THERMAL PLUMES ABOVE HEAT SOURCES IN ROOMS WITH A TEMPERATURE STRATIFICAT

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ABSTRACT

Information on thermal plume characteristics is essential for designing ventilation systems with displacement air supply. Empirical, analytical and computational fluid dynamics are the commonly used approaches to evaluate air temperatures, velocities and airflow rates in thermal plumes above different heat sources. However, only limited information is available on the behavior of thermal plumes in rooms with a temperature gradient along the room height.

This paper presents the data results from the numerical simulation of thermal plumes above the heat sources of different sizes, shapes, location relative to the floor surface and the heat strength (e.g., seating and standing person, process equipment, cigarette, etc.). These studies were a part of the comprehensive research conducted by the international team and were sponsored by Philip Morris Management Corporation. As a result, a practical "Design Guide for Displacement Ventilation" (Zhivov, et al. 1997a,b) was developed.

KEYWORDS

Displacement ventilation, plumes, numerical method, temperature gradient.

INTRODUCTION

Thermal plumes have been studied for many years. Among the earliest publications are those from Zeldovich (1937), Schmidt (1941), and Shepelev (1978). Analytical equations to calculate velocities, temperatures, air flow rates and other parameters in thermal plumes over point and linear heat sources with given heat loads were derived based on the momentum and energy conservation equations and assuming Gaussian velocity and excessive temperature distribution in thermal plume cross-sections. These equations correspond with those received experimentally by other researchers (Popiolec, 1981; Mierzwinski et al.,1994) e.g., the equation for the air flow rate in the thermal plume is as follows:

$$V_z = C_1 \, W^{1/3} Z^{-1/3} \tag{1}$$

$$\Delta T_z = C_2 \, W^{1/3} Z^{-5/3} \tag{2}$$

$$Q_z = C_3 \, W^{1/3} Z^{5/3} \tag{3}$$

where: V_z, ΔT_z, Q_z = maximum air velocity, excessive air temperature and air flow rate respectively in the thermal plume at the height Z, W = convective component of the heat source, Z = height above the heat source level, C_1, C_2, and C_3 = dimensionless coefficients.

These equations were derived with the assumption that the heat source size was very small and did not account for the actual source dimensions.

The adjustment of the point source model to the realistic sources using the virtual source method gives a reasonable estimate of the air flow rate in thermal plumes (Figure 1): $Z = Z_s + Z_0$. The weak part of this method according to Skistad (1994) is how to estimate the location of the virtual point.

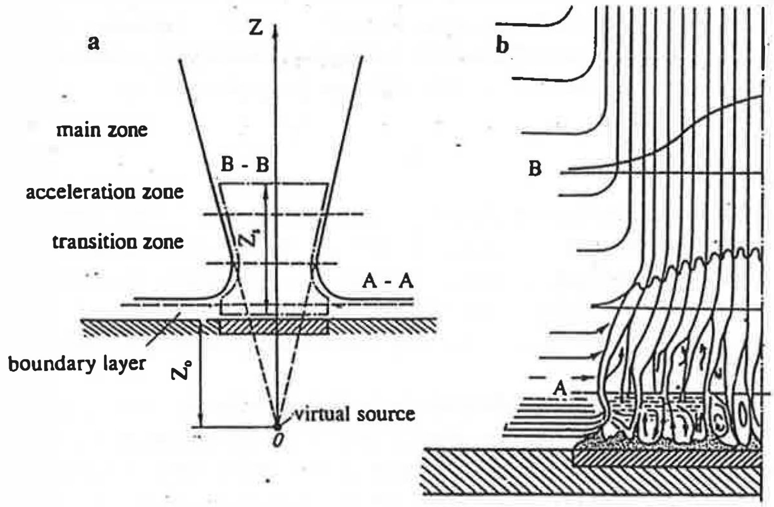

Figure 1. Thermal plume above a heat source: Zs = distance from the source surface to the virtual source; Z - distance from the source surface to the plume cross-section of interest; a - thermal plume schematic; b - boundary layer (b - reproduced from Elterman, 1980)

Shepelev (1978) derived equations to compute velocity and excessive temperature along transition, acceleration and main zones of the plume above the flat sources. E.g., for the round heat source:

$$V_z = A_1 \left(\frac{W}{R}\right)^{1/3} \left(\frac{Z}{R}\left[1 - e^{-B_1\left(\frac{R}{Z}\right)^2}\right]\right)^{1/3} \qquad (4)$$

$$\Delta T_z \cdot V_z = A_2 \frac{W}{R^2}\left(1 - e^{-B_2\left(\frac{R}{Z}\right)^2}\right) \qquad (5)$$

From equation (4), the value of air velocity, V_z, at the height Z = 0 is equal to 0. The value V_z increases along the acceleration zone and drops along the main zone. Experimental coefficients A_1, A_2, B_1 and B_2 in equations (4) and (5) should be obtained from physical experiments. Equations (1) through (5) do not account for the temperature stratification in the space.

Thermal plume parameters also can be predicted using computational fluid dynamics (Nielsen, 1993; Shaelin et al., 1992; Aksenov et al., 1994). According to this approach, the air flow in the thermal plume is described by the system of Navier-Stokes equations and the equation for energy. Velocity, and temperature in the thermal plumes can be calculated with these equations. This approach can be considered as a numerical experiment that is carried out at thousands of points in the area of interest.

The room size for thermal plumes simulation in the presence of temperature gradient was selected to eliminate the confinement effect. For all simulated cases the room height was selected to be 8 m and the room floor area exceeded 5 to 6 times the heat source horizontal dimension.

Thermal plumes above most of heat sources were studied with a temperature gradient Dt/H equal to 0, 0.5°C/m, 1°C/m and 2°C/m. For the cigarette, temperature gradient Dt/H was selected to be equal to 0, 0.25°C/m, 0.5°C/m, 0.75°C/m and 1°C/m. Heat sources listed in Table 2 under numbers 1 through 7 were located on the surface, source number 8 was located at the height of 1 m from the surface and the source number 9 - at a height 0.2 m from the surface. Velocity and excessive temperature distributions in two perpendicular planes of symmetry for representative heat sources are presented in Figures 2 and 3.

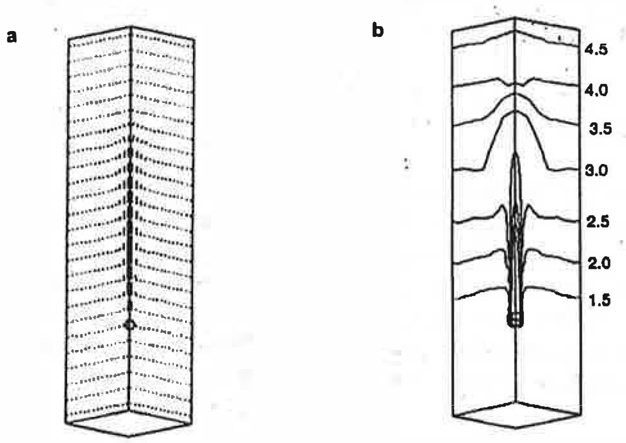

Figure 2. Velocity (a) and temperature difference (b) distribution in two vertical planes of symmetry for hanging lamp @ Dt/H = 1°C/m

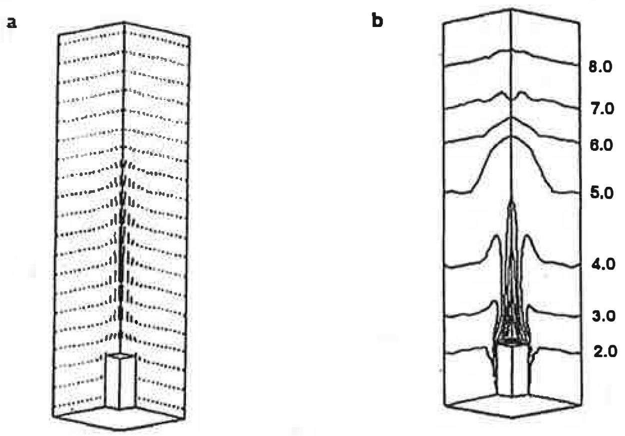

Figure 3. Velocity (a) and temperature difference (b) distribution in two vertical planes of symmetry for TV @ Dt/H = 2°C/m

From the theoretical assumptions used by other researchers for spot and realistic heat sources, and experimental data collected by the author, Mundt (1992) adjusted existing equations to account for the influence of the temperature stratification on plume parameters. Analytical predictions and tests were conducted for thermal plumes above a simulated person, a desk lamp, a fluorescent lamp, and a personal computer in the space, with different levels of temperature stratification. It was concluded that in the presence of the temperature gradient, the convective plume reaches the point where temperature difference in the plume and in the ambient air at the corresponding height (Z_t) disappears and there is another point in the plume, where the air velocity equals zero. This is referred to as the maximum height of the plume (Z_{max}). The following equations resulted from this analysis:

$$Z_{max} = 3.76 \left(\frac{W_c \, g}{273 \, \rho \, C_p} \right)^{1/4} \cdot \left(\frac{g}{273} \frac{d\theta}{dz} \right)^{-3/8} \tag{6}$$

$$Z_t = 2.85 \left(\frac{W \, g}{273 \, \rho \, C_p} \right)^{1/4} \cdot \left(\frac{g}{273} \frac{dT}{dZ} \right)^{-3/8} \tag{7}$$

Mundt (1992) concluded that the deviation of the air flow rate in the realistic thermal plume from the one predicted for the space without temperature stratification becomes greater with a temperature gradient increase and a distance from the virtual source.

Displacement ventilation systems assume temperature stratification along the room height and the temperature gradient can be as high as 1.5°C/m. Thus, in designing displacement ventilation systems, the influence of temperature stratification on characteristics of thermal plumes above room heat sources should be accounted for.

METHOD

FlowVision software (Aksenov et al. 1993, 1994) was used to evaluate excessive air temperature, air velocity and airflow rates in different horizontal cross-sections of thermal plumes above the heat sources specific for the restaurant dining area listed in Table 1.

Table 1. Simulation parameters for typical heat sources in restaurant dining area

No	Source characteristic	Source size, m			Source convective heat component, W	Simulated room size, L x B x H, m	Horizontal computation grid, m
		A	B	H			
1	Person sitting	Ø = 0.3		1.3	45	1.5 x 1.5 x 8.0	0.02
2	Person standing	Ø = 0.3		1.8	55	1.5 x 1.5 x 8.0	0.02
3	TV	0.66	0.66	0.66	225	1.5 x 1.5 x 8.0	0.03
4	Cashier register	0.46	0.46	0.3	250	1.5 x 1.5 x 8.0	0.04
5	Bottle box	0.1	0.76	0.71	400	2.0 x 2.0 x 8.0	0.025
6	Mug chiller	1.2	0.76	0.71	400	3.0 x 2.5 x 8.0	0.05
7	Ice cream cabinet	0.46	0.6	0.9	180	1.5 x 1.5 x 8.0	0.03
8	Lamp hanging	0.15	0.15	0.10	100	1.5 x 1.5 x 8.0	0.025
9	Cigarette	Ø = 0.05		0.02	11	1.5 x 1.5 x 8.0	0.01

RESULTS

Maximum air velocity, maximum temperature difference (related to the ambient room air temperature at the same height) and air flow rate in thermal plumes were computed for the following heights Z, m, above the lowest point of the heat source: Z = 0.1 m, 0.2 m, 0.5 m, 0.75 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 4.0 m, 5.0 m. Sample graphs showing maximum velocity change along thermal plumes above a TV and a cigarette are presented in Figures 4 and 7. Graphs with a maximum temperature difference change and an air flow rate change along thermal plumes above the same heat sources are presented in Figures 5, 6, 8 and 9.

The distance to the point where the maximum temperature difference equals to 0 is considered to be the maximum plume rise. A summary of the data on maximum thermal plume rise for different temperature gradients is presented in Table 2.

Table 2. Maximum raise of thermal plume in the room with temperature gradient.

No.	Heat source category	Dt/H = 0.5°C/m	Dt/H = 1.0°C/m	Dt/H = 2.0°C/m	
1	Person seated	3.58	2.84	2.37	
2	Person standing	4.28	3.44	2.80	
3	TV	5.43	4.30	3.22	
4	Cash register	5.66	4.26	3.16	
5	Bottle box	6.20	4.85	3.64	
6	Mug chiller	5.72	4.65	3.49	
7	Ice cream cabinet	5.36	4.11	3.19	
8	Lamp hanging	3.69	2.80	1.99	
9	Cigarette	Dt/H = 0.25°C/m	Dt/H = 0.50°C/m	Dt/H = 0.75°C/m	Dt/H = 1.0°C/m
		0.75	0.5	0.2	0.1

The results of numerical simulation show significant influence of temperature gradient on air flow rate in thermal plumes and its maximum rise. Comparison of the data received for the TV and for the cigarette shows, that for the larger heat source and the greater heat load, the influence of the temperature gradient is smaller. When the maximum rise of thermal plume above the combined heat and contaminant source is lower than the height of the stratification level created by displacement ventilation system, contaminants get "locked" in the occupied zone, which results in a higher contaminant concentration in inhaling air. Thus, the temperature gradient may have a significant effect on contaminant removal efficiency and should be accounted for when the system is designed.

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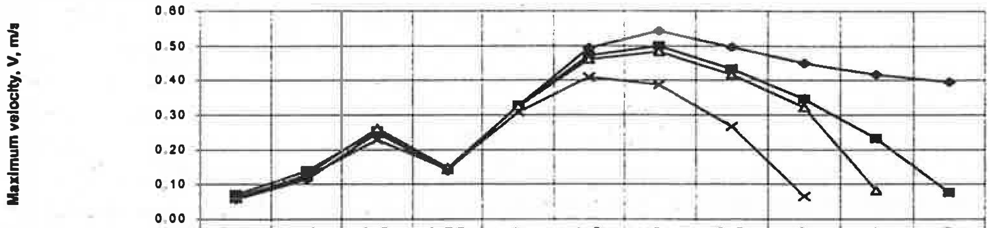
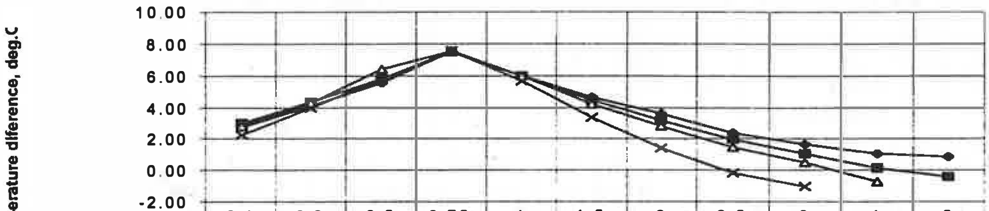


Height above the floor level, m	0.1	0.2	0.5	0.75	1	1.5	2	2.5	3	4	5
Dt/H = 0	0.06	0.11	0.25	0.14	0.33	0.49	0.54	0.50	0.45	0.42	0.40
Dt/H = 0.5	0.07	0.14	0.25	0.14	0.33	0.47	0.50	0.44	0.35	0.23	0.08
Dt/H = 1.0	0.06	0.13	0.28	0.15	0.32	0.48	0.48	0.42	0.32	0.08	
Dt/H = 2.0	0.06	0.12	0.23	0.14	0.31	0.41	0.39	0.27	0.08		

Height above the floor level, m

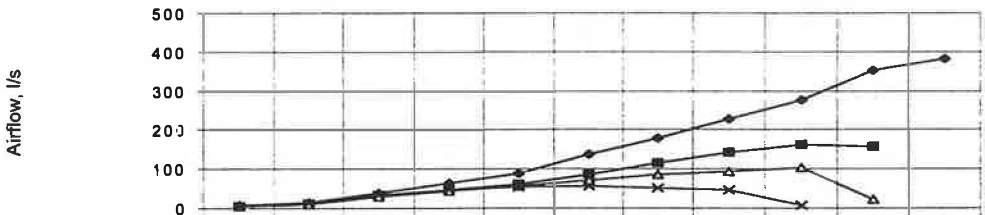
Figure 4. Maximum velocity , V, m/s in the horizontal cross-section of the buoyant plume above TV.



Height above the floor level, m	0.1	0.2	0.5	0.75	1	1.5	2	2.5	3	4	5
Dt/H = 0	2.76	4.08	5.56	7.56	5.96	4.65	3.60	2.40	1.66	1.06	0.84
Dt/H = 0.5	3.00	4.36	5.79	7.51	5.98	4.46	3.19	1.94	1.04	0.16	-0.40
Dt/H = 1.0	2.83	4.25	6.38	7.57	5.96	4.24	2.81	1.50	0.52	-0.74	
Dt/H = 2.0	2.24	3.97	5.80	7.57	5.66	3.39	1.42	-0.17	-1.05		

Height above the floor level, m

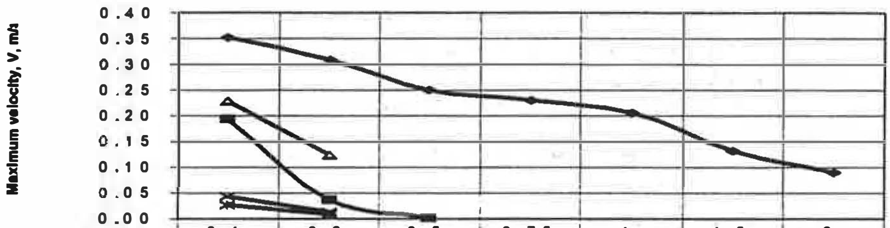
Figure 5. Maximum temperature differential, $\Delta t_{max.h}$, °C in the horizontal cross-section of the buoyant plume above a TV.



Height above the floor level, m	0.1	0.2	0.5	0.75	1	1.5	2	2.5	3	4	5
Dt/H = 0	7	14	39	63	89	137	180	229	278	354	383
Dt/H = 0.5	5	10	31	47	61	85	114	142	161	156	
Dt/H = 1.0	5	10	31	45	57	71	85	94	102	22	
Dt/H = 2.0	6	11	35	46	54	55	52	47	7		

Height above the floor level, m

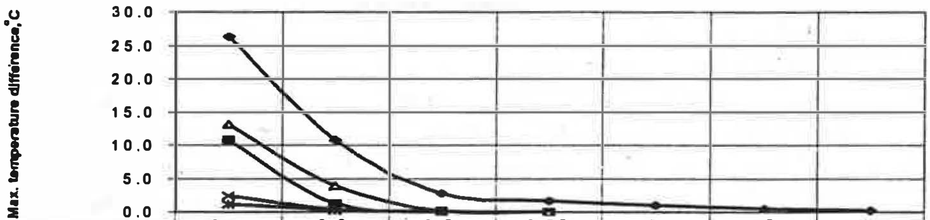
Figure 6. Airflow, Q, l/s, in the horizontal cross-section of the buoyant plume above a TV.



	0.1	0.2	0.5	0.75	1	1.5	2
D t/H = 0	0.35	0.31	0.25	0.23	0.21	0.13	0.09
D t/H = 0.25	0.19	0.04	0.00				
D t/H = 0.5	0.23	0.12					
D t/H = 0.75	0.04	0.01					
D t/H = 1	0.03	0.01					

Height above the cigarette, m

Figure 7. Maximum velocity , V, m/s in the horizontal cross-section of the buoyant plume above a cigarette.



	0.1	0.2	0.5	0.75	1	1.5	2
D t/H = 0	26.3	10.8	2.8	1.8	1.0	0.5	0.2
D t/H = 0.25	10.8	1.3	0.1	0.0			
D t/H = 0.5	13.2	4.0	0.2	0.0			
D t/H = 0.75	2.4	0.4	0.0				
D t/H = 1	1.2	0.2					

Height above the cigarette, m

Figure 8. Maximum temperature differential, $\Delta t_{max.h}$, °C in the horizontal cross-section of the buoyant plume above a cigarette.

	0.1	0.2	0.5	0.75	1	1.5	2
D t/H = 0	0.78	1.09	2.55	4.38	7.03	14.10	19.30
D t/H = 0.25	0.44	0.33	0.00	0.01			
D t/H = 0.5	0.51	0.06	0.00	0.01			
D t/H = 0.75	0.23	0.13	0.01				
D t/H = 1	0.15	0.00					

Height above the cigarette, m

Figure 9. Airflow Q, l/s in the horizontal cross-section of the buoyant plume above a cigarette.

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