the plume becomes one of the factors influencing ventilation flows in the room.

The idea of the process description is based on the model of processes of "filling a box with a plume" (Baines and Turner 1969) complemented by Gomeles (1975) and Sandberg (1987) with the result of the air inflow and outflow. The model is illustrated in Figure 13.

Air transport and circulation in an enclosure appears in result of the air entrainment by the plume. At an arbitrary level the difference between upward directed plume mass flux and downward directed circulation air mass flux is equal to the ventilation air flux $V_v$. Particular value of $V_v$ and particular level $z_H$ at which the heat source is placed correspond to the position $z_{stat}$ of the interface that separates two regions. In the lower region the plume is supplied only with the ventilating air $V_v$, and the air entrainment process is described by Equation 7 where the entrainment factor, $\alpha$, is of significant influence on the result.

In the upper region the upward convective flow entrains only recirculated flow and thus thermal buoyancy vanishes owing to the circulation and the plume vertical movement occurs at the cost of the momentum. Having preserved the momentum from the level of the interface plane, the plume transforms into a jet (Sandberg 1987).

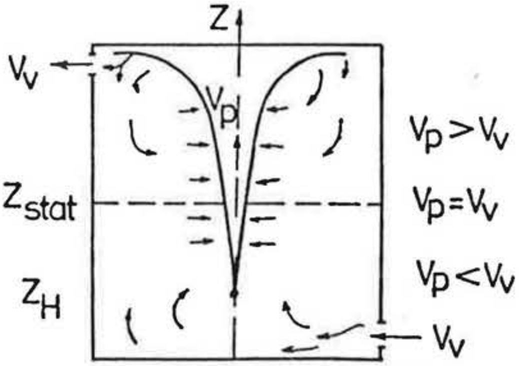

Figure 13. Filling-box with a plume

Having introduced the model of self-similar plume to the filling-box model, one ought then to assume carefully the value of the entrainment factor $\alpha_p$ in the Equation 7. From the analysis of experimental tests of Popiołek and Kofoed discussed above it is apparent that the entrainment rate in plume depends on $Q_o$, $Ar_o$ and S and moreover to great extent also on the degree of choking of the air supply to the enclosure filled with the plume, $V_v/V_{free}$.

$$\alpha_p = f\left( Q_o,\ Ar_o,\ S,\ V_v/V_{free} \right) \tag{28}$$

After the tests carried out by Popiołek in the elastic chamber described above where the plume developed freely the value m was about 40. The analysis of tests of Kofoed proved that the value of m increased and thus the plume got narrower as the ventilating air supply to the enclosure $V_v$ was choked. At the ratio $V_v/V_{free}$ of about 5%, m reached the value 62±4. Hance, the volume flux of the plume may be reduced even twice as the air flow to the enclosure is choked owing to the increased induction of air circulation.

## 5.2. Plumes in confined ventilated spaces

It is worth differentiating two characteristic ventilation types:

- Displacement ventilation of rooms with relatively low heat gains (e.q. offices, welding halls) where the role of plumes in the generation of flow of the stagnant ambient air is distinct and employed purposevely.
- Natural ventilation of large spaces with significant heat gains (e.g. hot industrial halls) where plumes are included in the turbulent flow of the ambient air which is generated also by other factors such as wind etc.

The idea of displacement ventilation employs the effect of separate single plumes on quasi-stable calm flow of ambient air. Thus, analyses of entrainment flow and calculation of plume based on integral methods may be directly applied e.g. to improve the filling-box model or in physical scale models of ventilation processes.

One may refer here to numerous interesting tests of displacement ventilation carried out by Sandberg, Skaret, Mathinsen, Malmstrom and Fitzner as well as to physical scale model tests extensively applied for predicting ventilation processes of large rooms by many researchers (Mierzwiński 1987).

It is worth mentioning also the industrial applications (Baines 1983) where the idea of establishing an interface in a building with plumes was applied to ventilation systems design in metallurgical cell houses for non-ferrous metals.

In the cases of natural ventilation of hot halls, the influence of geometrical parameters and the effect of turbulent movement of large masses of the ambient air on plumes is essential. Apparent influence of plumes on the air motion and the vertical air temperature distribution is observed in the whole space. This influence, however sinks into the complex process of air distribution and it cannot be separated in the form of a simplified model. Hence prediction of air flow pattern in such the cases requires either physical scale modelling where integral methods for calculation of plumes may be helpful or calculating by means of differential and numerical methods where a plume model must be coupled with a flow model for environment.

## 6. CONCLUSIONS

Convective flows contribute to essential factors causing air movements in rooms. They are, however, still difficult to identify and predict in ventilation processes.

The paper is based on the research directions that gradually aim at overcoming these difficulties.

Much consideration is given to good knowledge of plume properties. In ventilation processes have been individuated cases where the role of a single plume in the flow pattern in room is apparent and then the integral method can be useful in the flow predicting.

The presented results, acquired by other researchers or at our University, proved that entrainment and diffusion processes in plumes in rooms conditions have not been sufficiently well explained yet. Measurement methods have been much advanced and the required range of direct experiment have been reduced giving place to integral calculation methods. The integral methods may already be practically efficient in plume predicting in various conditions of the plume generation, in analysis of experiment results and in improvement of physical scale modelling of complex ventilation processes.

But, it is difficult to extend the integral methods to complex turbulent flow patterns in complex ventilation processes. In those cases the physical scale model tests discussed in the paper and differential methods with proper turbulence models may be more effective.

However, research ought to be directed differently when differential methods are considered although there are many elements in common in the accompanying experiment.

## ACKNOWLEDGMENTS

The present paper includes the results of the research partially supported by Polish Committee for Scientific Research within the frame of the Grant No. [illegible]934/6/91

The author would wish to express his thanks to Professor Peter V.Nielsen and Mr Peter Kofoed from the University of Aalborg for their kind making the test results available for computer analysis. The author is also grateful to Professor Zbigniew Popiołek from the Technical University in Gliwice for his colaboration and creative discussions, to Miss Ewa [illegible] for the translation of the text, to Miss Bożena Polityńska for typing the manuscript and to Miss Halina Kokosińska for the drawings.

## LIST OF SYMBOLS

g = gravitational acceleration
m = velocity distribution factor
p = temperature distribution factor
Q = enthalpy flux/source power
r = radial distance from axis
R = profile width
S = dimensionless stratification
s = stratification
t = temperature

Greek symbols

$\alpha$ = entrainment factor
$\beta$ = thermal expansion coefficient
$\gamma$ = heat turbulent diffusion factor
$\lambda$ = ratio of profiles widths
$\rho$ = density

$\overline{\Delta t}$ = mean temperature excess
$V$ = volume flux
$\bar{w}$ = velocity mean value
$w'$= fluctuation velocity
$z$ = elevation

PPHS = plume above point heat source

Indices

e = environment
j = jet
m = maximum value
o = at the beginning cross-section
p = plume
v = ventilation
w = velocity
t = temperature
z = vertical component

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