Experimental Study of Inlet Openings in Multi-Story Underground Construction

HAUKUR INGASON[1,]* AND PER WERLING[2]

[1]*Swedish National Testing and Research Institute (SP), P.O. Box 857, S-501 15 BORÅS, Sweden*

[2]*Swedish Defence Research Establishment (FOA), Grindsjön, 147 25 Tumba, Sweden*

ABSTRACT: This paper describes an investigation of the effect of inlet openings in a multi-story underground building or station. Smoke filling tests were carried out in a model test rig consisting of a fire compartment and a three-story model structure with horizontal openings between each floor. A 0.25 m × 0.25 m kerosene pool fire was arranged in the fire compartment. The fire compartment and the lowest floor of the three-story model building were connected with a door opening. A shaft was arranged at the top of the fire compartment to make it possible to investigate the spread of smoke from the fire compartment into the three-story building, i.e., the inlet air was drawn down through the horizontal openings at each floor level and into the fire compartment. The height of the shaft was varied, as was the size of the horizontal openings and the door opening. The aim of the work is to determine the critical conditions needed to prevent the smoke from spreading from the fire compartment to the first floor compartment.

KEY WORDS: multi-story underground construction, fire compartment, inlet opening, smoke control, model scale test.

INTRODUCTION

A VERY IMPORTANT FIRE safety feature in underground construction is the ventilation system. The ventilation system creates a smoke-free environment near the floor, which facilitates escape and firefighting. The technique requires a balance between exhausted smoke and inlet air. The size of the inlet openings will govern the efficiency of the smoke exhaust system. In a multi-level underground building, it is often difficult to arrange

*Author to whom corresponding should be addressed. E-mail: haukur.ingason@sp.se

1042-3915/02/02 0079–14 $10.00/0 DOI: 10.1106/104239102024785

inlet openings for smoke evacuation, since the inlet air must be drawn down from ground level. Special arrangements for the inlet openings are required but they may be quite expensive. Examples of multi-story underground construction with such problems are car garages, underground stations or hydro-electric power stations.

If a fire occurs in the lower levels, the hot gases and smoke will spread upwards through the horizontal openings between each floor. In a naturally ventilated system, each floor above the fire origin will be successively filled with smoke. The consequence will be an enormous problem for escape from the lower levels up to ground level.

In many cases, underground structures consist of a multi-story building or station connected to side compartments. If a fire occurs in such compartments, it is not appropriate to evacuate the smoke through the multi-story building or station up to ground level, since it may create problems with evacuation. One way to prevent the smoke from spreading into the multi-story building or station is to install a shaft from the fire compartment. Smoke will then be evacuated directly up to ground level, and hopefully no smoke will spread into the rest of the structure.

The aim of the study is to find the limitation and efficiency of such natural ventilation systems for side compartments in underground structures. Even if underground construction is the motivation for this work, the application of the results is much broader. The focus of the work presented here is on the critical flow conditions preventing smoke from a fire compartment to spread through a door vent. The basic theory is obtained from Heskestad and Spaulding's [1] work on inflow of air required at wall and ceiling apertures to prevent escape of smoke.

This paper describes the experimental and theoretical methods used to estimate the critical flow rate to prevent smoke from spreading to nearby compartments. The size of the shaft, door openings, horizontal floor openings and fire size were all designed in such a way as to make it possible to find the critical conditions for the system to work satisfactorily.

EXPERIMENTAL PROCEDURE

The floor area of the multi-story model building was 2×2 m. The ceiling height of each floor level was 1 m. The adjacent fire compartment measured 2×0.95 m and was 1 m high. The material of the surrounding walls, floor and ceiling of each level consisted of a 12 mm Promatec fiber/silica board – except for the front wall of each level, which consisted of 5 mm thick fire-resistant window glass. One of the short sides (see Figure 1) of the fire compartment was also equipped with a fire-resistant window glass. The shaft consisted of a 1 mm thick circular steel duct, 0.315 m in

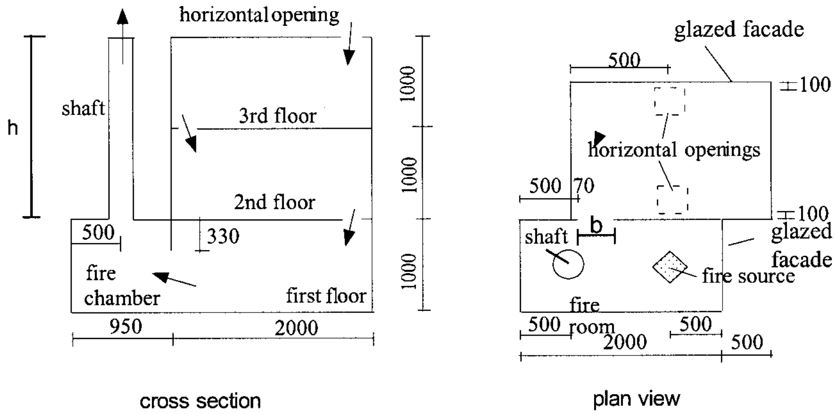

Figure 1. *The test rig used in the study. The positions of the fire source, fire compartment, shaft, horizontal openings and the three-story structure are shown. Two different heights, h, of the shaft were used, 1 and 2 m respectively, and two different door widths, b = 0.33 m and 0.66 m. All units are mm.*

diameter. A hood system was placed above the model test rig in order to evacuate the smoke. The fire tests were carried out indoors. Figure 1 shows a cross section and a plan view of the test rig.

The 1 and 2 m high shaft was mounted on the top of the fire compartment, 0.5 m from the walls. Two different door openings were used, 0.33 × 0.66 m and 0.66 × 0.66 m, respectively. The door was located close (70 mm) to the corner of the multi-story structure, as shown in Figure 1. The horizontal openings between each floor level in the three-story model building were varied as follows: 0.1 × 0.1 m, 0.3 × 0.3 m and 0.6 × 0.6 m, respectively. As a reference test, the entire glazed wall of the three-story building was opened, simulating free access to inlet air. The horizontal openings were arranged in the floors in three different positions. The first floor opening was close to the glazed window, the second adjacent to the fire compartment and the third at the same position as the first floor opening. Rulers were placed inside the model in order to estimate the height of the smoke layer. The smoke layer height was estimated visually through the glazed windows. All the test parameters are shown in Table 1. A total of 15 tests were performed.

The fuel used was kerosene, burned in a square steel pan (0.25 × 0.25 m), and positioned 0.5 m from the walls. For practical reasons, the fuel pan was placed in a diagonal position to the walls (see Figure 1). In order to measure the mass loss rate of the fuel, the pan was placed on a weighing platform located under the Promatec floor. The floor consisted of a 12 mm Promatec silica board. The distance between the Promatec floor and the concrete floor

Table 1. Summary of tests performed in the study.

Test No.	Door opening (m × m)	Openings at different floor levels (m × m) 1st floor	2nd floor	3rd floor	Shaft height, *h*(m)	Smoke-free height (m) Fire com.	1st floor	2nd floor	3rd floor
01	0.33 × 0.67	∞	∞	∞	1	0.52	1	1	1*
03	0.33 × 0.67	0.1 × 0.1	0.1 × 0.1	0.1 × 0.1	1	0	0*	1	1
05	0.33 × 0.67	0.3 × 0.3	0.3 × 0.3	0.3 × 0.3	1	0.35	0	1	1
06	0.33 × 0.67	0.6 × 0.6	0.6 × 0.6	0.6 × 0.6	1	0.40	1	1	1
07	0.33 × 0.67	0.6 × 0.6	0.6 × 0.6	0.6 × 0.6	2	0.43	1	1	1
08	0.33 × 0.67	0.3 × 0.3	0.3 × 0.3	0.3 × 0.3	2	0.36	1	1	1
09	0.33 × 0.67	0.1 × 0.1	0.1 × 0.1	0.1 × 0.1	2	0	0	1	1
10	0.33 × 0.67	∞	∞	∞	2	0.60	1	1	1
11	0.67 × 0.67	∞	∞	∞	2	0.48	0.8	1	1
12	0.67 × 0.67	0.1 × 0.1	0.1 × 0.1	0.1 × 0.1	2	0	0	1	1
13	0.67 × 0.67	0.3 × 0.3	0.3 × 0.3	0.3 × 0.3	2	0.36	0	1	1
15	0.67 × 0.67	0.6 × 0.6	0.6 × 0.6	0.6 × 0.6	2	0.38	0	1	1

1*means 1 m smoke-free height, i.e., no smoke in the room
0*means that the room is full of smoke
∞ one side fully open

of the test hall was 95 mm. Figure 2 shows a schematic figure of the weighing platform and the fuel pan. Four 30 mm diameter stainless steel rods passed through the Promatec floor, transferring the weight of the pan to the weighing platform. The gas temperature close to the load cell did not increase by more than 2°C during the test. The precision of the load cell is ± 1 g.

Extensive work was carried out to obtain a steady mass loss rate during the pool fire tests. Usually, the rim of a fuel pan will be heated up, and the heat balance at the fuel surface will be continuously changing. This will lead to a mass loss rate curve, which is unsteady during the fire test. Preliminary experiments conducted showed that the mass loss rate curve for fuel pans in similar size as used here had a shape similar to a hunchback. A new approach was therefore tried here. The simplest way to do this is by controlling the heat balance at the fuel surface. This can be done by cooling the rim with circulating water. The problem is to find the appropriate geometry of the rim and an appropriate water flow rate. After extensive work, it was found that the best results for the 250 × 250 mm square pan were obtained with a water flow of 2 L/min and a cross-sectional area of the rim of 15 mm width and 50 mm height. The rim itself consisted of a U-profile, measuring 15 × 40 mm, with a 250 × 250 mm steel sheet (the bottom of the fuel pan) welded to the U-profiles. A 10 mm high steel edge was welded to the top of the rim in order to avoid fuel leaking over the edge

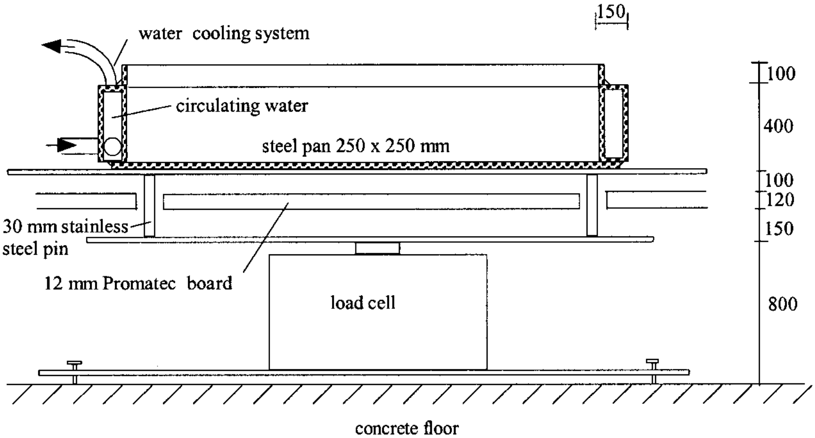

***Figure 2.** A cross-sectional view of the weighing platform and the fuel pan. All units are mm.*

of the rim. Thus, the height of the inner surface of the pan was 50 mm. The water-cooled part was 40 mm. The thickness of the steel used in the rim was 2 mm. A 15 mm waterbed was used in every test and the initial fuel depth for every test was 25 mm. This means that the fuel surface was 40 mm above the bottom of the pan. The temperature of the water flowing into the rim of the fuel pan was 10°C, and the water temperature flowing out from the rim was about 30–35°C. The mass loss rate curve shown in Figure 3 shows that good results were obtained with this robust and inexpensive method. The mass loss rate reached steady state after only one minute and was kept steady for about 9 min for all the tests. The mass loss rate decreased relatively sharply just before the fuel was fully consumed after more than 10 min from ignition.

The position of the instruments used is shown in Figure 4. The measured quantities were the mass loss rate of the fuel, the gas temperatures, the optical density, the oxygen concentration in the shaft and the velocity of the hot gases in the shaft and the horizontal openings. All measurements were registered every two seconds. The test time was 10 min. The gas temperature was measured by thermocouples arranged 0.15 m apart along a vertical line. At each level, this vertical line was positioned 0.33 m from the nearest wall along the centerline of the level. The same type of thermocouple was used in the fire compartment, on both sides of the fire source. All thermocouples were welded type K, with a wire diameter of 0.25 mm. The optical density was measured on all three levels on the same vertical line at a height 0.85 m above the floor. The optical density measuring equipment used consisted of smoke extinction meters over a path length of 2 m, which was also the depth of the compartments. The device itself consists of a lamp, a

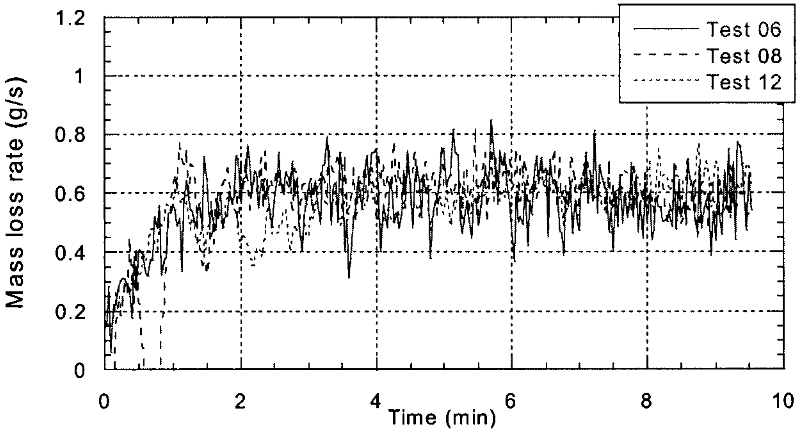

Figure 3. *Mass loss rate measurement from three different tests with three different inlet opening sizes. The mass burning rate stabilized after only one minute. A list of experiments is given in Table 2.*

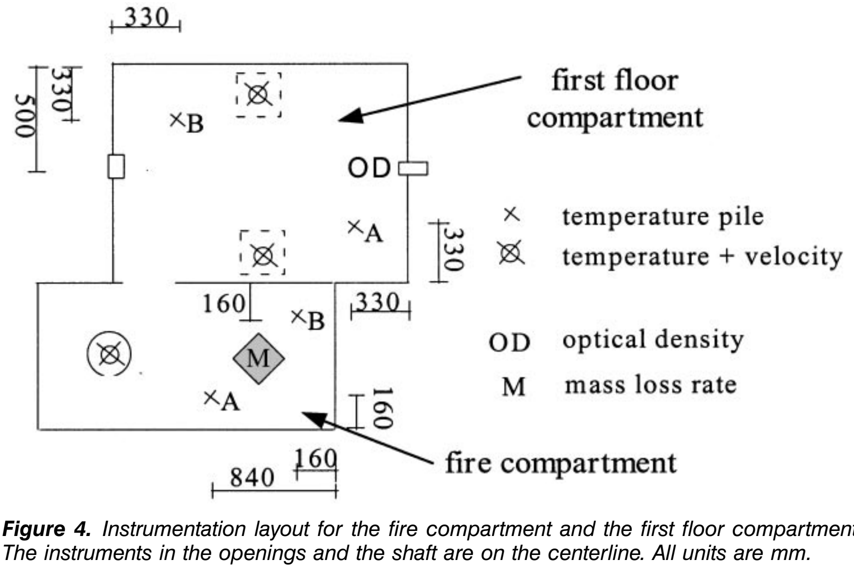

Figure 4. *Instrumentation layout for the fire compartment and the first floor compartment. The instruments in the openings and the shaft are on the centerline. All units are mm.*

lens and a photocell. The lamp is of halogen type and the lens aligns the light to a parallel beam. The intensity of the beam, and any reduction, is then measured by the photocell. The centerline gas temperature and gas velocity were measured at the top of the shaft. A differential pressure probe (bi-directional probe) was used to measure the velocity, see McCaffrey and

Heskestad [2]. The oxygen concentration in the shaft was measured using an open steel tube with a diameter of 6 mm and an oxygen analyzer of type PMA 10 from M&C Instruments.

THEORETICAL ASPECTS

Using model scale experiments is an effective way to obtain approximate answers concerning smoke spread in buildings in large scale. In the present study, the data can be considered in the context of Froude number (*Fr*) modeling [1]:

$$Fr = \frac{u}{\sqrt{2gH\Delta T/T}} \tag{1}$$

where u is the air velocity at the door opening, H is the aperture height and $\Delta T = T - T_0$ where T is the temperature at the top of the aperture. Froude modeling is only possible for situations in which viscous forces are relatively unimportant. Constancy of the Froude number requires that velocities are scaled relative to the square root of the characteristic length (height in this case). If the geometric similarity is conserved, the heat release rate, Q, must be scaled relative to the 5/2 power of the characteristic length and the temperature is reproduced from scale to scale. Accordingly, the results obtained in this study can be transformed to large-scale situations provided that geometrically similar construction is used.

The aim of the work is to find the critical conditions needed to prevent the smoke from spreading from the fire compartment to the first floor compartment. If, however, the smoke does spread from the fire compartment, it is also of interest to know the critical flow conditions needed to prevent the smoke from spreading further from the first floor compartment to the second floor compartment. The air velocity through the door opening must exceed a critical value in order to prevent the smoke from spreading from the fire compartment through the door opening and into the first floor compartment. An estimate of this critical velocity can be obtained from Heskestad and Spaulding [1] for wall apertures:

$$Fr_c = \frac{u_c}{\sqrt{2gH\Delta T/T}} \tag{2}$$

where Fr_c is the critical Froude number, u_c is the critical air velocity, H is the aperture height (the door opening, in this case) and $\Delta T = T - T_0$ where T is the temperature at the top of the aperture. Heskestad and Spaulding [1] give the following expression for the critical Froude number:

$$Fr_c = CP \tag{3}$$

where C is the discharge coefficient for the aperture and P is a temperature distribution parameter for the hot space [1]. For a uniform vertical temperature profile, P is equal to 2/3. For values of P varying from 0.53 to 0.67, Heskestad and Spaulding [1] found the critical Froude number to vary from 0.32 to 0.43 for numerous types of wall apertures. The range in P from 0.53 to 0.67 may cover most practical cases, from highly non-uniform vertical temperature profiles at low heat release rates to nearly uniform profiles at high heat release rates. Equation (3) is most appropriate for the case where the aperture extends from the floor to the ceiling and where the cold air flows from the surrounding space through the aperture into the hot (fire) space, forming a jet into the fire space which has a *vena contracta* considerably narrower than the width of the aperture [1]. If the aperture does not extend from floor to ceiling, as in the present study, there are difficulties with the simple theory since it cannot be assumed that there is no contraction of the cold jet into the hot space in the vertical direction. However, Heskestad and Spaulding [1] expect Equation (3) to be applicable for such cases, but with a different value of C.

The critical velocity in the horizontal openings (ceiling apertures) can be estimated from the following equation [1]:

$$Fr_c = \frac{u_c}{\sqrt{2gW\Delta T_l/T}} \tag{4}$$

where W is the width of the opening (the smaller dimension in rectangular apertures), and $\Delta T_l/T$ is evaluated at ceiling level (away from the thermal boundary layer at the ceiling). Here $\Delta T_l = T_l - T_0$ and $T = T_l$. There are two distinct critical Froude numbers appearing, depending on the Grashof number given below:

$$Gr = \frac{g\rho_0^2 W^3 \Delta T_l/T}{\mu^2} \tag{5}$$

where μ is the dynamic viscosity and ρ_0 is the density in the quiescent cold space. Heskestad and Spaulding [1] show the effect of the Grashof number on the critical Froude number. In this case, there is a definite effect of the Grashof number, with a high Grashof number asymptote close to $Fr_c = 0.23$

and for an apparent low Grashof number asymptote close to $Fr_c = 0.38$, separated by a transition range.

TEST PROCEDURE AND RESULTS

The parameters varied in the study were the height of the shaft, the size of the inlet openings and the size of the door opening to the fire compartment. The smoke spread between the fire compartment and the first floor in the building was both visually observed and measured. The optical density was measured on all three planes in order to quantify the amount of smoke spreading from the fire compartment. A summary of the test program and the visually observed smoke-free heights are given in Table 1.

Other measured and calculated quantities are shown in Table 2. The values are based on a simple arithmetic 5-min average applied at the end of the test, except for the last minute, which is excluded. Despite steady state burning rate after only 1 min from ignition, the gas temperature conditions in the room will not become steady state until after more than 4 min from ignition. This can be observed in Figure 5 which shows both the gas temperatures in the fire compartment at Measuring Point B and the gas temperature in the shaft in Test 08.

In Table 2, m_f is the mass loss rate of the fuel in g/s and Q is the heat output based on a value of effective heat of combustion, ΔH_c, multiplied by m_f. The value of ΔH_c for kerosene was obtained by using a cone calorimeter [2]. A sample of 39 g of the kerosene was tested in the cone without any external heat radiation. For practical reasons, the sample was placed in a semi-spherical cup with a diameter of 90 mm. 4.5 g of heptane was used in order to assist ignition of the kerosene. The measured average effective heat of combustion, ΔH_c, was 39.5 MJ/kg. This value was used to calculate the heat release rate, Q, by multiplying the mass loss rate and ΔH_c, see Table 2.

The gas temperatures T_A and T_B are the average gas temperatures at Measuring Points A and B in the fire compartment, 0.825 m above the floor (see Figure 4). This height corresponds to half the distance between the top of the fire compartment (1 m) and the top of the aperture (door opening at 0.67 m). As the height of the aperture (door opening) was not the same as the ceiling height, which the theory requires, this value was assumed to be a good compromise. This can be justified as the calculation of P according to the method given by Heskestad and Spaulding [1] yields a value of $P = 0.63$ for Test 08, which is relatively close to the case with uniform temperature distribution, $P = 2/3$. The gas temperature in the shaft, T_s, is based on the centerline temperature at the top of the shaft. T_l is the average temperature at Measuring Point B (theory requires temperature at the ceiling) on the first

Table 2. Experimental and calculated results.

Test No.	m_f (g/s)	Q (kW)	T_0 (°C)	T_A (°C)	T_B (°C)	T_s (°C)	T_l (°C)	u_s (m/s)	u_h (m/s)	m_s Equation (6) (kg/s)	u_d Equation (7) (m/s)	*Fr* door Equation (1)	*Fr* ceiling opening Equation (4)	OD_1 (L/m)
01	0.55	21.7	19.0	121.0	115.7	126.6	20.20	2.59	–	0.155	0.91	0.53	–	0.003
03	0.46	18.2	19.7	200.4	144.9	150.2	77.7	1.09	−2.01	0.062	0.37	0.17	15	1.93
05	0.57	22.5	20.7	184.7	147.0	146.5	38.3	2.00	−1.10	0.113	0.67	0.33	3.0	0.20
06	0.59	23.3	19.4	154.2	139.1	137.9	20.9	2.61	−0.45	0.152	0.89	0.47	2.4	0.06
07	0.94	37.1	20.4	167.7	178.0	167.2	20.7	3.73	−0.60	0.201	1.18	0.60	7.1	0.02
08	0.62	24.5	21.1	167.7	156.0	147.9	21.0	2.63	−1.43	0.149	0.88	0.45		0.01
09	0.53	20.9	20.8	212.0	161.5	155.1	70.3	1.50	−2.72	0.083	0.49	0.23	22	1.41
10	1.26	49.8	21.8	190.9	196.1	176.0	28.4	4.09	–	0.217	1.28	0.62	–	0.001
11	0.71	28.0	19.9	130.0	123.4	128.9	34.1	3.66	–	0.217	0.63	0.35	–	0.02
12	0.61	24.1	21.3	231.4	170.2	165.0	100.0	1.63	−2.69	0.089	0.25	0.12	19	1.58
13	0.70	27.6	23.5	205.0	155.1	151.7	58.4	2.83	−1.43	0.158	0.46	0.22	3.1	0.31
15	0.85	33.6	21.3	166.1	152.0	152.9	37.0	3.89	−0.66	0.218	0.63	0.32	1.1	0.13

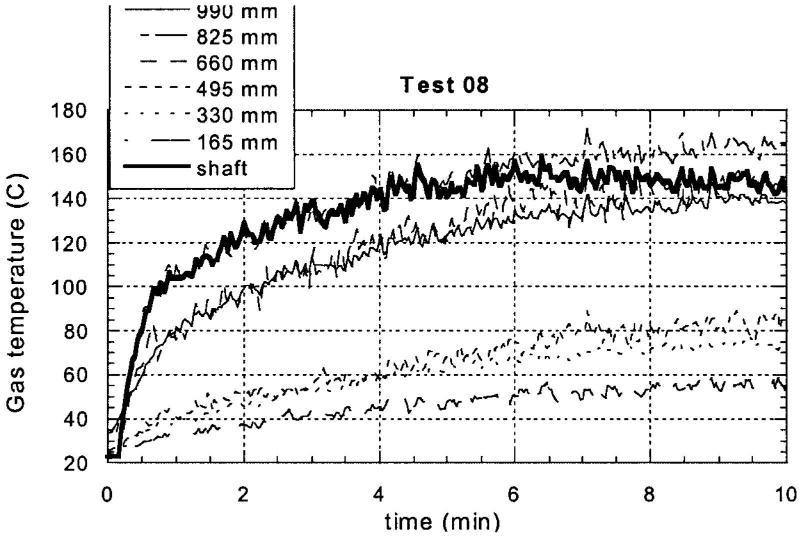

Figure 5. Gas temperature in the fire compartment at Point B at six different heights and in the shaft for Test 08. The average values in Table 2 are for a 5 min time period from the 4th to the 9th min of the tests.

floor compartment at ceiling height (0.99 m above floor, see Figure 4), u_s is the centerline velocity at the top of the shaft, and u_h is the velocity at the horizontal opening between the first and second floors. Negative values indicate that the direction of flow is from the second floor to the first floor. u_d is the calculated velocity through the door opening into the fire compartment, based on the mass flow rate, m_s, obtained in the shaft. The mass flow rate is obtained from the following equation:

$$m_s = 0.87\frac{\rho_0 T_0}{T_s} u_s A_s \tag{6}$$

where 0.87 is the flow coefficient for a circular tube with fully developed turbulent flow and A_s is the cross-sectional area of the shaft. The velocity, u_d, through the door opening is obtained from the following equation:

$$u_d = \frac{m_s}{0.64\rho_0 A_d} \tag{7}$$

According to Heskestad and Spaulding [1], the discharge coefficient is 0.64 for wall apertures (door opening). A_d is the geometrical area of the door opening. The Froude number, Fr, for the door is obtained from Equation (1) using the temperature $T = (T_A + T_B)/2$ and $\Delta T = (T - T_0)$, $H = 0.67$ m, i.e., the height of the door opening as proposed by Heskestad and Spaulding [1] when the aperture is lower than the ceiling height, and $u = u_d$. Fr in the ceiling opening is obtained from Equation (4), where $T = T_l$ and $\Delta T_l = (T_l - T_0)$, W is the width of the opening and $u_c = u_h$.

It can be seen from Table 1 that the height of the smoke-free layer in the fire compartment varies in most cases between 1/2 the door height up to 3/4 of the full door height (0.67 m). As the size of the horizontal opening is reduced, the smoke-free height and velocity (u_d) are reduced but the temperature remains constant. This can be seen in Table 2. As the openings are reduced in size, the pressure losses over the openings increases and the exhaust flow through the shaft will decrease. Consequently, the velocity through the door opening will decrease and there will be a greater risk of smoke spreading. With the lower shaft height (1 m), the smoke spread from the fire compartment and filled the first floor level with smoke for half of the cases. When there was free access to air, i.e., one side fully open (∞ in Table 1) and when the horizontal opening was 0.6 by 0.6 m, no spread was observed to the first floor compartment. When the shaft height was increased to 2 m, the smoke did not spread back into the first floor compartment except for the smallest size of horizontal opening (0.1×0.1 m). This shows that the height of the shaft as well as the geometrical openings plays an important role in the efficiency of preventing the smoke spread.

This study shows that the critical Froude number in the vertical door opening must exceed a value of 0.4, as can be seen from Figure 6, in order to prevent the spread of smoke from the fire compartment into the rest of the structure. This value of Fr_c is in the range given by Heskestad and Spaulding [1], i.e., Fr_c is in the range of 0.32–0.43. Further, it can be shown that Equation (3) yields a critical Froude number equal to 0.4 for the door opening using $C = 0.64$ and $P = 0.63$ (calculated for Test 08). This shows that a critical Froude number of 0.4 for this type of configuration as used here is reasonable.

In no case did the smoke spread from the first floor compartment to the second or third floor compartments. This means that the critical value of Fr in the horizontal openings cannot be determined from the experimental data using Equation (4). However, it can be seen that the values given by Heskestad and Spaulding [1], i.e., $Fr_c = 0.23$ or 0.38 depending on the Grashof number, are much lower than the Fr values given in Table 2 ($F_r = 1.1$–22). This indicates that, under no circumstances, was there a risk for the smoke to spread from the first floor compartment to the second floor compartment.

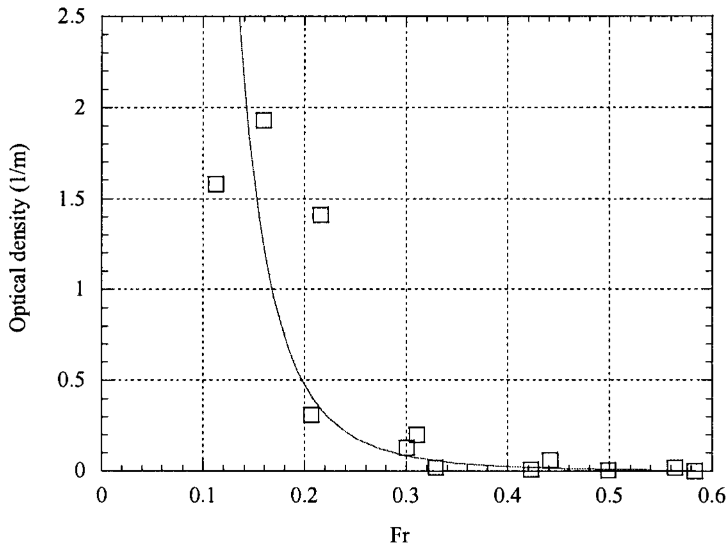

Figure 6. *Measured optical density at the first floor (0.85 m) vs. calculated Froude number from Equation (1). The Froude number is for the door flow.*

CONCLUSIONS

The effect of inlet opening sizes in a multi-story underground building or station was studied. The work was done using a model test rig with a fire compartment and vertical chimney shaft, drawing its combustion air downwards through a three-story model building. The inlet air was drawn through horizontal openings at each floor in the building and into the fire compartment. The height of the shaft was varied, as were the sizes of the horizontal openings and the door opening. The study shows that the critical Froude number in the door opening must exceed 0.4 in order to prevent the smoke from spreading from the fire compartment backwards into the multi-story building. This value is in good agreement with the semi-empirical theory founded by Heskestad and Spaulding [1].

No smoke spread was observed through the horizontal openings between the floor heights. The system of using a shaft to prevent smoke from spreading through the underground building is found to work satisfactorily, assuming that the fire starts in the same room as that from which the shaft rises.

The results obtained in this study can be transformed to large-scale situations provided that geometrically similar construction is applied.

NOMENCLATURE

A_s	area of the shaft, h is the shaft height (m^2)
C	discharge coefficient for the aperture
Fr	Froude number
Fr_c	critical Froude number
Gr	Grashof number
H	aperture height (m)
ΔH_c	effective heat of combustion (MJ/kg)
m_f	mass loss rate of the fuel (kg/s)
m_s	mass flow rate of combustion gases in the shaft (kg/s)
Q	chemical heat release rate (kW)
P	temperature distribution parameter for the hot space
T	temperature at the top of the aperture (the door) (°C)
T_A	average gas temperatures at Measuring Point A in the fire compartment (°C)
T_B	average gas temperatures at Measuring Point B in the fire compartment (°C)
T_l	average gas temperature at ceiling (°C)
T_0	ambient temperature (°C)
ΔT	$T - T_0$ (°C)
W	width of the opening (the smaller dimension in rectangular apertures) (m)
u_c	the critical air velocity (m/s)
u_d	the calculated velocity through the door opening into the fire compartment (m/s)
u_h	the velocity at the horizontal openings (m/s)
u_s	the centerline velocity at the top of the shaft (m/s)
ρ_c	density in the quiescent cold space (kg/m^3)
ρ_0	ambient density (kg/m^3)
μ	dynamic viscosity (kg/m s)

REFERENCES

1. Heskestad, G. and Spaulding, R., "Inflow air required at wall and ceiling apertures to prevent escape of fire smoke", In: *Fire Safety Science. Proceedings of the 3rd International Symposium*, 1991, pp. 919–928.
2. McCaffrey, B.J. and Heskestad, G., "A robust bi-directional low-velocity probe for flame and fire application", *Combustion and Flame*, Vol. 26, 1976, pp. 125–127.