CONVECTION FLOWS IN ROOMS WITH TEMPERATURE GRADIE
- THEORY AND MEASUREMENTS

Elisabeth Mundt
Department of Building Services Engineering
Royal Institute of Technology
Stockholm, SWEDEN

INTRODUCTION

Convection flows are the driving forces for displacement ventilation in transporti
air within the room. The principle for displacement ventilation is to supply cool a
low level in the room with a low velocity and exhaust the air at a high level in the
This implies that the lower part of the room will have a better air quality than the
part of the room since the polluted air is transported to the upper region.The flow p
within the room is then of great interest as it tells up to which level the polluted
transported and how much air the convection flows are transporting as well as the m
with the surrounding air.

The base for the dimensioning of the displacement ventilation has so far mostly be
scale experiments. The mechanism for the temperature gradient in the room a
coupling of the convection flows with this gradient has not yet been fully investigat

Some results concerning both these factors was presented in [1] and this paper pr
some more results concerning the convection flows. For the temperature gradient a
lified calculation model was earlier given [1, 2] which gives the temperature gradie
function of supply air/m^2 floor area. With this model the required amount of vent
air also can be calculated as a function of the cooling capacity for a specified grad
the room. The temperature difference between the supply air and the room air at a
level can also be obtained.

For the convection flows, however, a simplified calculation method, which takes th
dient in the room into account, has not been given so far. Many factors influence
flows, the dimension of the source as well as the convective output from the sourc
play a major role. The gradient in the room is also of great importance as the buoya
the flow is dependant on the temperature difference between the plume a
surrounding air at the same level.

Some earlier measurements have been reported by different authors. Reference [3]
a great influence of the temperature gradient on the flow above a heat source and pr

results where the flow above a human being is reduced by 50% when the gradient is increased to 1.5°C/m. Reference [4] also presents a great influence of the room temperature gradient on the convection flow above a person. References [5,6] gives a minor influence of the gradient on the flow above a heat source.

BACKGROUND

The basic integrated conservation equations for an axisymmetric turbulent plume in an still environment are well known, see e g reference [7].

Continuity equation:

$$\frac{d(w_o \cdot R^2)}{dz} = 2 \cdot \alpha_G \cdot w_o \cdot R \qquad (1)$$

Momentum equation:

$$\frac{d(w_o^2 \cdot R^2)}{dz} = 2 \cdot \beta \cdot g \cdot \Delta\theta_o \cdot R^2 \cdot \lambda^2 \qquad (2)$$

Energy equation:

$$\frac{d(w_o \cdot \Delta\theta_o \cdot R^2)}{dz} = - \frac{d\theta_\infty}{dz} \cdot \frac{\lambda^2+1}{\lambda^2} R^2 \cdot w_o \qquad (3)$$

Equations (1) - (3) are valid with the following assumptions

- the entrainment coefficient is proportional to the centre line velocity at the same height
- the profile of the mean vertical velocity and of the mean buoyancy force are of similar form at all heights and can be described by a gaussian profile

The gaussian profiles are defined by:

$$w = w_o \cdot \exp -(r/R)^2 \qquad (4)$$

$$\Delta\theta = \Delta\theta_o \cdot \exp -(r/\lambda \cdot R)^2 \qquad (5)$$

For the plume in an environment without a gradient the buoyancy force, F_o is a constant. If the velocity and the volume flux at the source is zero the following solution is obtained:

$$R = \frac{6 \cdot \alpha_G}{5} \cdot z \qquad (6)$$

$$w_o = \left(\frac{3 \cdot (\lambda^2+1) \cdot F_o}{2\pi}\right)^{1/3} \cdot \left(\frac{5}{6 \cdot \alpha_G}\right)^{2/3} \cdot z^{-1/3} \qquad (7)$$

$$\Delta\theta_o = \left(\frac{2}{3\pi^2}\right)^{1/3} \cdot \frac{\left(F_o \cdot (\lambda^2+1)\right)^{2/3}}{g \cdot \beta \cdot \lambda^2} \left(\frac{5}{6 \cdot \alpha_G}\right)^{4/3} \cdot z^{-5/3}$$

The flux in a plume of gaussian shape is:

$$q = \pi \cdot w_o \cdot R^2$$

The buoyancy force F_o can be described by

$$F_o = \pi \cdot w_o \cdot \Delta\theta_o \cdot R^2 \cdot g \cdot \beta \cdot \frac{\lambda^2}{\lambda^2+1} = P_k \cdot g \cdot \beta / (\rho \cdot c_p)$$

Equation (9) then gives, together with equations (6), (7) and (10) with data f
normal room temperature

$$q = 5.5 \cdot P_k^{1/3} \cdot z^{5/3} \text{ (l/s)}$$

This is the well known formula for the volume flux from a point source. For a line
the following formula is given in the literature:

$$q = 14 \cdot P_k^{1/3} \cdot z \text{ (l/s m)}$$

Equation (11) and (12) are only valid in an environment without a temperature gra

For the case with a gradient in the room, reference [7] give an alternative sol
which the buoyancy force at the source and the temperature gradient in the room a
to transform equations (1) to (3) to nondimensional form. The following transfor
are used where F_o is given by equation (10) and $G = \beta \cdot g (d\theta_\infty / dz)$. The temperat
velocity field are assumed to have the same width (λ=1).

$$z = 0.410 \cdot \alpha_G^{-\frac{1}{2}} \cdot F_o^{\frac{1}{4}} \cdot G^{-\frac{3}{8}} \cdot z_1$$

$$R = 0.819 \cdot \alpha_G^{\frac{1}{2}} \cdot F_o^{\frac{1}{4}} \cdot G^{-\frac{3}{8}} \cdot R_1$$

$$w_o = 1.158 \cdot \alpha_G^{-\frac{1}{2}} \cdot F_o^{\frac{1}{4}} \cdot G^{\frac{1}{8}} \cdot w_{01}$$

$$\beta \cdot g \cdot \Delta\theta_o = 0.819 \cdot \alpha_G^{-\frac{1}{2}} \cdot F_o^{\frac{1}{4}} \cdot G^{-\frac{5}{8}} \cdot \Delta\theta_{01}$$

equations (1)-(3) then transforms to

$$\frac{dm_1}{dz_1} = v_1 \qquad \frac{dv_1^4}{dz_1} = f_1 \, m_1 \qquad \frac{df_1}{dz_1} = -m_1$$

where

$$m_1 = R_1^2 \, w_{01} \qquad v_1 = R_1 \, w_{01} \qquad f_1 = m_1 \, \Delta\theta_{01}$$

The numerical solution to these equations is given in reference [7] in the form of a table for m_I, v_I and f_I, and in graphical form for R_I, w_{0I} and $\Delta\theta_{0I}$ as a function of z_I. In fig 1 the latter is shown, from which can be seen that the density difference $\Delta\theta_{0I}$ vanishes at $z_I = 2.125$, but the velocity remains up to $z_I = 2.8$, which is the maximum height for the plume.

The maximal height, as well the height where the temperature difference disappears, can for a point source be calculated from equation (13), which for $\alpha_G = 0.093$ gives

$$z_{max} = 3.76 \cdot F_0^{\frac{1}{4}} \cdot G^{-\frac{3}{8}} \qquad z_{den} = 2.85 \cdot F_0^{\frac{1}{4}} \cdot G^{-\frac{3}{8}} \tag{17 a,b}$$

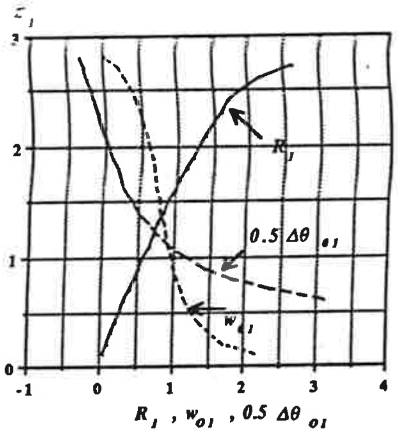

Fig 1. The relation between the nondimensional plume parameters, reference [7].

MODEL

With help of the solution in reference [7] the influence of a temperature gradient on the convection flow can be studied.

Equation (9) together with equations (14) and (15) gives:

$$q = \pi \cdot 1.158 \cdot 0.819^2 \cdot \alpha_G^{\frac{1}{2}} \cdot F_o^{\frac{3}{4}} \cdot G^{-\frac{5}{8}} \cdot m_I \tag{18}$$

If m_I can be given as a function of z_I the flow in the plume can be calculated when α_G is known. Fitting a polynom to m_I as a function of z_I gives a polynomial of third degree with the regression coefficient R=1.

$$m_I = 0.004 + 0.039 \cdot z_I + 0.380 \cdot z_I^2 - 0.062 \cdot z_I^3$$

The convection flow can then be calculated at different levels with equations (13
(18), for a given gradient and source output.

For extended flat sources, reference [7] gives an approximate method for the calcul
of the virtual source location. It defines an effective radii where the velocity has decr
to 1% of the maximal velocity and say that this radii equals the actual radii of the so
In this way, the radii of the source, R_k, can be given as a function of R in the plume:

$$0.01 w_o = w_o \cdot \exp -(R_k/R)^2 \quad \Rightarrow \quad R_k = 2.146 \cdot R$$

With equation (6) the location of the virtual source can be calculated from:

$$z_{virt} = \frac{5 \cdot R_k}{6 \cdot \alpha \cdot 2.146}$$

For vertically extended surfaces it is here suggested to calculate the boundary layer
ness at the top of the source and add to the source radii. The boundary layer thickne
be calculated using the following formula, [8]:

$$\delta = 3.93 \cdot \left(\frac{Pr + 0.952}{Pr}\right)^{1/4} \cdot (Gr \cdot Pr)^{-1/4} \cdot z$$

where $\delta =$ boundary layer thickness (m)
$Pr = \mu \cdot c_p / \lambda_a$
$Gr = g \cdot \beta \cdot \Delta\theta \cdot z^3 / \nu^2$

With data for air of normal temperature it follows

$$\delta = 0.048 \cdot \sqrt[4]{\frac{z}{\Delta\theta}}$$

The calculation method with this model (for air of normal room temperature) can b
marised in the following steps:

1) Vertical extended sources: Calculate the boundary layer thickness δ m
Horizontal sources: $\delta = 0$

$$\delta = 0.048 \cdot \sqrt[4]{\frac{z}{\Delta\theta}}$$

where $z =$ height of source (m)
$\Delta\theta =$ temperature difference source - surrounding (°C)

2) Calculate the location of the virtual source

$$z_v = 4.18\cdot(R_k + \delta)$$

where $R_k =$ source radii (m)

3) For different heights z above the source calculate z_l

$$z_l = 2.86\cdot(z - z_v)\cdot s^{.375} P_k^{-.25}$$

where $s =$ room gradient (°C/m)

$P_k =$ convective heat from the source (50% for extended sources; 80% for lamps) (W)

If $2.125 < z_l < 2.8$ the density difference has disappeared and the calculations a bit uncertain; if $z_l > 2.8$ the plume has reached its maximal height.

4) For different z_l calculate

$$m_l = 0.004 + 0.039\cdot z_l + 0.380\cdot z_l^2 - 0.062\cdot z_l^3$$

$$q = 2.38\cdot P_k^{\frac{3}{4}}\cdot s^{-\frac{5}{8}}\cdot m_l \text{ (l/s)}$$

In fig 2 the convection flows for different heat sources and different gradients are shown. The curves end at the maximal height to which the plumes rise for different conditions. As can be seen from the figure the influence of a gradient is minor at lower heights but strongly influences the maximal heights for the plumes.

The model based on reference [7], although some presumptions which may be a bit too simple are made, gives an easy way to calculate the influence of a gradient on the convection flows and the height to which they rise.

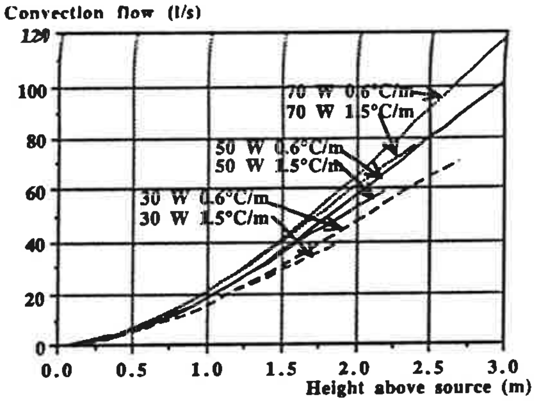

Fig 2 Convection flow above a heat source with 30, 50 and 70 W and different gradients, $\alpha = 0.093$.

MEASUREMENTS

The convective flows from different heat sources, common in offices, have been sured in different laboratories. The project has been supported by some Scandin: manufacturers of supply devices for displacement ventilation, which have made sor the measurements in their own laboratories.

All measurements have been carried out under steady state conditions in rooms with lacement ventilation and a temperature difference between supply and exhaust ai enough to take away all excess heat produced within the room. The excess heat cons of the measured object and in some series of an extra radiator to increase the gradie the room. The dimensions of the test room was in most cases 3.6x3.6x2.7 m.

Four different objects have been tested in altogether six laboratories. The first o objects was a simulator of a human being, made of 1 m ventilation duct with a dian of 0.4 m. The duct was painted on the outside so the emission coefficient would be e to that of a man and inside four 25 W bulbs were placed (100W). The second object a desk lamp with a 60 W bulb, placed over the centre of a table. The table was place the wall opposite the air inlet device. The third object tested was a fluorescent lamp 36 W placed over the above mentioned table. Finally some measurements were done a simulator of a personal computer made of aluminium with another box inside. computer had a source of 75 W placed inside. The measured objects are shown in f

In order to obtain the flows above the objects the velocity and temperature profiles measured at two perpendicular directions at different heights. The temperature gra in the room was also measured in several locations in the room as well as the suppl exhaust air temperatures. The temperatures on all the surfaces in the room were rec so that the convective heat output from the measured objects could be calculated.

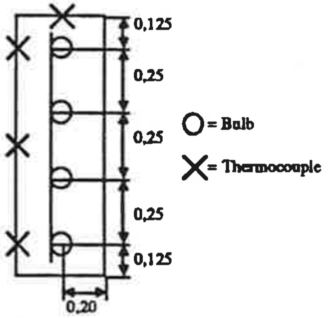

Fig 3 Person simulator (100W)

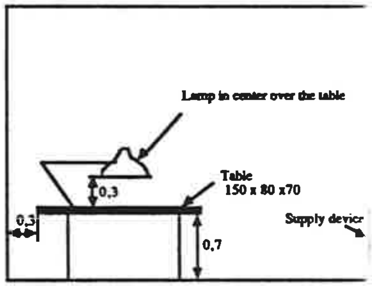

Fig 4 Desk lamp (60W)

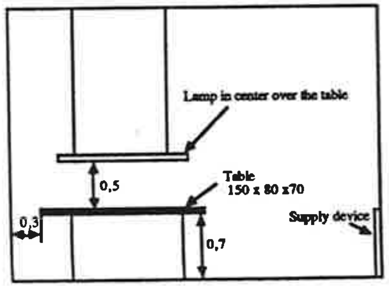

Fig 5 Fluorescent lamp (36 W)

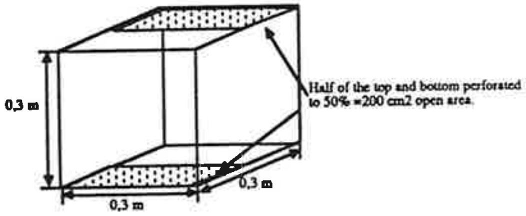

Fig 6 Personal computer simulator (75W)

The velocity profiles were measured with anemometers and the temperature profiles with thermocouples. The centre of the plume was found and a gaussian profile fitted, by means of the least square method, to the measured values. Equation (9) could then be used to calculate the convection flow at the measured heights.

For the first object three different situations were measured, two of them with the person simulator as the only heat load and different ventilation flow rates and the third with an extra heat load in the room in order to increase the gradient.

The other three objects were measured for four different situations, two different ventilation flow rates with and without the extra heat load. All the objects gave a nice gaussian shaped plume above them. Although the spread in results between different laboratories was rather big. This can can be explained by the use of different anemometers, but also these types of measurements are very difficult because of the low velocities being measured. All the results however indicate the same growth of the convection flows with height and the same influence of a gradient present in the room.

Person simulator

In table 1 the calculated convection flows, the centre velocities and the radii for the convection plume are shown for the person simulator as well as the correlation coefficient for the gaussian fit of the velocity curves. For the lowest height the convection flows are obtained by simply integrating the velocity profile, as the gaussian shape of the profiles have not yet been developed at that height. As can be seen from the table the correlation coefficient is quite high at the lower levels but less good at the highest measured level. It is also obvious that the ventilation flow and the gradient in the room both influence the convection flows. An increased ventilation flow rate increases the convection flow and an increased gradient in the room both influences the convection flow and the maximal height for the plume. With a gradient of 1.5 °C/m the plume starts to disintegrate at 1.2 m above the source.

In fig 7 the values calculated with the model are compared with all the measured values. The virtual source is from the model found to be at floor level. According to the model the maximum height of the plume is 1.2 m above the source when the gradient is 1.5 °C/m. This agrees quite well with the results obtained here. The plumes are almost

Table 1 Measurement results with person simulator

Lab	Ventilation flow (l/s)	Gradient (°C/m)	Height above source (m)	Convection flow (l/s)	w_{max} (cm/s)	R (m)
Lab 1	20.8	0.6	0.1	23		
			0.4	32	19.5	0.23
			0.8	35	20.7	0.23
			1.2	46	19.4	0.27
	41.6	0.6	0.1	24		
			0.4	35	16.4	0.26
			0.8	43	19.2	0.26
			1.2	60	16.6	0.34
	41.6	1.5	0.1	21		
			0.4	27	17.2	0.22
			0.8	31	15.0	0.25
			1.2	17	7.8	0.26
Lab 2	20.8	0.6	0.1	30		
			0.4	40	21.8	0.24
			0.8	52	23.8	0.26
			1.2	66	23.5	0.30
	41.6	0.6	0.1	35		
			0.4	49	22.2	0.27
			0.8	62	22.8	0.30
			1.2	76	21.1	0.34
	41.6	1.5	0.1	29		
			0.4	37	19.4	0.25
			0.8	43	18.8	0.27
			1.2	34	11.5	0.31
Lab 3	20.8	0.6	0.1	24		
			0.4	[illegible]	[illegible]	[illegible]
			0.8	41	[illegible]	[illegible]
			1.2	48	18.9	0.29
	41.6	0.6	0.1	29		
			0.4	40	18.6	0.26
			0.8			
			1.2	68	17.9	0.35
	41.6	1.5	0.1	26		
			0.4	37	21.6	0.23
			0.8	46	19.5	0.28
			1.2	37	7.1	0.40
Lab 4	20.8	0.6	0.1	32		
			0.4	44	15.8	0.3
			0.8	47	16.9	0.3
Lab 5	70	0.9	0.1	27		
			0.4	51	17.8	0.30
			0.8	56	17.6	0.32
			1.2	77	17.0	0.38
		1.2	0.1	26		
			0.4	37	17.8	0.26
			0.8	52	16.2	0.32
			1.2	72	11.9	0.44

disintegrated at this level with the higher gradient in the room. As can be seen from 1 the flows obtained at this level are rather uncertain, the correlation coefficients rather low. In fig 7 the flows calculated with equation (11) are also shown, these are calculated for a virtual source 1 m below the actual source.

Fig 7 shows that the model gives a rather good approximation of the real flows and a good hint of the height at which the plumes disintegrates.

In fig 8 the temperature difference between the plume and surroundings is shown at different heights for the different gradients. The temperature profile is very interesting as it shows that the plume remains rather unmixed with the surrounding air up to the plane where it disintegrates. At the higher gradient, the plume has an undertemperature relative the ambient at the higher levels. The buoyancy force is negative and the plume acts like a jet with a limited reach.

For the higher gradient the temperature difference vanishes around 0.8 m above the source. Equation (17) gives the relation between z_{den}/z_{max} to be 0.76 which, with a z_{max} of 1.2 m, gives $z_{den} = 0.9$. This computed result is quite close to the measured value.

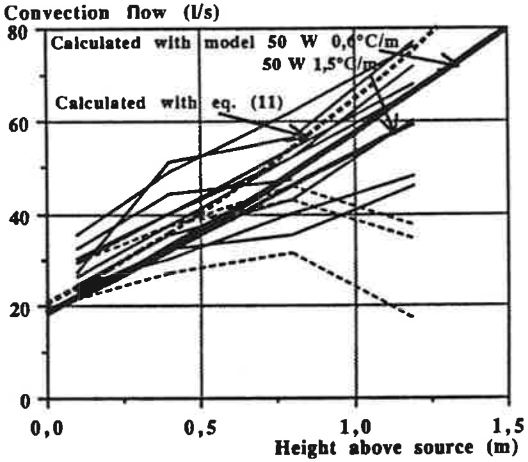

Fig 7. The measured convection flows over the person simulator, gradient 0.6°C/m full lines and gradient 1.5°C/m dotted lines. Calculated convection flows with model, thick full lines and with equation (11), thick dotted line.

Desk lamp

The measurements conducted on the desk lamp (fig 4) are shown in table 2. Fig 9 shows a comparison between the convection flows above the lamp calculated from the measurements as well as the flows calculated with the model and equation (11). The location of the virtual source has been calculated in the same way as for the person simulator. The radii for the lamp at the top is 2.5 cm, which gives the location of the virtual source 10 cm below this edge.

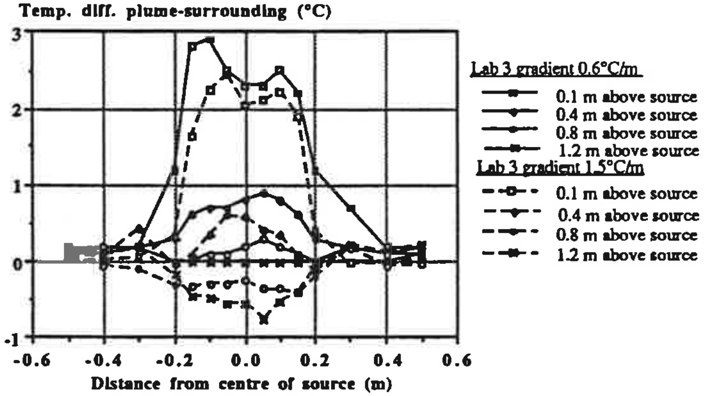

Fig 8 Temperature difference plume- surrounding at different levels. Ventilation flow rate 41.6 l/s, gradient 0.6 °C/m and 1.5 °C/m.

According to the model the influence of a gradient for this case is negligible and the maximum plume height is above the ceiling. From fig 9 it is evident that the flow is not increasing 0.8 m above the source, which is equal to 0.4 m from the ceiling. The plume is, however, not disintegrating in the way it did for the person simulator. The velocities at this level are still quite high and the plume has a well defined gauss shape. The influence of the ventilation flow rate on the convection flow noticed before was not evident for this measured object.

Table 2. Measurement results with desk lamp.

Lab	Ventilation flow (l/s)	Gradient (°C/m)	Height above source (m)	Convection flow (l/s)	w_{max} (cm/s)	R (m)	C co
Lab 3	20.8	0.8	0.4	6	38.6	0.07	0
			0.6	11	33.0	0.10	0
			0.8	12	31.0	0.11	0
			1.0	13	28.4	0.12	0
	20.8	2.4	0.4	6	36.4	0.07	0
			0.5	7	33.4	0.08	0
			0.6	10	30.1	0.11	0
			0.8	13	25.3	0.12	0
	41.6	0.8	0.4	5	31.1	0.07	0
			0.6	9	31.5	0.10	0
			0.8	11	32.9	0.11	0
			1.0	12	29.4	0.12	0
	41.6	2.5	0.4	5	34.9	0.07	0
			0.6	10	32.0	0.10	0
			0.8	13	27.1	0.12	0
			1.0	12	23.6	0.13	0

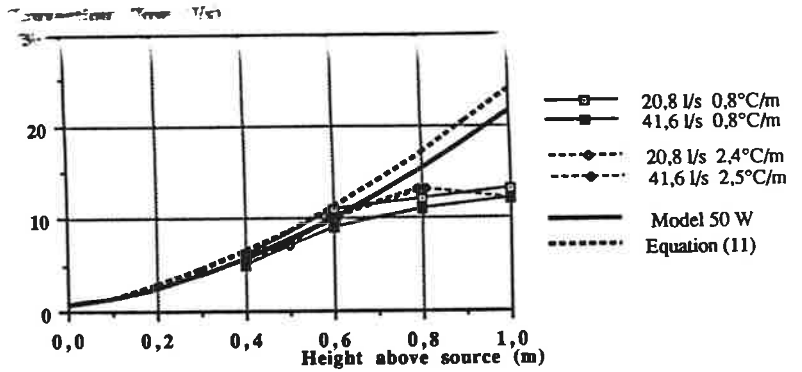

Fig 9 Convection flow over a desk lamp by different ventilation flow rates and temperature gradients.

Fluorescent lamp

The measurements conducted on the fluorescent lamp (fig 5) are shown in table 3.This [illegible] being a line source rather than a point source, means that the gaussian curve can not be integrated rotational symmetrical, but has to be integrated in the plane, this gives

$$q = w_o \cdot R \cdot \sqrt{\pi}$$

Table 3. Measurement results with fluorescent lamp.

Lab	Ventilation flow (l/s)	Gradient (°C/m)	Height above source (m)	Convection flow (l/s)	w_{max} (cm/s)	R (m)	Corr coeff.
Lab 1	42	0.3	0.4 0.8	11 22	7.8 7.4	0.08 0.17	0.67 0.81
	42	1.0	0.1 0.4 0.8	7 16 0	10.1 8.1	0.04 0.11	0.99 0.63
Lab 3	41.6	0.4	0.4 0.6 0.7	11 25 27	14.5 11.9 10.2	0.04 0.12 0.15	0.98 0.99 0.99
	41.6	1.1	0.2 0.3 0.4 0.5 0.6 0.7	8 14 15 17 21 0	10.7 9.8 9.6 9.5 7.6	0.04 0.08 0.09 0.10 0.16	0.8 0.98 0.91 0.97 0.98
	20.8	0.5	0.4 0.6 0.8	16 23 25	12 10.5 9.2	0.07 0.12 0.15	0.99 0.99 0.99
	20.8	1.1	0.3 0.4 0.5 0.6 0.8	11 15 18 21 0	10.5 10.4 9.0 7.8	0.06 0.08 0.11 0.15	0.99 0.95 0.97 0.99

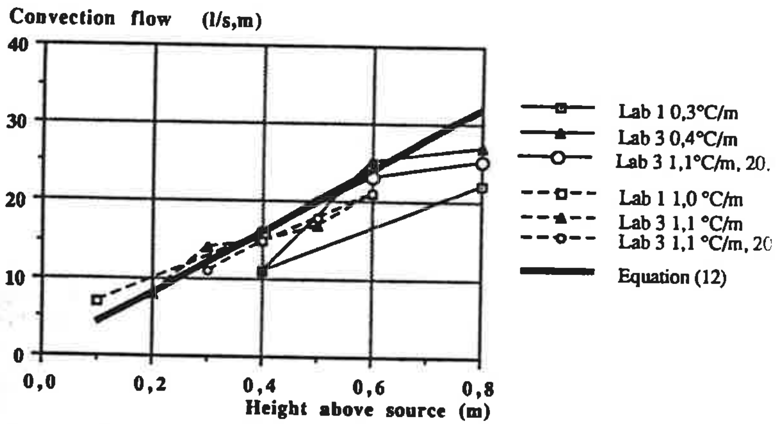

Fig 10 Convection flow over a fluorescent lamp by different ventilation flow rates and temperature gradients.

Table 3 shows that the convection flows could be measured up to 0.8 m for a low tem rature gradient, but with a higher gradient the flows [illegible] measured values of the convection flows are shown in fig 10 together with the va calculated with equation (12), valid for a line source. The convective output from lamp has been set to 80% of the total heat. The model could not be used for this case a is only valid for a point source.

Personal computer simulator

These measurements were performed in two laboratories with different ventilation f rates. From table 4 can be seen that the difference between the two is quite large.

Table 4. Measurement results with personal computer simulator.

Lab	Ventilation flow (l/s)	Gradient (°C/m)	Height above source (m)	Convection flow (l/s)	w_{max} (cm/s)	R (m)
Lab 2	41.6	0.6	0.4 0.8 1.2	16 30 54	44 38 36	0.11 0.16 0.22
	41.6	2.0	0.4 0.8 1.2	20 31 40	36 40 32	0.13 0.16 0.20
Lab 5	70	0.7	0.4 0.8 1.2	30 47 63	27 26 25	0.19 0.24 0.28
	70	1.5	0.4 0.8 1.2	25 45 64	27 26 22	0.17 0.24 0.31

The flows measured in Lab 2 are smaller than the ones obtained in Lab 5. The results conform with the results obtained for the person simulator at different ventilation flow rates.

Fig 11 shows the measured convection flows as well as the one calculated with the model and equation (11). The convective heat output is 50% of the total heat output.

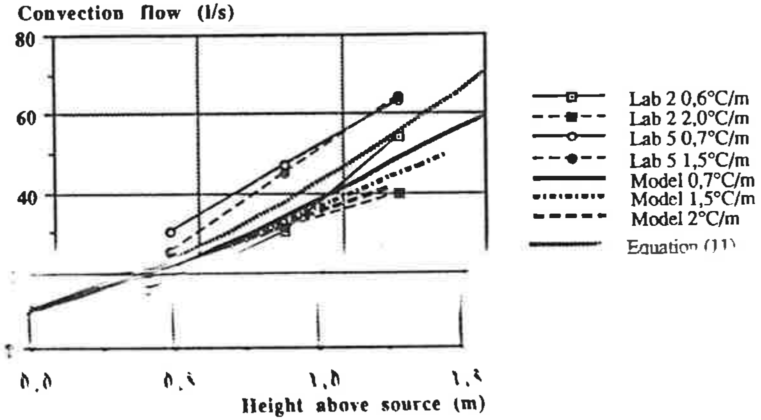

Fig 11 Convection flow over a personal computer simulator by different ventilation flow rates and temperature gradients.

CONCLUSION AND SUMMARY

The convection flows above different heat sources measured in this project have not shown the great dependence of the temperature gradient reported earlier. For extended heat sources with low effects an influence of the ventilation air flow in the room has been noticed.

The hitherto mostly used equations for the calculation of the convection flows valid in rooms without a temperature gradient, give convection flows with greater increase with height than measured here.

A model developed in this paper gives better values for the convection flows in the presence of a temperature gradient. This model also gives a good approximation of the height to which the plume rises.

ACKNOWLEDGEMENT

The Swedish Council for Building Research supported this work.

REFERENCES

[1] Mundt, E.: **Convection flows above common heat sources in rooms with displacement ventilation.** Proc. Room-Vent 90, Oslo, 1990.

[2] Mundt, E.: **Temperturgradienter och konvektionsflöden vid deplacerande ventilation.** Meddelande nr 16, Installationsteknik, KTH, Stockholm 1991.

[3] Danielsson, P.O.: **Convective flow and temperature in rooms with displacement system.** Proc. Room-Vent 87, Stockholm, 1987.

[4] Fitzner, K.: **Förderprofil einer Wärmequelle bei verschidenen Temperaturgradienten und der Einfluß auf die Raumströmung bei Quellüftung.** Ki nr 10, 1989.

[5] Kofoed, P., Nielsen, P.: Thermal plumes in ventilated rooms. An [illegible] in Environmental Protection, Silesian Technical University, Gliwice, Polen, 19

[6] *Kofoed, P., Nielsen, P.V.:* ***Thermal plumes in ventilated rooms-*** **Measurements in stratified surroundings and analysis by use of an extrapolation method.** Proc. Room-Vent 90, Oslo, 1990.

[7] Morton, B.R., Taylor, G., Turner, J.S.: **Turbulent gravitational convecti from maintained and instantaneous sources.** Proc. Royal Soc., Vol 234 p.1, 1956.

[8] Holman, J.P.: **Heat transfer.** McGraw Hill Book Company, Singapore, 1989

NOMENCLATURE

c_p = specific heat at constant pressure (J/(kg·K))

F_0 = $P_k \cdot g \cdot \beta/(\rho \cdot c_p)$ = buoyancy force at the source (m^4/s^3)

g = acceleration of gravity (m/s^2)

P_k = convective effect (W)

q = volume flow (l/s, m^3/s, m^3/h)

R = radii of the plume (gaussian shape where the velocity equals e^{-1}) (m)

r = distance from centre of plume (m)

s = gradient in the room (°C/m)

w_{max} = calculated maximum velocity in the plume (cm/s)

w_o = centre velocity in the plume (cm/s, m/s)

z = height above source (m)

z_v = distance to virtual source (m)

α = entrainment coefficient