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Thermal plumes in ventilated rooms – Measurements in stratified surroundings and analysis by use of an extrapolation method

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Peter Kofoed
Peter V. Nielsen
University of Aalborg
Aalborg, Denmark

THERMAL PLUMES IN VENTILATED ROOMS - Measurements in Stratified Surroundings and Analysis by use of an Extrapolation Method.

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University of Aalborg
Aalborg, Denmark

Summary.

The design of a displacement ventilation system involves determination of the flow rate in the thermal plumes. The flow rate in the plumes and the vertical temperature gradient influence each other, and they are influenced by many factors. This paper shows some descriptions of these effects.
Free turbulent plumes from different heated bodies are investigated. The measurements have taken place in a full-scale test room where the vertical temperature gradient have been changed. The velocity and the temperature distribution in the plume are measured. Large scale plume axis wandering is taken into account and the temperature excess and the velocity distribution are calculated by use of an extrapolation method.
In the case with a concentrated heat source (dia 50mm, 343W) and nearly uniform surroundings the model of a plume above a point heat source is verified. It represents a borderline case with the smallest entrainment factor and the smallest angle of spread. Due to the measuring method and data processing the velocity and temperature excess profiles are observed more narrowly than those reported by previous authors.
In the case with an extensive heat source (dia 400mm, 100W) the model of a plume above a point heat source cannot be used. This is caused either by the way of generating the plume including a long intermediate region or by the environmental conditions where vertical temperature gradients are present. The flow has a larger angle of spread and the entrainment factor is greather than for a point heat source.
The exact knowledge of the vertical temperature gradient is essential to predict the flow propagation due to its influence on the entrainment, e.g. in an integral method of plume calculation . Since the flow from different heated bodies is individual full-scale measurements seem to be the only possible approach to obtain the volume flow in thermal plumes in ventilated rooms.

Nomenclature.

- Ar — Archimedes number, $Ar = \beta g \Delta T R / v^2$
- c_p — specific heat at constant pressure
- E — kinetic energy flux
- F_0 — buoyancy flux
- G — air volume supplied
- H — enthalpy flux
- I — momentum flux
- m — velocity distribution factor
- n — air change rate in room
- p — temperature distribution factor
- r — radial distance from plume axis
- R — profile width where 1/e of the maximum value is obtained
- Q_0 — convective heat from source
- ΔT — mean temperature excess, $\Delta T = T - T_\infty$
- x — vertical height above source
- V — volume flux
- v — vertical mean velocity
- dT/dx — vertical temperature gradient
- $-g\Delta\rho/\rho_\infty$ — buoyancy in plume, $\Delta\rho = \rho - \rho_\infty$

Greek Symbols.

- α — entrainment factor
- β — thermal expansion coefficient
- λ — ration between profile width, $\lambda = R_T/R_V$
- ρ — local plume density

Subscripts.

- 0 — source condition
- F — floor
- M — maximum value
- ∞ — ambient condition
- R — return
- ST — stratification
- T — temperature
- V — velocity

1. Introduction.

1.1. Thermal Plumes in Ventilated Rooms.

During the last 10 years vertical displacement systems have grown popular as comfort ventilation in rooms with heat loads e.g. office rooms. The plumes from hot surfaces, from equipment located at different heights and from persons together with cold downdraught from cold surfaces make a rather complicated situation as shown in fig.1., ref. (17,18).

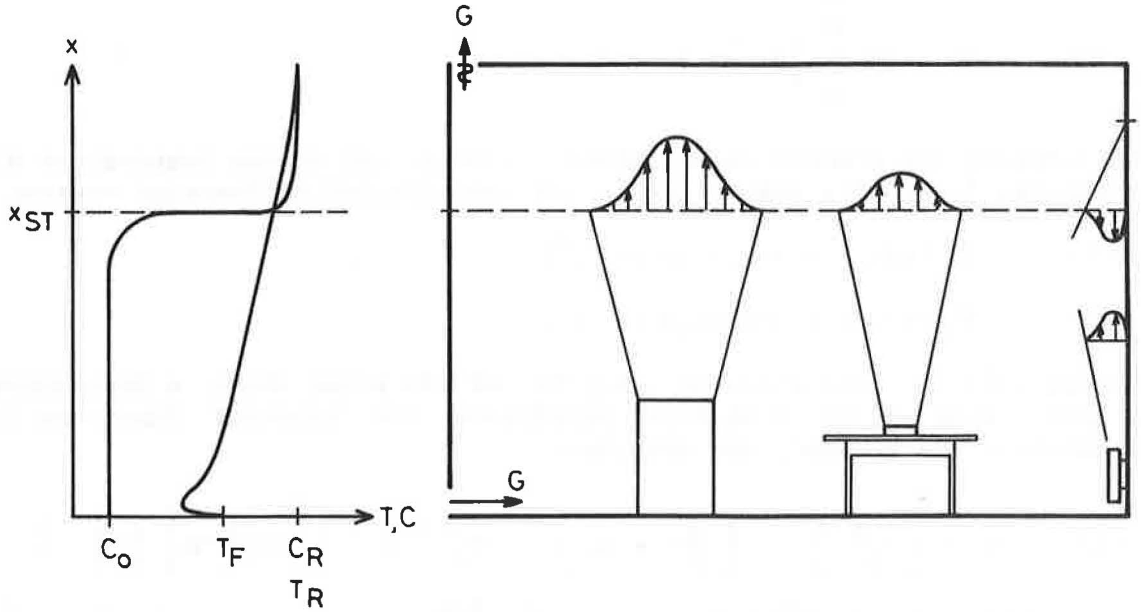


Fig.1. Vertical displacement flow in an office room. The primary air is supplied in the occupied zone and is entrained in the hot plumes from the heat sources and in the cold downdraught. Dependent on the air flow supplied G and the vertical air flow in the room there must be a height x_{ST} where the upward moving air flow is equal to the supplied air flow. This is experimentally shown by Heiselberg & Sandberg (4). The graphs to the left show: I. the vertical temperature gradient created by interaction between the different plumes and by radiation between the surfaces in the room and II. the contaminant distribution created only by the plumes.

The design of a displacement ventilation system involves determination of the flow rate in the thermal plumes so that a reasonable supply air quantity G can be chosen. In practice simple formula systems based on plume models above a point heat source have been used. However, the flow is much more complex and is influenced by many factors, e.g. vertical temperature gradients. Experiments and literature study show this, ref. (1,2,5,6,7,12, 17). At the present moment no satisfactory description of the flow is given. It is the purpose of this work to verify a possible approach.

1.2. Previous Works.

Turbulent buoyant axisymmetric plumes have been investigated for around 50 years. Turbulent plumes in a uniform environment are treated by Schmidt (16) in 1941. Schmidt makes basic assumptions about the flow from a point heat source extending Prandtl's mixing length theory. For the axial velocity and excess temperature and the width the results are:

(1) $$v \approx x^{-1/3}$$

(2) $$\Delta T \approx x^{-5/3}$$

(3) $$r \approx x$$

Rouse, Yih and Humphreys (15) in 1952 introduce a similarity hypothesis. The result is consistent with Schmidt's and the following expressions for volume flux V, momentum flux I and kinetic energy flux E are obtained:

$$(4) \qquad V = 2\pi \int_0^\infty vr\,dr \approx x^{5/3}$$

$$(5) \qquad I = 2\pi \int_0^\infty \rho v^2 r\,dr \approx x^{4/3}$$

$$(6) \qquad E = 2\pi \int_0^\infty \tfrac{1}{2}\rho v^3 r\,dr \approx x$$

Traditionally the dimensionless radial velocity and excess temperature distributions f_1 and f_2, respectively, are approximated by Guassian curves:

$$(7) \qquad f_1(r/x) = \exp(-m(r/x)^2)$$

$$(8) \qquad f_2(r/x) = \exp(-p(r/x)^2)$$

Popiolek (12) in 1981 gives an analysis of the plume above a heat source and also takes up the similarity hypothesis. The following functions for the velocity and buoyancy are obtained:

$$(9) \qquad v = \left(\frac{3}{2\pi}\right)^{1/3} \left(\frac{m^2}{p} + m\right)^{1/3} F_0^{1/3}\, x^{-1/3} \exp\left(-m\left(\frac{r}{x}\right)^2\right)$$

$$(10) \qquad \frac{-g\Delta\rho}{\rho_\infty} = \left(\frac{2}{3\pi^2}\right)^{1/3} \left(\frac{p(m+p)^2}{m}\right)^{1/3} F_0^{2/3}\, x^{-5/3} \exp\left(-p\left(\frac{r}{x}\right)^2\right)$$

where F_0 is the buoyancy flux connected with the convective heat output Q_0 from the source in the following way:

$$(11) \qquad F_0 = Q_0 \beta g / c_p \rho$$

If equation 11 together with the values c_p=1005 J/kgK and ρ =1.205 kg/m^3 are assumed, Popiolek gets:

$$(12) \qquad v = 0.023 \left(\frac{m^2}{p} + m\right)^{1/3} Q_0^{1/3}\, x^{-1/3} \exp\left(-m\left(\frac{r}{x}\right)^2\right)$$

$$(13) \qquad \Delta T = 0.011 \left(\frac{p(m+p)^2}{m}\right)^{1/3} Q_0^{2/3}\, x^{-5/3} \exp\left(-p\left(\frac{r}{x}\right)^2\right)$$

Morton, Taylor and Turner (8) in 1956 consider plumes also in stratified surroundings. Integral forms of the continuity, momentum and buoyancy equations together with similarity variables for velocity and density are used. The problem is closed by adopting Taylor's entrainment assumption - simply that the entrainment is proportional to the mean centerline velocity:

$$(14) \qquad V_{ENTRAINMENT} = \alpha v$$

Fox (2) and Morton (9) in the beginning the 1970'es suggest some improvements of the entrainment assumption. Fox finds that the entrainment is a function of the Reynolds stresses α_1, form of the similarity profiles α_2 and the local Archimedes number Ar:

$$(15) \qquad \alpha = \alpha_1 + \alpha_2 Ar$$

Popiolek and Knapek (13) in 1982 analyse the integral method of plume calculation. Popiolek and Mierzwinski (14) present some calculations in 1984. The flow is strongly dependent on stratification, and the problem of the entrainment has not been completely solved yet.

In the 1970'es differential turbulence models are used to predict the flow in turbulent buoyant plumes. The level of sophistication is high and the drawback of this approach lies in the increased complexity of the formulation and consequent increased computer time required. A rewiev is given by Chen, ref. (1). The modelling of buoyant flows still presents uncertainties and additional work is necessary.

Many quantitative experiments are performed to confirm the theoretical predictions, ref. (1,3,5,6,7,8,11,12,15,16). The most cited experiment is Rouse et al. (15), where the velocity and temperature distribution factors in equation 9 & 10 are: m=96 and p=71 respectively.

2. Experimental Technique.

The measurements have taken place in a full-scale room - 8 x 6 x 4.6 m. A displacement ventilation system with 2 wall-mounted diffusers and 2 exhaust openings in the ceiling are installed, so that the room can be ventilated and different vertical temperature gradients created, if required. A picture of the room is given in fig.2.

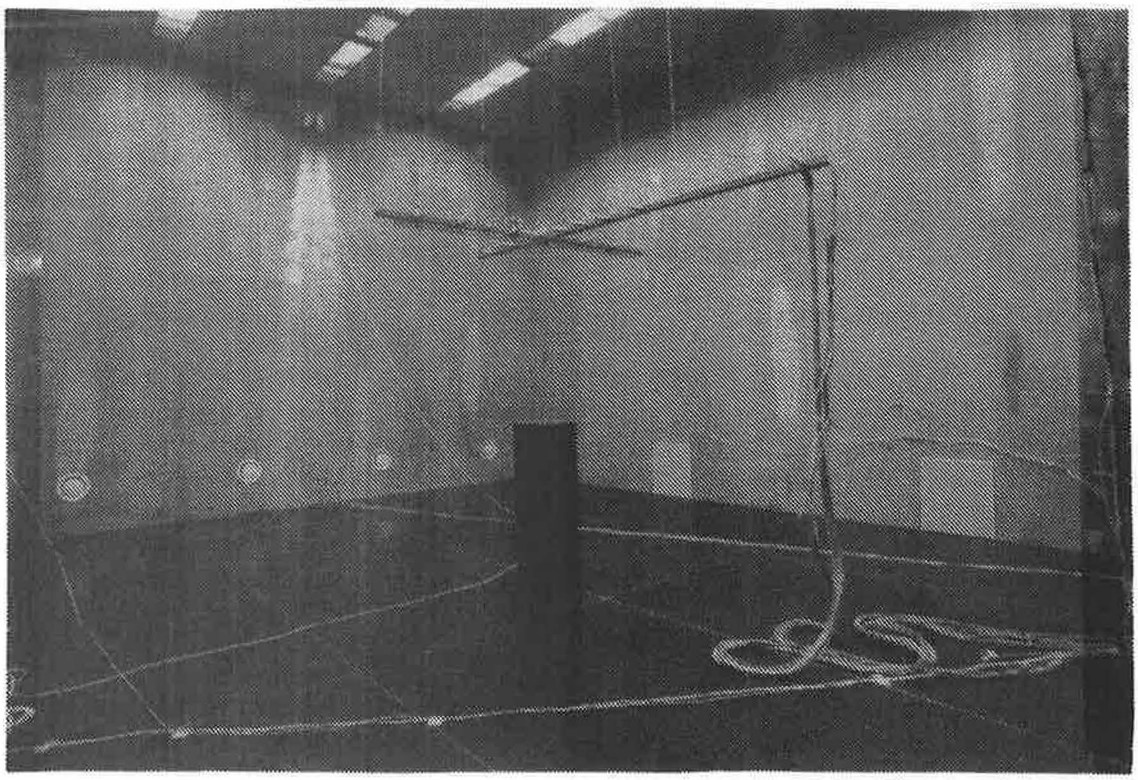


Fig.2. Full-scale room with wall mounted diffusers, heat source and measurement equipment.

The velocity measurements are carried out using a Dantec 54N10 low velocity multiflow analyser with Dantec 54R10 temperature compensated sphere probes. The temperature excess in the plume is measured with termocouples. 17 velocity probes and 17 termocouples are located in the flow. Additonal 33 thermocouples are used to get information about the surrondings.

2.2. Experimental Procedures.

In plume experiments large scale flow instability is often present. Rouse et al. (15) measurements show that the velocity and temperature profiles are symmetrical about the maximum. Rouse et al. (15) and Mierzwinski (6) observed that the maximum value often occurs at a point situated away from the vertical centerline to the source. Popiolek (12) presents a measuring method and data processing which take the plume axis wandering into account. In this paper it is called the extrapolation method:

The extrapolation method. The probes are placed in a coordinate system - in this work 9 velocity probes and 9 termocouples on each axis. The common probe or origin is located in the symmetry axis to the source. For each of the axes the temperature measurements are approximated by a Gaussian distribution curve. The symmetry axes of the 2 curves are found and thereby the position of the plume axis. Next the measuring points distances from the plume axis are calculated. On this basis it is possible to extrapolate the true temperature excess and velocity Gaussian curves.

The vertical temperature gradient in the room is held at different values by changing the inlet temperature. Measurements without mechanical ventilation also have taken place.

2.3. Calibration.

In general the flow velocity and temperature excess in thermal plumes are small - often less than 0.10 m/s and 0.5 K, respectively. **Velocity.** The effect of the natural convection around the hot sphere of the velocity probe has to be taken into account, therefore calibration in vertical flow is carried out. **Temperature.** To eliminate the accuracy of cold junction temperature stabilization as well as calibration accuracy the temperature excess in the plume are measured as a difference between temperatures in 2 points. Here the exact knowledge of the thermocouple sensitivity is essential.

3. Measurement Results and Discussion.

3.1. Preliminary Remarks.

The sampling time of measuring is 180 seconds. The treatment of the data is done using the extrapolation method. One single experiment has been performed several times to make sure the reproducibility of the data and constant values obtained. If account were not taken to the axis wandering the axial velocity v_M and temperature excess ΔT_M would be lower and the width of the profiles R_V & R_T greather. The plume axis wandering observed is of the order 25 % R_T.

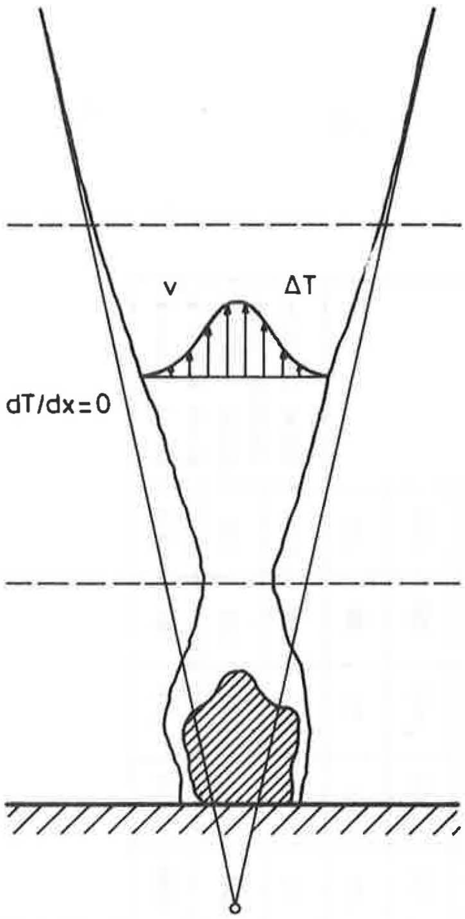
3.2. Plume in Uniform Environment.

The aim of this measurement series is the experimental verification of the point heat source model. In general the flow in the plume above a heat source propagating in environment without a vertical temperature gradient (dT/dx=0) can be divided into 3 zones as shown in fig.3., ref (7). The model of a plume above a point heat source is characterized by flow in zone 3.

In ventilated rooms environment with zero stratification very seldom occurs. During this measurement series the vertical temperature gradient <u>dT/dx is less than 0.05 K/m</u> in the measuring zone 0.75 to 3.50 m above the floor - the closest to uniform environment that is obtained. The heat source is concentrated - <u>a 343 W dia 50 mm vertical tube</u> with heating coils. The source is placed in mineral wool and the air is sucked through the source from below. The measurement results are shown in table 1.

Vertical tube dia=50mm h=150mm Q=343W	Recircl.flow $G=0m^3/s$ $n=0h^{-1}$							Ver.temp.grad. $dT/dx=0.05$ K/m				
Plume parameters	Height above source x m											Notice
	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	
vM m/s	.874	.607	.625	.624	.631	.615	.587	.572	.557	.535	.517	Gaussian fit by minimizing a sum of squares
Rv m	.106	.154	.186	.207	.231	.254	.284	.309	.331	.367	.391	
ΔTM C	13.3	11.7	7.6	5.3	4.1	3.4	3.0	2.4	1.9	1.5	1.3	
RT m	.085	.099	.129	.164	.214	.241	.273	.284	.319	.354	.376	
H W	195	187	206	208	241	240	232	223	210	202	191	Integral plume parameter values
V m^3/s	.031	.045	.068	.084	.106	.125	.149	.172	.192	.226	.249	
I kgm/s^2	16	16	25	31	40	46	52	59	64	73	77	
Ar	.062	.162	.124	.095	.080	.076	.075	.075	.068	.066	.065	
λ	.80	.64	.69	.79	.93	.95	.96	.92	.96	.96	.96	
m	281	96	125	125	94	95	94	112	112	117	124	Local approximation by a model of a plume above a point source
p	440	233	261	200	110	105	102	134	121	126	134	
α	.050	.085	.074	.075	.086	.086	.086	.078	.078	.077	.075	

Table 1. Measurement results.



Zone 3, the zone of complete similarity: The flow is fully developed, the plume spreads linearly, the local Archimedes number Ar and the ratio of temperature and velocity profiles widths λ are constant.

$$\lambda = \left(\frac{m}{p} \right)^{1/2} \qquad Ar = \frac{2}{3} \frac{p}{m^{3/2}}$$

Zone 2, the intermediate zone: The plume is turbulent and axisymmetrical, the velocity and temperature distribution curves are of Gaussian type, the plume spreads non linearly, the local Archimedes number Ar and the ration of temperature and velocity profiles widths λ change.

$$\lambda = \frac{R_T}{R_V}$$

Zone 1, the boundary layer zone. Transition from boundary layer to a plume form, laminar flow becomes turbulent.

Fig.3. The flow regions in the plume above a heat source without vertical temperature gradient, dT/dx=0 K/m, ref. (7).

The flow in a plume above a point heat source is characterized by complete similarity. In the area x = 1.75 to 3.25 m constant ratio between the velocity and temperature excess widths is observed, the mean ratio is λ = 0.96. The velocity and temperature excess distribution factors in equation 12 and 13 are: m = 110 and p = 115. The mean enthalpy flux H which equals the convective heat supplied is Q_o = 221 W.

3.2.1. Axial Distribution.

Width. The axial increase of the width is shown i fig.4.

The measurements have taken place in: <u>Zone 2, intermediate zone</u>, where the plume spreads non-linearly and the ration λ of the temperature and velocity profiles changes. <u>Zone 3, the region of complete flow similarity</u>, where the plume spreads linearly and the ration λ between the velocity and temperature excess profiles is constant. The experimental temperature width values in zone 3 are reduced to a strait line by means of a least mean square method. Note that the widths do not become zero at the top of the heat source. In this case the virtual point of plume propagation is situated below the heat source, x_o = -0.22 m. The strait line representing the velocity width values is drawn through the virtual point. The excess temperatur width spreads with an angle of 7.6 degrees. The spread of the velocity width is greather.

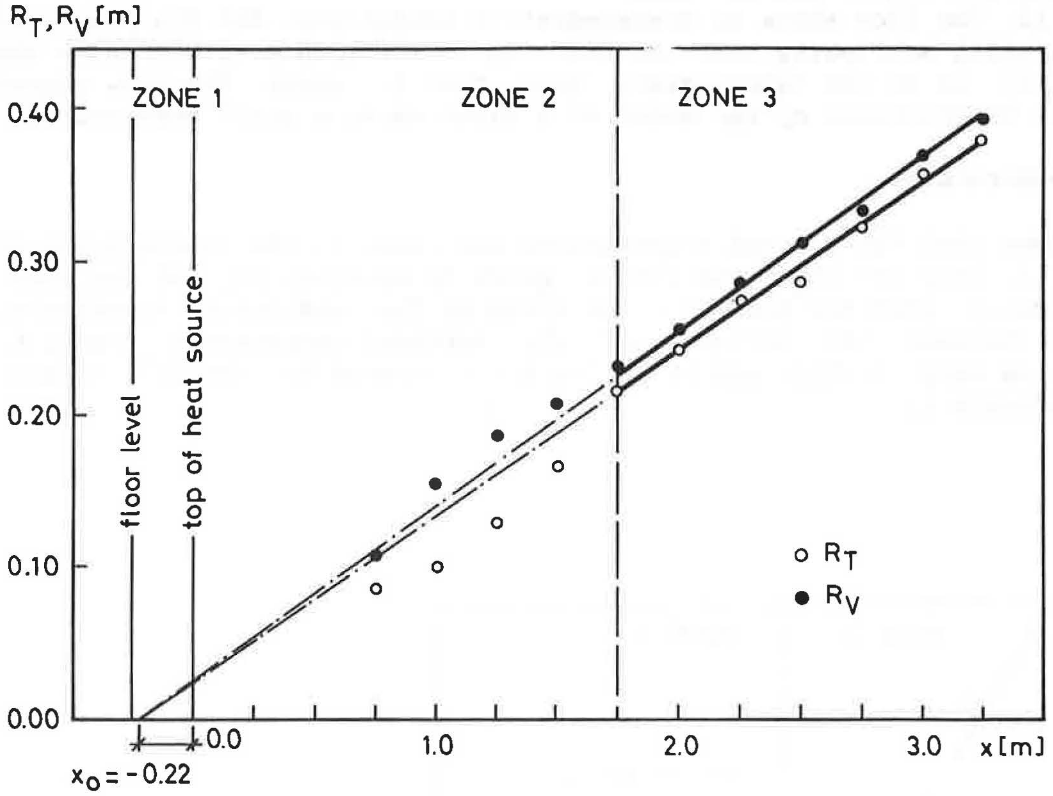


Fig.4. Increase of plume width R_T & R_V.

Velocity. The velocity measurements do also indicate that the flow can be divided in regions: <u>Zone 2</u> with acceleration and <u>zone 3</u> with a velocity decay of the type $v \approx (x-x_0)^k$ as shown in fig.5.

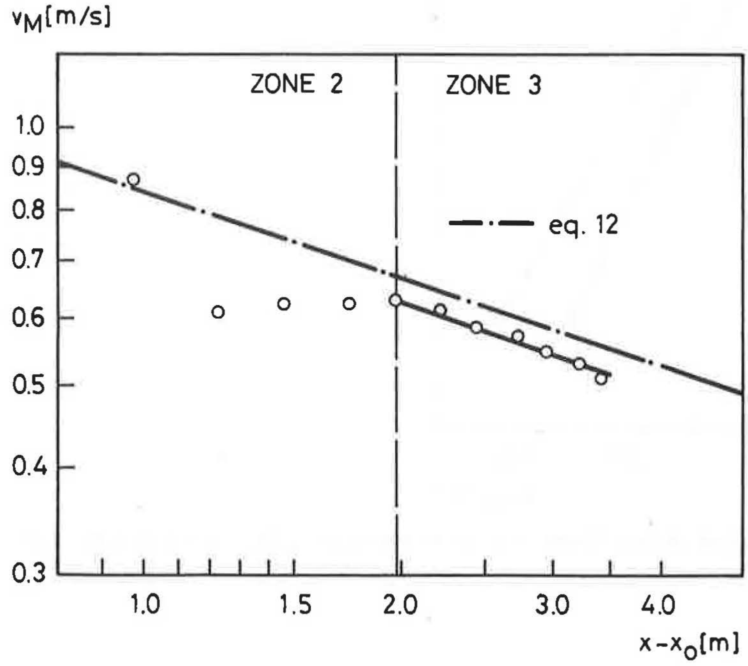


Fig.5. Distribution of maximum mean velocity v_M along the axis of the plume.

The power k = -1/3 as indicated in the similarity hypothesis is verified in zone 3. But the velocities are about 7 % lower than the values obtained by equation 12. The flow shows no disintegration tendencies. For the practical use it is worth mentioning that the flow up to x = 1.75 m (2.00m above the floor) still is in the intermediate zone, zone 2, where the flow cannot completely be described by the model of a plume above a point heat source.

Excess Temperature.

Fig.6. shows that the mesured temperatures are close to the values given by equation 13. They are below the values given by equation 13, and the power is numerically greather than -5/3 as given by the similarity hypothesis. This may indicate the influence of the vertical temperature gradient, though it is very little, and it is further indicated by the fall in heat flux H in table 1.

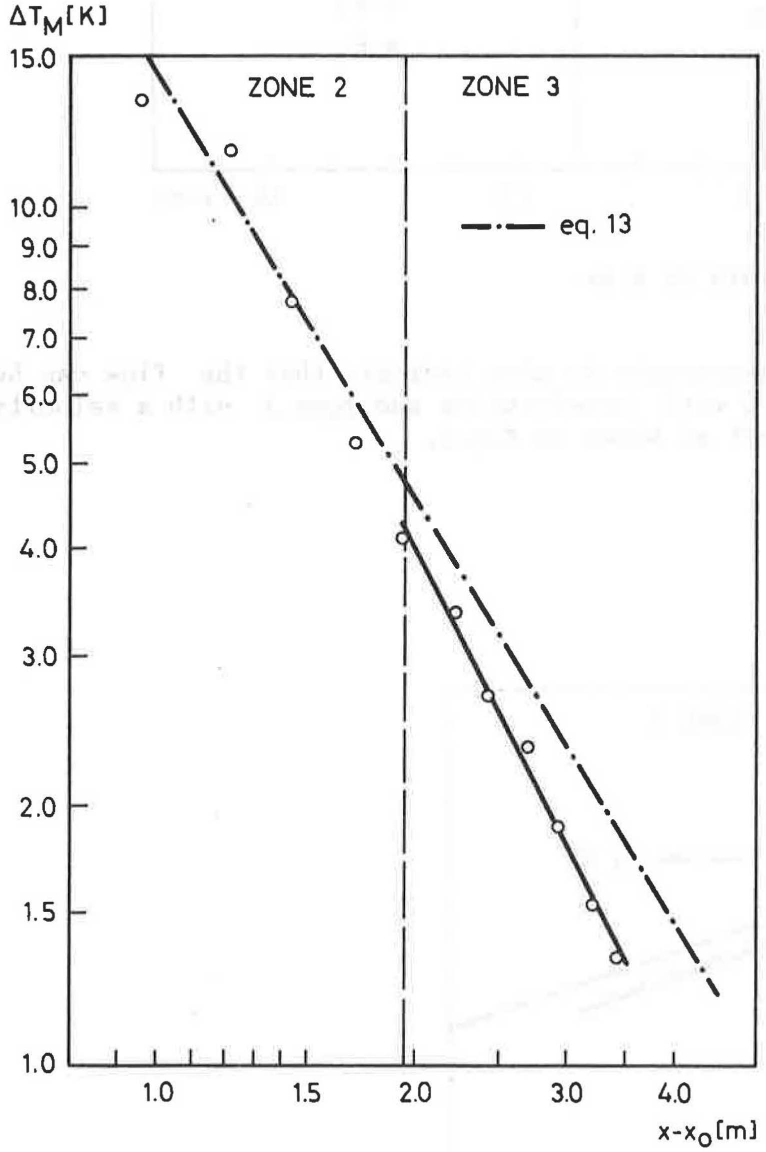


Fig.6. Distribution of maximum mean temperature excess ΔT_M along the axis of the plume.

Volume flux. The volume flux V in the plume is found as the volume of the rotation Gaussian distribution function. Eq. 4, 12, m = 110 & p = 115 give:

$$V = 0.0051\ Q_0^{1/3}\ (x-x_0)^{5/3} \tag{16}$$

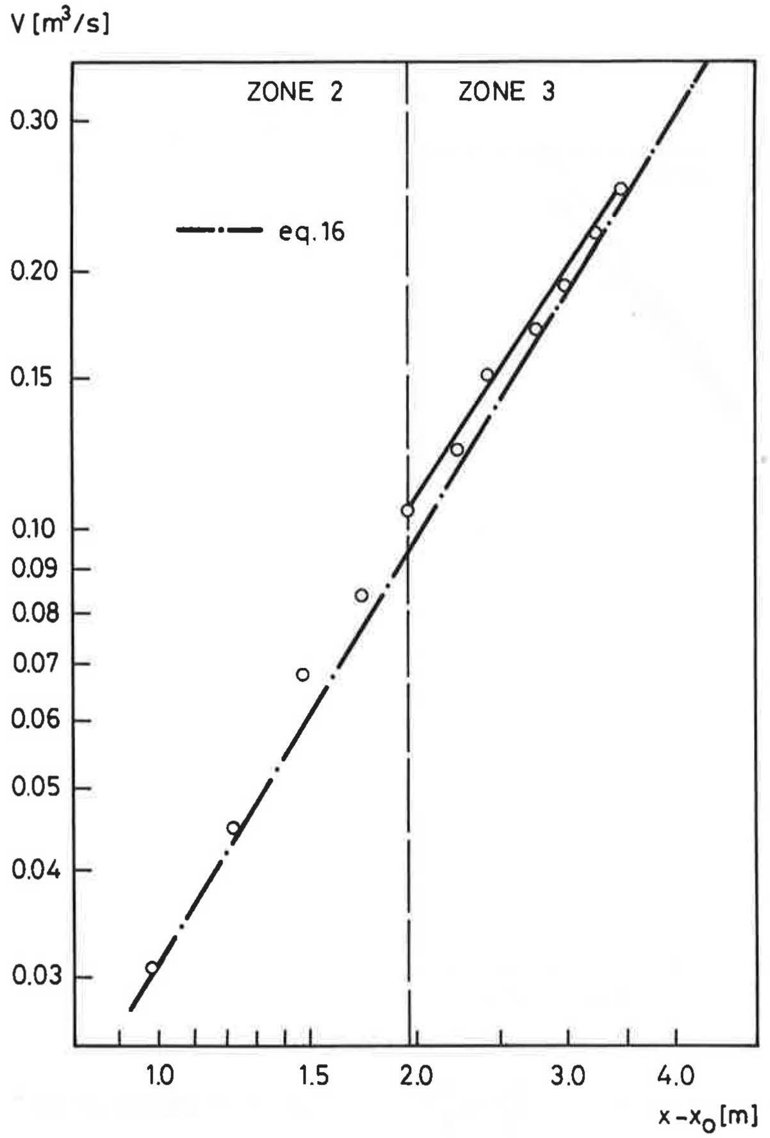


Fig.7. Distribution of volume flux $V = \pi v_M R_V^2$ along the plume axis.

The measurements show good aggrement with equation 16. The power 5/3 is observed in both zones, though the flow in zone 2 does not fulfil other elements of the flow in a plume above a point heat source. The explanation is that the width Rv of the velocity profile is greather than indicated by the strait line in fig.4, which compensates for the lower velocity vM in fig.5.

Momentum Flux. Equation 5,12,13, m=110 & p=115 give the following formula for the momentum flux I:

$$(17) \qquad I = 0.00043\ Q_0^{2/3}\ (x-x_0)^{4/3}$$

The measurements show good aggrement with equation 17 in both zones. The explanation is the same as before. The slope in zone 3 is a litte smaller than 4/3.

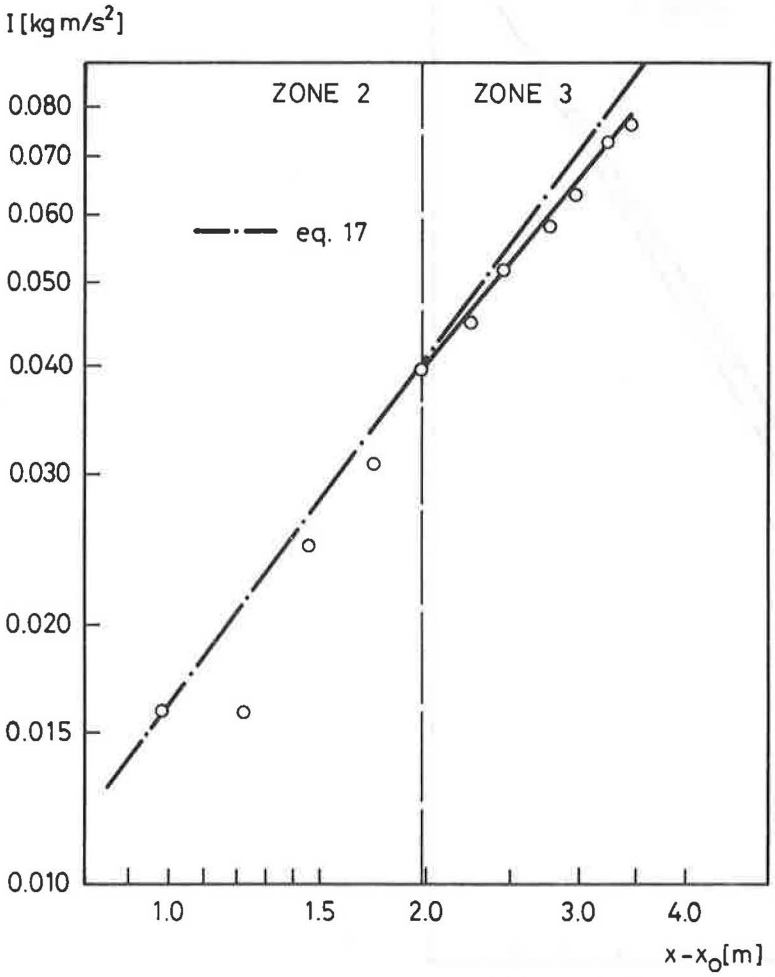


Fig.8. Distribution of momentum flux $I = \frac{1}{2}\pi\rho v_M^2 R_V^2$ along the plume axis.

3.2.2. Radial Distributions.

Mean velocity and temperature excess profiles. As mentioned before the similarity in mean profiles of velocity and temperature is reached at x = 1.75 m. The spread of the velocity profile is greather than that of the temperature, $\lambda = R_T/R_V = 0.96 < 1$. In table 2 the velocity and temperature distribution factors m and p from equation 7 & 8 are compared with the results from previous works.

Rouse et al. (15) indicate as the only author that the spread of buoyancy is greather than that of momentum, p = 71 < m = 96 and $\lambda = 1.16$. This result may be influenced by the fact that Rouse et al. used a wane anemometer (3 cm dia) with a lower limit of 6 cm/s. The accuracy of such an instrument is less than those reported here. In contrast the results of other authors are coincident with the present results. This means it is more likely that the spread af momentum is at least equal or wider than that of thermal energy, p > m and $\lambda < 1$. The profiles are compared in fig.9.

Velocity & temperature distribution factors and instrumentation			
m	p	Author	Instrumentation
45?	45	Schmidt 1941 (16)	1 HWA
55	65	George 1977 (3)	1 HWA & 1 RT
65	70	Nakagome 1976 (11)	1 HWA & 1 RT
80		Morton 1956 (8)	1 HWA
96	71	Rouse 1952 (15)	1 VA & 1 TC
110	115	Present work	17 HSA & 17 TC

Abbreviations:
HWA hot wire anemometer
VA vane anemoneter
HSA hot sphere anemometer
RT resistance thermometer
TC thermocouple

Table 2. Velocity and temperature distribution factors and instrumentation.

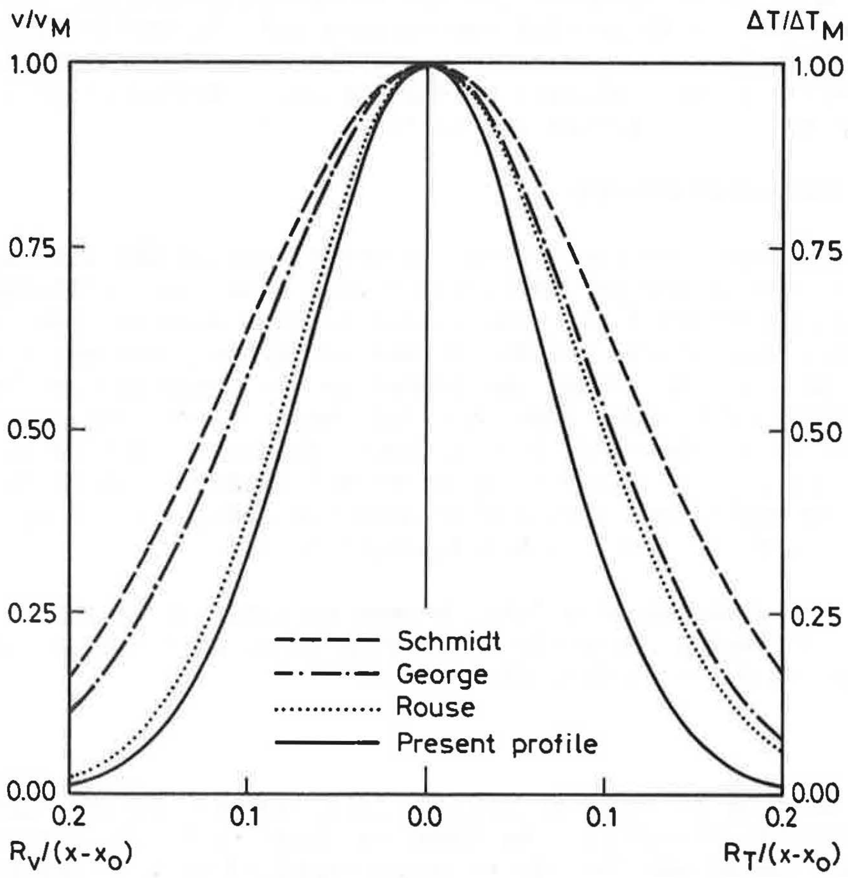


Fig.9. Distribution of dimensionless mean velocity v/v_M and mean temperature excess $\Delta T/\Delta T_M$ in a plume.

The results of the present work show more narrow profiles. The explanation is due to the measuring method and data processing, which take the plume axis wandering into account. George et al. (3) mention that the plume maybe has not reached a fully developed state resulting in a larger angle of spread. The same thing could be present in the results of Rouse et al. (15) because they use a gas burner as source giving a long intermediate zone.

3.2.3. Entrainment. The entrainment factor α based on a model of a plume above a point heat source is constant. In his similarity analysis Popiolek (12) presents the following formula:

$$(18) \qquad \alpha = \frac{5}{6}\, m^{-1/2}$$

The entrainment factor α calculated by Morton (8) using data of several authors are consistent with the data shown in table 3.

Entrainment factor: $\alpha = \frac{5}{6} m^{-1/2}$						
Author:	Schmidt	George	Nakago.	Morton	Rouse	Pr.Work
α :	0.124	0.112	0.103	0.093	0.085	0.080

Table 3. The constant entrainment factor α in the model of a plume above a point heat source calculated on the base of results from several authors.

The results are calculated using equation 18. The measuring method and data processing of the present work shows that the entrainment is smaller than previous assumptions. This is interesting, because the correct formulation of the entrainment factor is the closure of the integral method of plume calculation. More work has to be carried out in this field.

3.3. Plumes in stratified surroundings.

The measurements have been carried out to evalute the effect on the flow by vertical temperature gradients and by ventilation in a room. In ventilated rooms complex vertical convection flow from extensive heat sources such as human bodies will occur. Mierzwinski (6) has investigated the plume above a human body: The flow is too complex and influenced by too many factors to be described by the model of a plume about a point heat source, but quasi Gaussian profiles have been observed 0.5 m above the head. Kofoed and Nielsen (5) reported that the entrainment in a thermal plume can be influenced by the surrounding walls. And many author show the importance of vertical temperature gradients, ref. (1,2,5,6,7,12,13,14,17,18).

In general the flow in a plume above a heat source propagating in stratified surroundings is different from the one without stratification. A description af the flow is given in fig. 10., ref (7).

3.3.1. Measurements.

The source is a 1 m high black painted cylinder (dia 400mm) covered with plates in both ends directly placed on the floor as shown in fig.2. Inside the source 4 lamps are placed and the total power supplied is Q = 100 W. The source is equal to the one in Mundts project (10). The measurement results are shown in table 4,5 & 6. Table 4 represents a case without ventilation and a recirculation flow is present. Table 5 & 6 represent cases with displacement ventilation which could be expressed as a "co-flow" situation.

Vertical cylinder dia=400mm h=1000mm Q=100W Recircl.flow G=0m³/s n=0h⁻¹ Ver.temp.grad dT/dx=0.07 K/m												
Plume parameters	Height above source x m											Notice
	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	
vM m/s		.205	.247	.254	.258	.223	.203	.254	.236	.221	.202	Gaussian fit by minimizing a sum of squares
Rv m		.164	.202	.221	.253	.282	.326	.336	.351	.383	.431	
ΔTM C		2.1	1.4	.95	.71	.50	.43	.36	.29	.25	.18	
RT m		.155	.212	.240	.288	.355	.388	.417	.460	.429	.432	
H W		21	27	24	25	21	21	24	20	17	13	Integral plume parameter values
V m^3/s		.017	.032	.039	.052	.056	.068	.090	.091	.102	.118	
I kgm/s^2		2.1	4.7	6.0	8.0	7.5	8.3	13.8	13.0	13.5	14.3	
Ar		.279	.150	.109	.091	.095	.115	.062	.060	.065	.064	
λ		.95	1.05	1.09	1.14	1.26	1.19	1.24	1.31	1.12	1.00	
m		7	16	27	32	20	17	49	42	66	108	Local approximation by a model of a plume above a point source
p		8	15	23	25	12	12	32	24	53	107	
α		.312	.206	.161	.147	.189	.203	.119	.129	.102	.080	

Table 4. Measurement results.

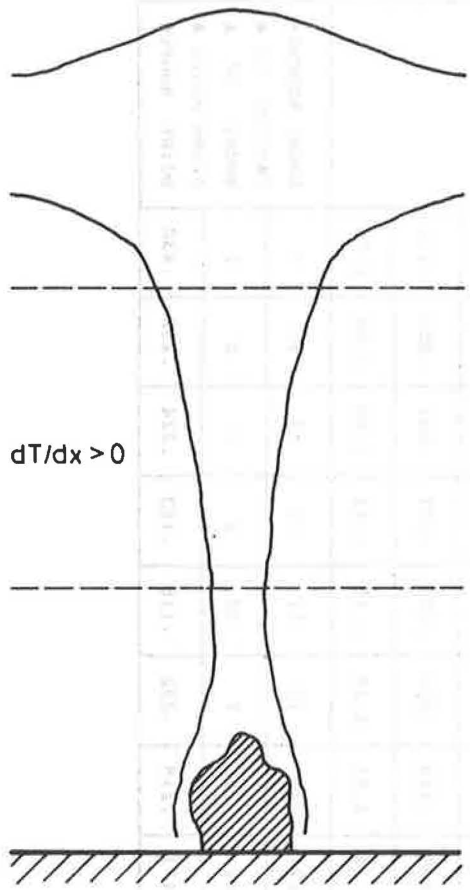
Vert.cyl. dia=400mm h=1000mm Q=100W "Co-flow" G=0.0042m^3/s n=0.7h^{-1} Ver.temp.grad. dT/dx= 0.09 K/m												
Plume parameters	Height above source x m											Notice
	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	
v_M m/s		.180	.254	.203	.238	.233	.210	.208	.174	.187	.168	Gaussian fit by minimizing a sum of squares
R_v m		.214	.205	.259	.297	.296	.380	.380	.414	.472	.510	
ΔT_M C		2.0	1.6	.82	.74	.58	.43	.31	.26	.25	.20	
R_T m		.198	.196	.305	.298	.336	.385	.564	.713	.781	.612	
H W		29	31	25	30	25	25	24	22	29	19	Integral plume parameter values
V m^3/s		.026	.034	.043	.066	.064	.095	.095	.094	.131	.137	
I kgm/s^2		2.8	5.1	5.2	9.4	9.0	12.0	12.0	9.8	14.8	13.8	
Ar		.446	.174	.172	.130	.106	.124	.090	.120	.115	.121	
λ		.93	.95	1.18	1.00	1.13	1.01	1.48	1.72	1.65	1.20	
m		3	18	8	26	24	27	11	4	5	15	Local approximation by a model of a plume above a point source
p		4	19	6	26	18	27	5	1	2	10	
α		.479	.198	.299	.164	.171	.247	.443	.393	.218	.080	

Table 5. Measurement results.

Vert.cyl. dia=400mm h=1000mm Q=100W "Co-flow" G=0.0042m^3/s n=0.7h^{-1} Ver.temp.grad. dT/dx= 0.30 K/m											
Plume parameters	Height above source x m										Notice
	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	
v_M m/s		.180	.221	.226	.200	.192	.204	.164	.159	.158	.119	Gaussian fit by minimizing a sum of squares
R_v m		.203	.206	.215	.263	.292	.303	.360	.381	.363	.478	
ΔT_M C		1.6	1.1	.75	.54	.37	.29	.17	.16	.11	.10	
R_t m		.180	.204	.248	.319	.404	.347	.508	.567	.703	.840	
H W		20	20	17	17	15	12	9	10	7	8	Integral plume parameter values
V m^3/s		.023	.029	.033	.043	.052	.059	.067	.072	.065	.086	
I kgm/s^2		2.4	3.8	4.4	5.1	6.0	7.2	6.6	6.9	6.2	6.1	
Ar		.369	.160	.106	.118	.097	.071	.077	.081	.054	.111	
λ		.88	.99	1.15	1.21	1.38	1.15	1.41	1.49	1.94	1.76	
m		5	18	22	15	13	51	19	14	11	4	Local approximation by a model of a plume above a point source
p		7	18	17	10	7	39	9	6	3	1	
α		.361	.197	.177	.218	.232	.116	.193	.224	.252	.430	

Table 6. Measurement results.

The results show that the zone of complete similarity does not occur in any of the measurements independent of height. This is caused either by the way of generating the plume or by the environmental conditions. The velocity and temperature distribution factors m & p are below the values indicated in the model of a plume above a point heat source and the entrainment factor is larger. This means that the plume has a larger angle of spread and propagates with a lower velocity.



Zone 3, zone of maximum plume rise: The maximum elevation is reached, the air flows out horizontally as a stratified layer.

Zone 2, intermediate zone: As zone 2 in the case without stratification dT/dx=0, but the effect of stratification is significant.

Zone 1, the boundary layer zone: As zone 1 in the case without stratification dT/dx=0, the stratification affects the flow.

Fig.10. The flow regions in the plume above a heat source, with vertical temperature gradient, dT/dx > 0 K/m, ref. (7). (Compare with fig.3.).

In the case with little vertical temperature gradient dT/dx = 0.07 K/m and recirculating flow, table 4, it looks like the plume approaches the complete similarity at x = 2.50 m above the source (3.50 m above the floor), because the entrainment factor approaches the value α = 0.08 and the velocity and distribution factors are greather than 100. This indicates that the intermediate zone is long and extends the height of a normal office room.

In the case with the vertical temperature gradient dT/dx = 0.30 K/m and "co-flow" disintegration tendencies are shown, see table 6. The heat flux H and the temperature excess ΔT_M decrease fast. The velocity and temperature distribution factors m and p approach zero level and the entrainment factor α is often more than 2 times greather than the value α = 0.08. The results in table 5 show the same characteristics as in table 6. But it is not so clear because the vertical temperature gradient is less dT/dx = 0.09 K/m.

Fig.11. and fig.12. show the flow rate in the thermal plumes as a function of the distance from the top of the heat source. The characteristics reported are observed in more experiments with other heat source geometries, e.g. tubes and plates.

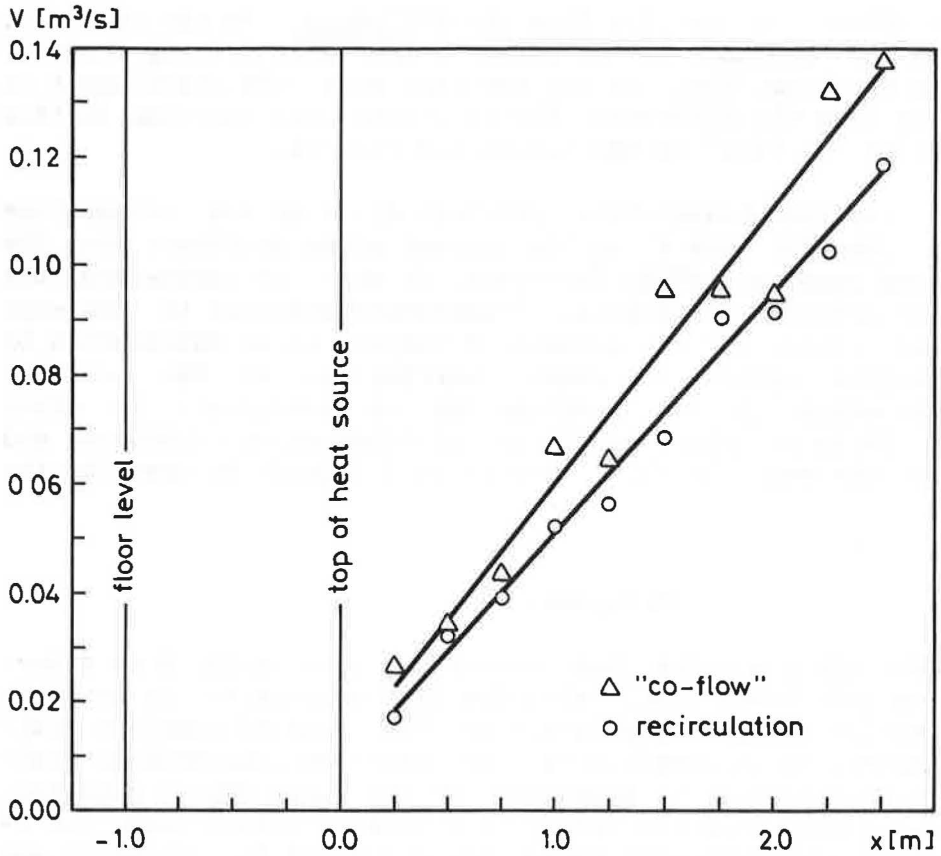


Fig.11. Distribution of volume flux $V = \pi v_M R_V^2$ along the plume axis. Recirculation flow and "co-flow" are compared. Table 4 & 5.

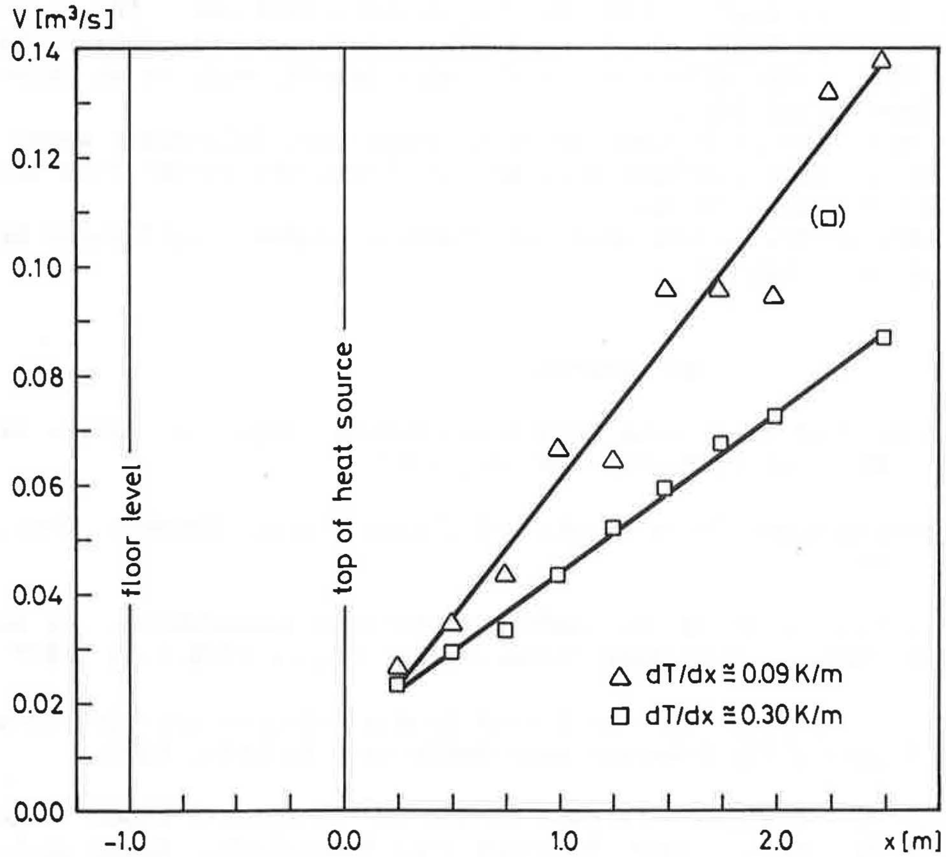


Fig.12. Distribution of volume flux $V = \pi v_M R_V^2$ along the plume axis. "Co-flow", the effect of vertical temperature gradient is shown. Table 5 & 6.

Fig.11. shows the effect of the flow from the diffusers. In the case with recirculation flow the buoyancy in the plume is the main driving force of the total flow in the room. This is not the case when the entrainment is supported with flow from the diffusers. The flow rate will increase in this case, which is called "co-flow" in the tables and figures.

The effect of the vertical temperature gradient dT/dx on the volume flux appears in fig.12. The flow rate V in the thermal plume decreases when the vertical temperature gradient dT/dx increases. It must be emphasized that it is important to relate the vertical temperature gradient to the zone where the flow takes place. For the purpose of buoyant plume calculation by means of an integral method the exact distribution of the vertical temperature distribution in the surroundings is essential. In other experiments than those reported here total disintegration tendencies and horizontal flow are observed. In this case it is difficult to describe the flow.

Conclusion.

The model of a plume above a point heat source has been verified as a borderline case which only takes place when the flow propagates in surroundings without a vertical temperature gradient. The zone of complete similarity where the modelling is possible is found above an intermediate region. The length of this region is dependent on the heat source geometry, and it is observed longer than the height of a normal office room. Due to the measuring method and data processing the width of the velocity and temperature excess profiles are found to be more narrowly than that observed by previous authors, and the entrainment factor is smaller.
Even very small vertical temperature gradients make the modelling impossible. The entrainment factor strongly depends on the vertical temperature gradient. In the intermediate region the entrainment factor is greater than observed in the case without a vertical temperature gradient. The exact knowledge of the vertical temperature gradient is essential to predict the flow propagation due to its influence on the entrainment, e.g. in an integral method of plume calculation.
Since the flow from different heated bodies is individual full-scale measurements seem to be the only possible approach to obtain the volume flow in: thermal plumes in ventilated rooms.
At the present moment the entrainment in thermal plumes influenced by enclosing walls is investigated.

References.

(1) Chen C.J. & W. Rodi: Vertical turbulent buoyant jets - a review of experimental data, HMT, vol.4, Pergamon Press, 1980.

(2) Fox D.G.: Forced plume in a stratified fluid, Journ. Geophys. Res., 75, pp.6818-6835, 1970.

(3) George W.K., R.L. Alpert & F. Tamini: Turbulence measurements in an axisymmetric plume, Int. J. Heat Mass Transfer, Vol.20, pp.1145-1154, 1977.

(4) Heiselberg P. & M. Sandberg: Convection from a slender cylinder in a ventilated room, Roomvent'90, International conference in Oslo, 1990.

(5) Kofoed P. & P.V. Nielsen: Thermal plumes in ventilated rooms - an experimental research work, Indoor Environmental Technology, paper no.7, ISSN 0902-7513 R8833, 1988.

(6) Mierzwinski S.: Air motion and temperature distribution above a human body in result of natural convection, A4-series no.45, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1981.

(7) Mierzwinski S. & Z. Popiolek: Experimental verification and possibilites of application af a plume model above a point heat source, A4-series no.58, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1982.

(8) Morton B.R., G.I Taylor & J.S. Turner: Turbulent gravitational convection from maintained and instantanous sources, Proc. Roy. Soc. London, A, 234, pp.1-23, 1956.

(9) Morton B.R.: The choise of conservation equations for plume models, journ. Geophys. Res., vol.76, no.30, pp.7409-7416, Okt.20, 1971.

(10) Mundt, E.: Convection flows above common heat sources in rooms with displacement ventilation, Roomvent'90, International conference in Oslo, 1990.

(11) Nakagome H. & M. Hirata: The structure of turbulent diffusion in an axisymmetrical thermal plume, ICHMT, vol.1-2, Dubrovnik, 1976.

(12) Popiolek Z.: Problems of testing and mathematical modelling of plumes above human body and other extensive heat sources, A4-series no.54, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1981.

(13) Popiolek Z. & P. Knapek: Analysis of the integral method of plume calculation, A4-series no.59, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1982.

(14) Popiolek Z. & S. Mierzwinski: Buoyant plume calculation by mean of the integral method, A4-series no.89, Dept. of Heating and Ventilating, Royal Inst. of Technology, Stockholm, Sweden, 1984.

(15) Rouse H., C.S. Yih & H.W. Humphreys: Gravitational convection from a boundary source, Tellus, 4, pp.201-210, 1952.

(16) Schmidt, W.: Turbulente Ausbreitung eines Stromes erhitzter Luft, Z. angw. Math. Mech., Bd.21, Nr.5 & 6, Okt. & Dez., 1941.

(17) Skistad, H.: Fortrengningsventilasjon i komfortanlegg med lavimpuls lufttilførsel i oppholdssonene, Norsk VVS Teknisk Forening, 1989.

(18) Skåret, E.: Displacement ventilation, Roomvent'87, International conference on air distribution in ventilated spaces, Stockholm, 1987.