An Experimental Study of the Smoke Spread in a Two-Plane Compartment

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Abstract
Smoke spread tests were carried out in a two-plane compartment. The size of each plane was 5.6 x 5.6 x 3.0 m high. The fuel was kerosene burnt in square steel pans in the bottom plane. The parameters varied were the fire size, ceiling vent and the opening between the planes. Experimental data measured were the smoke-free height, temperature, mass flow, optical density and the oxygen concentration. Calculated data by zone and computational fluid dynamics (CFD) models were compared with the measured data from some test runs.

1. Background

In multi-level buildings, composed of two or more planes, there are in many cases horizontal openings between the planes. Such buildings are, for example, atriums and shopping malls but also garages, basements, hydro-electric stations and other underground facilities. The openings between the levels are arranged for stairs and ramps or for lifting and ventilation facilities. If a fire occurs at the bottom of such a building the smoke and hot gases spread upward through the planes and fill the building with smoke. Besides the fire plume at the bottom plane of the building secondary plumes are created at the other planes by the hot gases flowing through the horizontal openings. As is important for the fire plume, which must be fed by air in order to get a smoke-free height in the fire compartment, the secondary plumes must also be fed by air in order to get smoke-free heights in the other planes of the building.

One method to prevent a multi-level building from being filled with smoke is by using natural fire ventilation of the building. Smoky gases are removed through the horizontal openings at the ceiling level of each plane and air is provided by inlets at low levels to replace the hot gases leaving the plane through the ceiling vent. That means that each plume, the fire plume as well as the secondary plumes, must be fed by air through the inlets in order to get smoke-free heights in the planes.

An experimental study of the smoke filling process in a two-plane compartment was carried out [1]. Both full-scale and 1/3-scale fire tests of the same configuration were performed. In the present paper the measured data of the full-scale test series are presented. The size of each plane was 5.6 x 5.6 x 3.0 m high. The fuel was kerosene burnt in square steel pans in the bottom plane.

The main purpose of the experimental work was to study how different factors affect the smoke-free height in the upper plane when a fire occurs in the bottom plane. Another purpose of the work was to generate experimental data to be compared with fire modeling techniques. In the present paper the calculated data by zone and CFD models are compared with the measured data from some test runs.

2. Experimental layout

The side and plan view of the test compartment is shown in Figure 1. The material of surrounding walls of the two planes was concrete. Also the floor of the lower plane and the ceiling of the upper plane was composed of concrete. The slab between the two planes was composed of 12 mm Promatec fibre-silica board. In the figure is shown the position of the fire source, the ceiling vent and the vent opening between the two planes.

2.1. Fire sources

Kerosene was burnt in square steel pans of two different sizes in the lower plane. The fuel pans were placed on a weighing platform 0.55 meter above the floor, measuring the mass loss rate during the burning. The platform was protected from heat by insulation boards. The rim height of the fuel pans was 60 mm. The fuel pans including the rims were protected from heat by cooling the pan and the rims by circulating water. Referring to Figure 1 the distance between the wall and the nearest edge of the fuel pan was 0.75 m, independent of the fuel size. The following fuel sizes were used:

* 0.50 x 0.50 m (0.25 m^2)
* 0.75 x 0.75 m (0.56 m^2)

The fires showed a typical pool-fire burning: a build-up period of the mass burning rate which lasted for about 1 minute and a steady-state period during which the burning rate maintained at a constant, maximum value. The measured average values of the burning rate during the steady-state period are given below. Both the total mass and heat release rates and the corresponding values per unit horizontal fuel area are given. The value of the effective heat of combustion was assumed to be 30 MJ/kg, independent of the fuel size [2,3]. No measurements of the heat value were made. The fires were assumed to be well ventilated, i.e. there was no restriction on the ventilation for the fires.

Fuel size	Total mass and heat release rate	Mass release rate per unit horizontal area	Heat release rate per unit horizontal area
* 0.50 x 0.50 m	6 g/s (180 kW)	24 g/(m^2·s)	720 kW/m^2
* 0.75 x 0.75 m	14 g/s (420 kW)	25 g/(m^2·s)	750 kW/m^2

2.2 Ventilation

The ventilation conditions were defined by the following openings:

* the horizontal opening in the ceiling slab
* the horizontal opening in the slab between the planes
* the vertical inlet openings near the floor of each plane

2.2.1 Ceiling opening
The horizontal ceiling vent was varied as follows. The opening was positioned centrally in the ceiling slab.

* 1.0 x 1.0 m (1 m^2)
* 2.0 x 1.0 m (2 m^2)
* 2.0 x 2.0 m (4 m^2)

2.2.2 Opening between the planes
Two following sizes of the horizontal opening between the planes was used:

* 1.0 x 0.5 m (0.5 m^2)
* 1.0 x 1.0 m (1.0 m^2)

For the smaller opening the distance between the wall and the nearest edge of the opening was 0.6 m. For the bigger opening the corresponding value was 0.1 m.

2.2.3 Inlet openings
Four inlet openings were positioned at each plane at floor level, as shown in Figure 1, near each corner of the plane. The distance between the corner and the nearest edge of the opening was 0.2 meter. Each opening measured 2.0 x 0.5 m high.

2.3 Instrumentation
Measured quantities were the mass loss rate of the burning fuel, the gas temperature, the optical density, the oxygen concentration and the velocity of the hot gases through the horizontal openings. The measurements of the inflow of air into the planes through the vertical inlets were also made, giving low and, hence, uncertain values of the velocities. These values are not given in the present paper.

The position of the measuring points for temperature, optical density and oxygen concentration is shown in Figure 1. The gas temperature was measured by thermocouples distributed over a vertical line on a 0.50 m spacing. The vertical line was positioned at each plane at the distance of 1.0 m from the nearest wall along the central line of the plane. At the same line at height 2.5 m above floor the optical density and oxygen concentration were measured in the two planes. The optical density was measured over the path length of 1 m.

The velocity of the hot gases at the opening between the planes and at ceiling vent was measured by means of differential pressure probes and thermocouples mounted centrally at each opening. The probes were of the bidirectional type as described by McCaffrey and Heskestad [4].

The oxygen concentration was measured at each plane by probes consisting of an open steel tube of the diameter 6 mm. The measurements were carried out by using an oxygen analyser of type PMA 10 from M & C Instruments.

The optical density was measured at each plane by a smoke extinction meter over the path length of 1 m. The measuring device consists of a lamp, lens, windows and a photocell. The lamp is of the tungsten filament type. The lens aligns the light to a parallell beam. The photocell measures the reduced intensity of the light beam. The windows protect the interior of the meter from heat and smoke. Water cooling of the probe is provided, which allows the probe to be inserted into a heated atmosphere. Air is forced through the meter to prevent the deposition of soot on the windows during the test. The optical density per path length (OD) is defined by

$$OD = 1/L \cdot \log_{10}(\frac{I_0}{I}) = 1/L \cdot \log_{10}(\frac{100}{T})$$

where the initial light intensity of I_0 is reduced to a value of I over the path length L, resulting in T percent transmission. The unit for OD is m^{-1}.

During each test a video camera was recording the smoke layer heights in the upper plane. As reference the camera was facing measuring sticks hanging from the ceiling. Also visual estimates of the smoke layer height were made during each test run by observers.

3. Measured results

Twenty-one test runs were carried out based on different fuel sizes and ventilation conditions. Some tests were repeat runs. The tests were performed in calm weather. In some tests, however, external wind conditions affected the stability of the established smoke layers. Especially the smoke layer of the upper plane was easily influenced by external wind, even if the wind speed was at very low values. These tests influenced by wind are not presented in the present paper.

In Table 1 the average values of the measured quantities are given - for the period of approximately steady-state conditions. In Figures 2-6 the measured values of the smoke-free height, smoke layer temperature and mass flow through openings are displayed as a function of the fire size and the area of the horizontal openings. The smoke layer temperature denotes the average temperature value of the smoke layer. The mass flow values are based on the velocity values measured centrally at the opening. The flow coefficient is assumed to be 0.6 and the density of the hot gases is based on the temperature values measured near the ceiling.

The smoke-free heights were determined by video recordings and by visual estimates by observers. Stratified smoke layers were established in both planes, uniformly distributed in the upper parts of the planes. In the lower plane, the fire compartment, there was a distinct interface between the air and the hot smoke layer. In the upper plane the smoke layer surface was uneven and rough and a sharp interface between the air and the smoke layer was not observed. Also, for the smallest fuel size and the smallest opening between the planes, the smoke in the upper layer became thin and the interface between smoke and air was difficult to observe. The interface between air and smoke in the upper plane also became diffuse due to mixing of air and smoke near the inlet openings.

4. Comparing calculated data with measured data

Calculated data by zone and CFD models are compared with the measured data from some test runs. A rough comparison is presented. More work will be done in comparing the measured data with the calculated data of fire modeling techniques.

In the calculations the size of each plane is 5.6 x 5.6 x 3.0 meter high. The fire size is 420 kW. The area of the opening between the planes is 1 m^2 and the ceiling vent ranges from 1.0 to 4.0 m^2. The total area of the four inlets at each plane is 4 m^2. For both modeling techniques a free burning fire is assumed, i.e. sufficient oxygen needed for the burning is entrained into the burning zone.

4.1 Calculated results - zone model

The zone model calculations are based on CFAST, version 2.0, in the environment of the HAZARD I package [5]. Sometimes in fire safety engineering calculations the horizontal openings in a two-plane configuration - when using a zone model - are replaced by vertically oriented openings near the ceiling level of each plane. One reason for that may be that horizontal openings are not inserted into the model used. In the calculations presented here the two cases of ventilation are treated, i.e. the ceiling opening and the opening between the planes are assumed to be horizontally or vertically oriented. In the latter case the vertical openings are assumed to be near the ceiling level of each plane and of height 0.5 meter.

The calculated results - for the period of approximately steady-state conditions - are displayed in Figure 7 as a function of the ceiling opening. For the lower plane (fire compartment) the calculated values of the smoke-free height and temperature compare well with the measured values. For the upper plane - and for the case of vertically oriented openings - there is a good agreement between the calculated and measured values of the smoke-free height. For the case of horizontally oriented openings there is a bad agreement.

4.2 Calculated results - CFD model

The CFD calculations are based on the code CFX 4.1 [6]. The fire was modelled using a volumetric heat source represented by the experimental heat release data as a function of time. The soot concentration and optical density were calculated using a given soot yield value implemented in the cells of the volumetric heat source. The soot yield was assumed to be 0.06, corresponding to the effective value of 200 m^2/kg for the smoke potential of kerosene [2]. Radiative heat transfer was not modelled in the calculations except for the reduction of the experimental heat release rates by 25 percent due to the radiative heat loss from the fire plume. Isothermal walls were assumed. The turbulence was modelled using the k-ε model. The use of a symmetry plane down the central line of the two planes meant that only half the volume of the two-plane configuration was modelled. The computational domain consisted of 75 000 cells.

In Figure 8 the calculated smoke-free heights are compared with the measured data for the period of approximately steady-state conditions. The calculated values agree reasonably well with the measured data. In the lower plane (fire compartment) the calculated smoke-free heights are lower than the measured values.

In Figures 9-10 the calculated values of the temperature are plotted along two vertical planes of the test configuration for two values of the ceiling vent: 2 and 4 m^2. The same tendencies as observed in the experimental tests are shown by the calculated data in the the figures. In the lower plane there is a distinct interface between the air and the hot smoke layer. In the upper plane the smoke layer surface is uneven and rough and a sharp interface between the air and the smoke layer is not observed. The plots of the optical density are not given in the present paper.

5. Summary and conclusions

Experimental smoke spread tests were carried out in a two-plane configuration. The fuel was kerosene burnt in square steel pans in the bottom plane. The parameters varied were the fire size, ceiling vent and the vent opening between the planes. Experimental data given are the smoke-free height, temperature, mass flow, optical density and the oxygen concentration - for the period of approximately steady-state conditions.

Calculated data by zone and CFD modeling techniques were compared with the measured data from some test runs. Using a zone model the calculated values of the smoke-free height and temperature in the lower plane (fire compartment) agree well with the measured data. There is also a good agreement for the upper plane if the ceiling opening and the opening between the plane are treated as vertical openings in the calculations. If horizontal openings are applied there is a bad agreement between calculated and measured data. Using a CFD model there is a reasonable agreement between the calculated and measured values of the smoke-free height. More work will be done in comparing the measured data with the calculated results of zone and CFD models.

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ACKNOWLEDGEMENTS

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TABLE 1

Fuel size, Average hot layer temperature of plane 1 and 2, Smoke-free height of plane 1 and 2, Optical density of plane 1 and 2, Oxygen concentration of plane 1 and 2 and Velocity and temperature of hot gases measured centrally at the horizontal openings between the planes and at ceiling level.

TEST NO (Vent between planes/ceiling vent, m²)

Fuel size	TEMP (°C) plane1/plane2	SMOKE-FREE HEIGHT (m) plane1/plane2	OD (1/m) plane1/plane2	O_2 (vol %) plane1/plane2	VELOCITY, TEMP (m/s, °C) between planes/ceiling
Test 200 (0.5/2.0)					
0.50x0.50 m	110/40	1.75/1.0-1.25	1.8/--	--/--	2.8/2.0 (130/40)
Test 201 (1.0/2.0)					
0.50x0.50 m	90/35	2.25/0.75	1.2/0.4	19.9/20.6	2.3/2.2 (100/45)
Test 202 (1.0/4.0)					
0.50x0.50 m	90/30	2.25/1.0	1.1/0.3	20.1/20.8	2.3/1.7 (110/35)
Test 203 (0.5/4.0)					
0.50x0.50 m	100/30	2.0/1.5-2.0	1.6/0.3	19.4/20.8	2.8/1.5 (120/35)
Test 204 (0.5/2.0)					
0.75x0.75 m	200/50	1.5/0.5	3.5/1.0	17.5/20.1	4.5/3.0 (240/65)
Test 205 (0.5/2.0)					
0.75x0.75 m	180/50	1.5/0.5-1.0	2.8/1.2	--/--	4.0/2.5 (200/55)
Test 206 (0.5/2.0)					
0.75x0.75 m	190/50	1.5/1.0	3.2/1.0	17.4/20.0	--/--
Test 207 (1.0/2.0)					
0.75x0.75 m	180/60	2.0/0.5-1.0	--/0.9	--/--	3.1/3.0 (190/70)
Test 208 (1.0/4.0)					
0.75x0.75 m	160/50	2.0-2.25/1.0-1.25	--/0.7	19.1/20.4	3.0/2.6 (170/55)
Test 209 (0.5/4.0)					
0.75x0.75 m	190/45	1.5-1.75/1.0-1.25	--/0.8	18.2/20.4	4.0/2.3 (220/50)

Test 210 (0.5/2.0)					
0.75x0.75 m	180/60	1.5/1.0	--/1.0	--/--	--/--
Test 211 (1.0/2.0)					
0.75x0.75 m	160/50	2.0-2.25/1.0	--/1.0	18.9/20.0	2.8/2.9 (180/60)
Test 212 (2x0.5/2.0) */					
0.75x0.75 m	160/55	2.0/0.75	--/1.0	19.2/20.4	3.3/3.0 (170/60)
Test 213 (1.0/2.0) **/					
0.75x0.75 m	160/55	2.0-2.25/1.0-1.5	--/0.9	19.1/20.3	3.0/2.8 (180/60)
Test 214 (1.0/4.0) ***/					
0.75x0.75 m	160/90	2.0/0.0	--/1.6	19.4/19.4	4.0/-- (160/90)
Test 215 (1.0/1.0)					
0.75x0.75 m	160/60	1.75/0.25	--/1.8	18.8/19.7	3.3/4.1 (180/75)
Test 216 (0.5/1.0)					
0.75x0.75 m	200/60	1.5/0.25	--/1.5	17.4/19.4	4.2/4.0 (220/75)
Test 218 (1.0/1.0)					
0.50x0.50 m	90/45	2.0/0.5	--/0.6	20.2/20.5	1.8/3.3 (95/50)
Test 219 (0.5/1.0)					
0.50x0.50 m	100/45	1.75/1.0	--/0.7	19.7/20.4	2.6/3.2 (110/50)
Test 220 (1.0/4.0)					
0.50x0.50 m	80/35	2.25/1.25-1.50	--/0.3	20.2/20.7	--/--
Test 221 (0.5/4.0)					
0.50x0.50 m	--/--	2.0/1.5	--/--	--/--	--/--

--/-- The measurements failed.

*/ Instead of one opening there were two openings (2 x 0.5 m2) between the planes. The distance between the openings was 1.5 meter. For the opening near to the wall the distance between the wall and the opening was 0.6 meter. The velocity was measured at the opening located near to the wall.

**/ The opening between the planes (1 m^2) was located 2.0 meter from the wall.

***/ The inlet openings in the upper plane were closed during the test run. The upper plane was filled with smoke approximately 60 seconds after fire start. The steady-state smoke-free height in the lower plane was 2.0 meter.

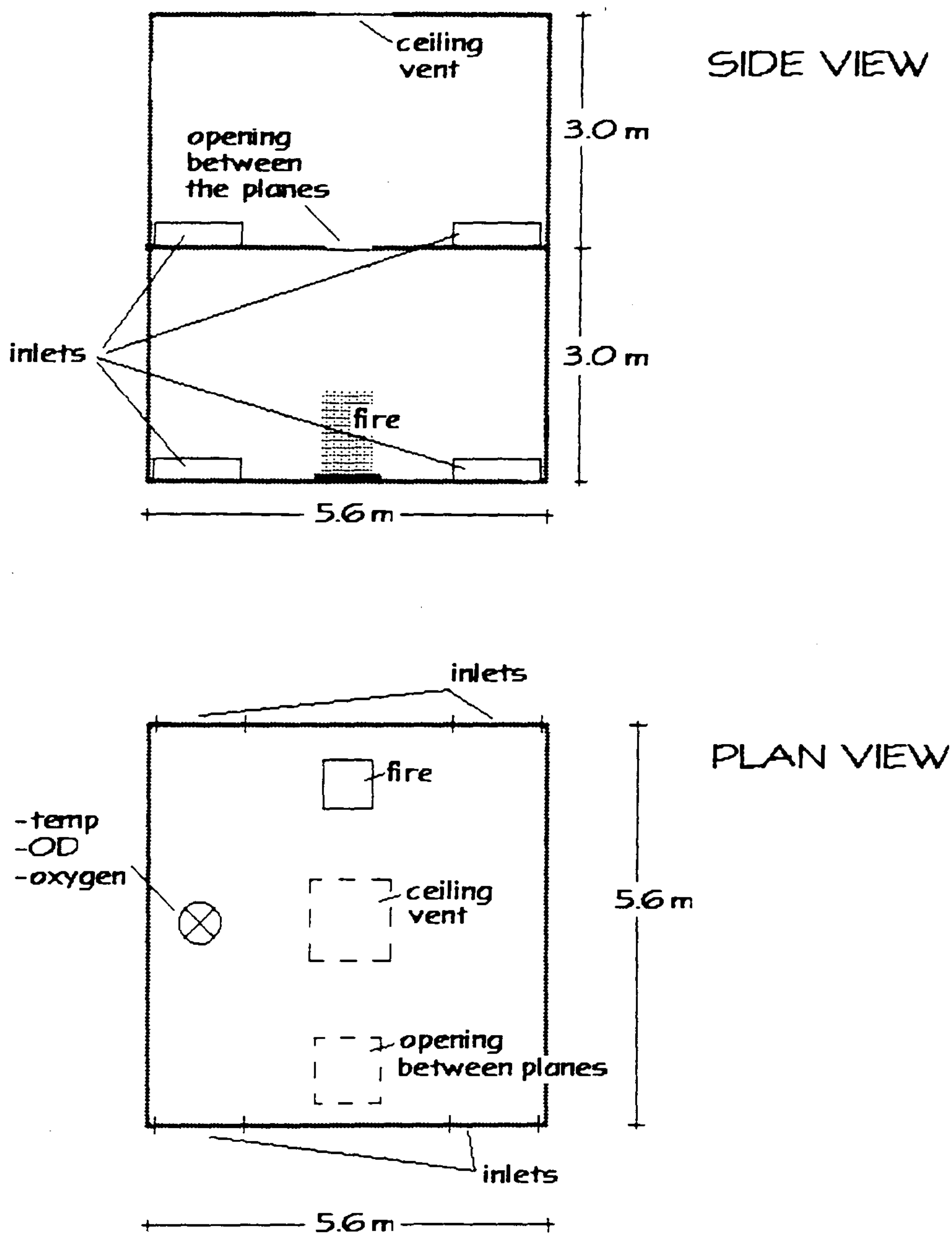
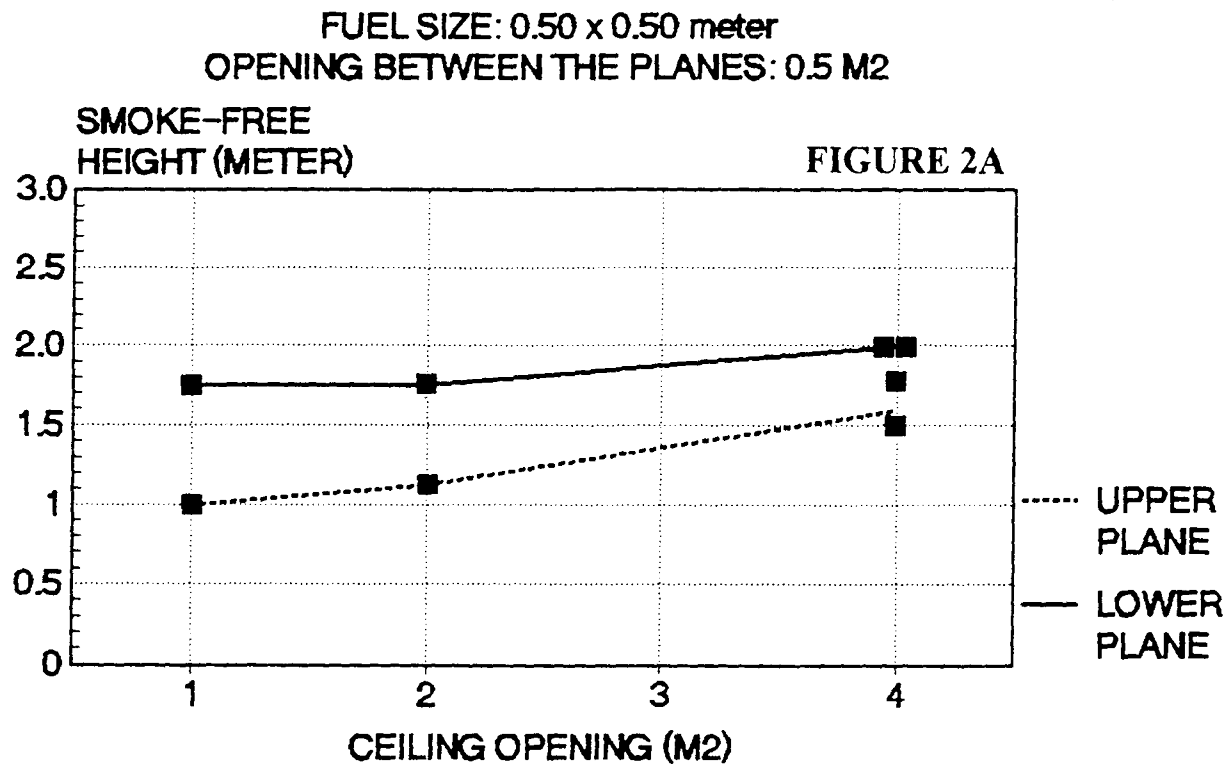


Figure 1. Test geometry and instrumentation.



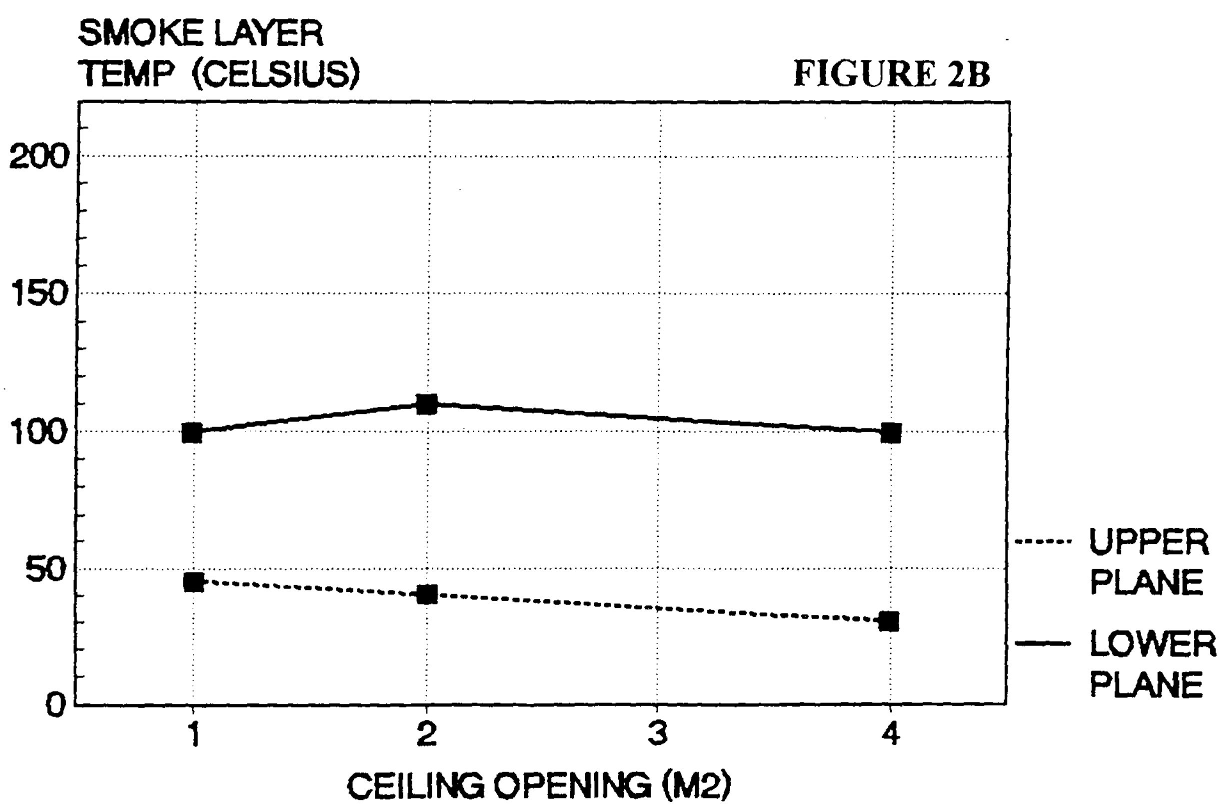
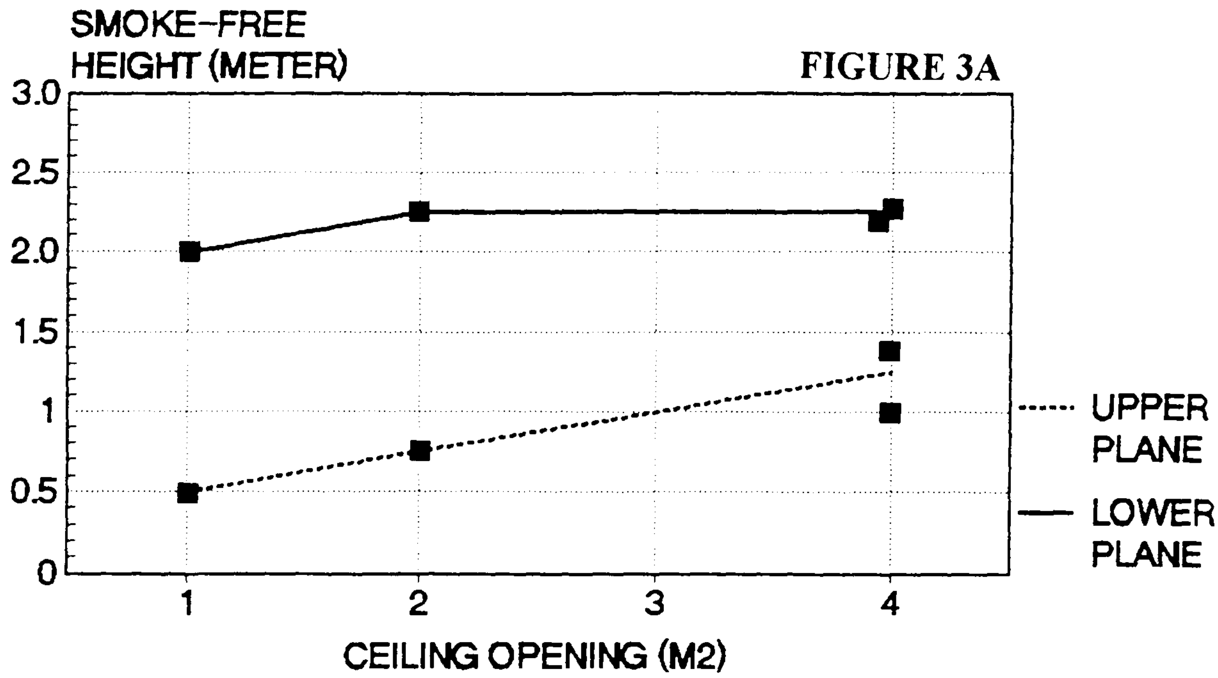


Figure 2A-B. Measured smoke-free height and average smoke layer temperature. Fuel size is 0.25 m^2. Opening between planes is 0.5 m^2.

FUEL SIZE: 0.50 x 0.50 meter
OPENING BETWEEN THE PLANES: 1.0 M2



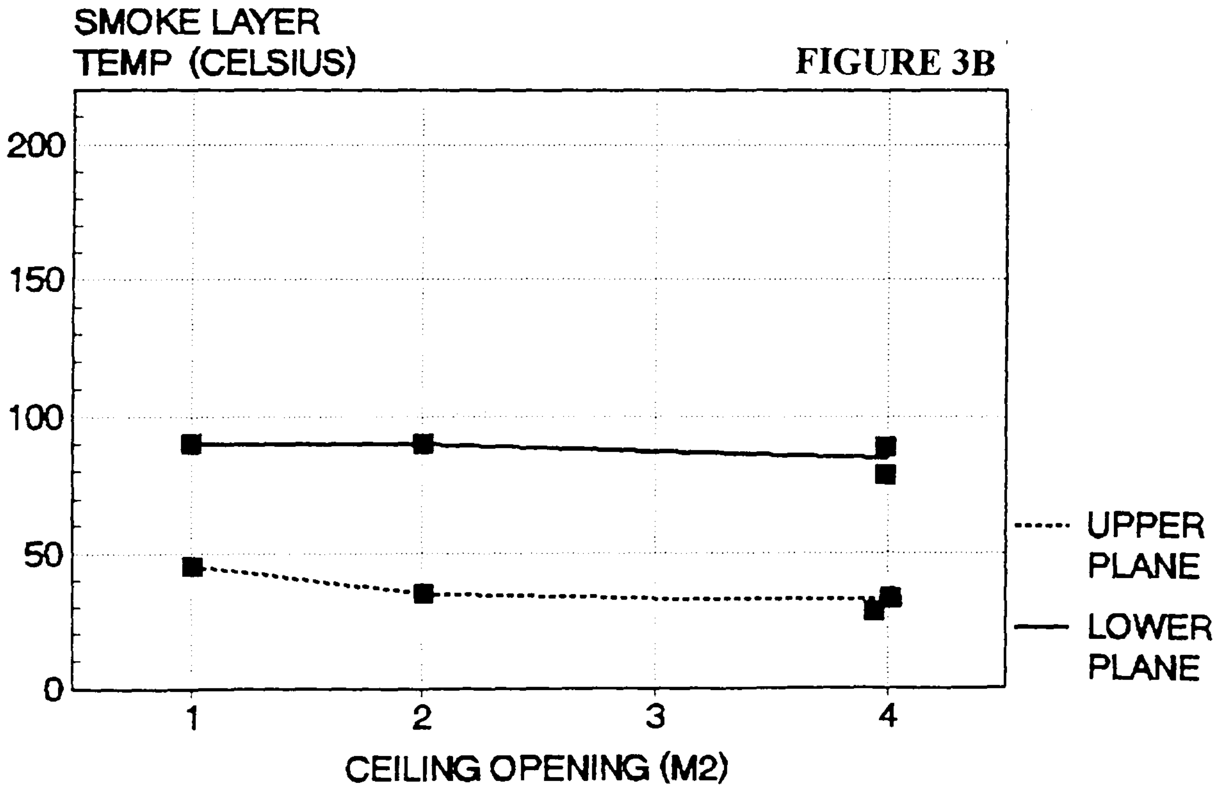


Figure 3A-B. Measured smoke-free height and average smoke layer temperature. Fuel size is 0.25 m^2. Opening between planes is 1.0 m^2.

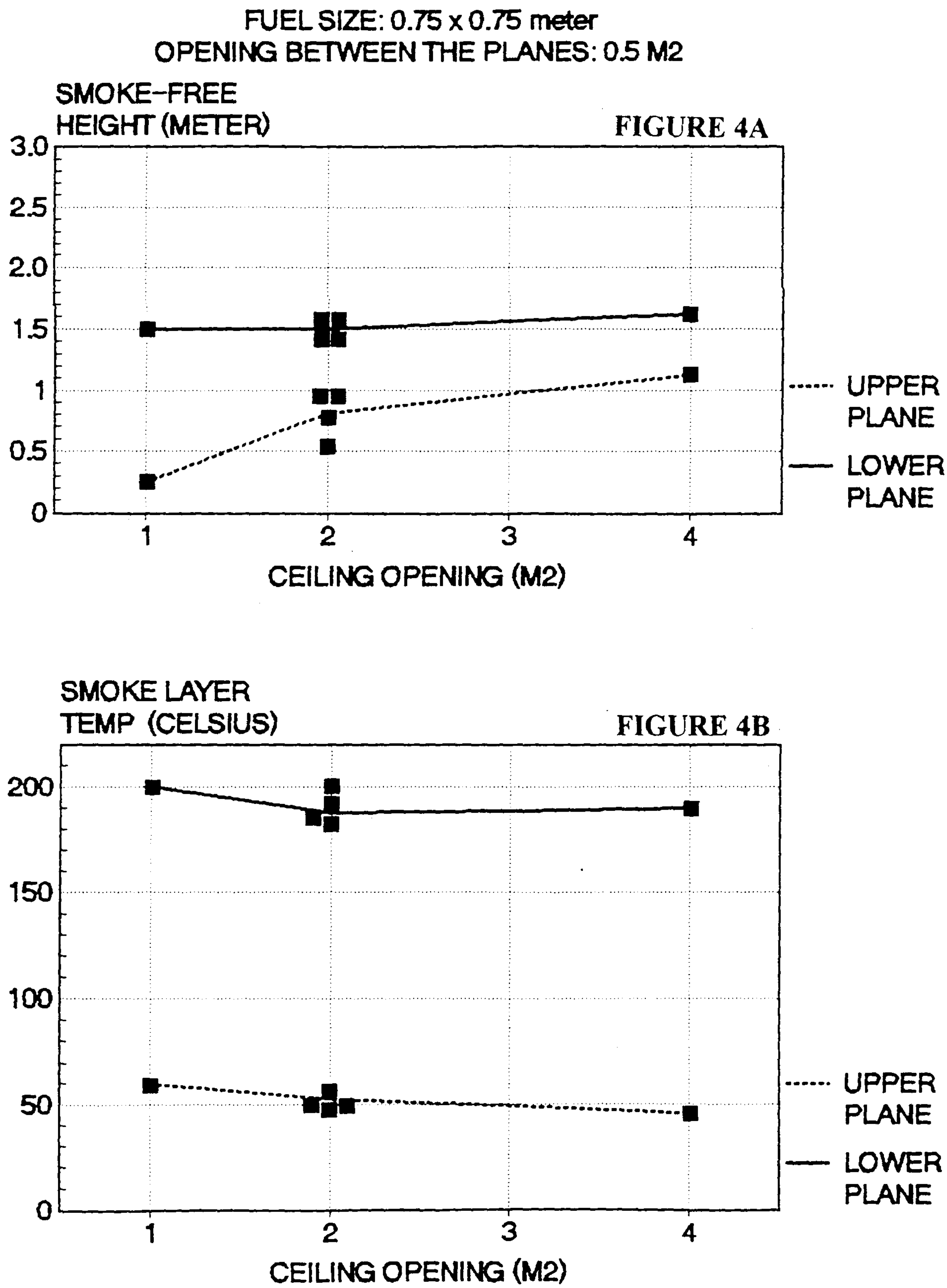
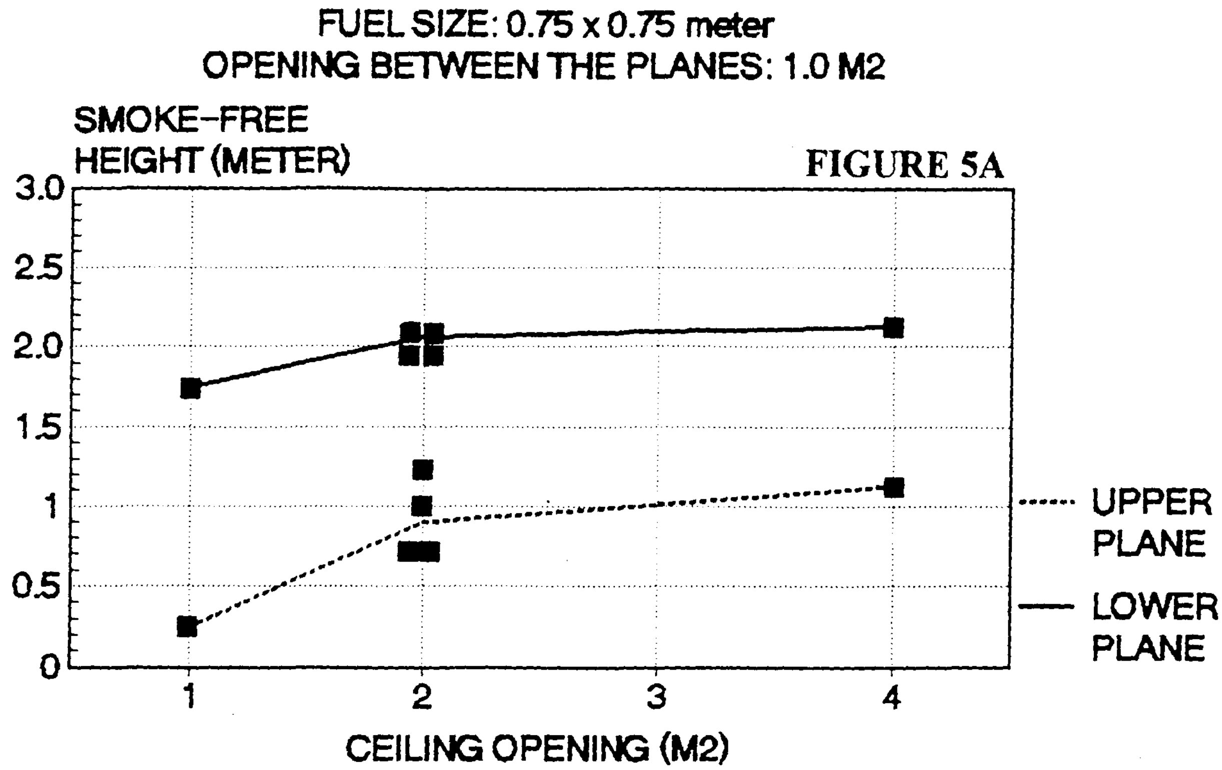


Figure 4A-B. Measured smoke-free height and average smoke layer temperature. Fuel size is 0.56 m^2. Opening between planes is 0.5 m^2.



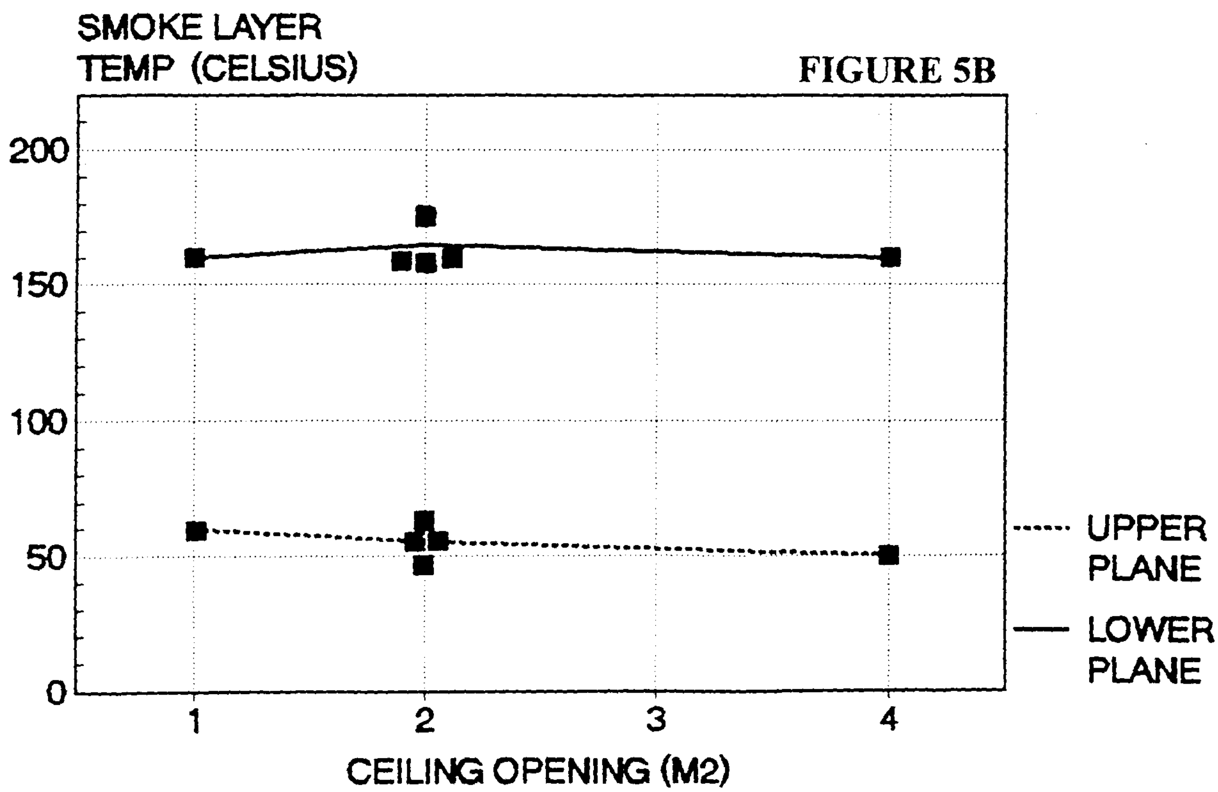


Figure 5A-B. Measured smoke-free height and average smoke layer temperature. Fuel size is 0.56 m^2. Opening between planes is 1.0 m^2.

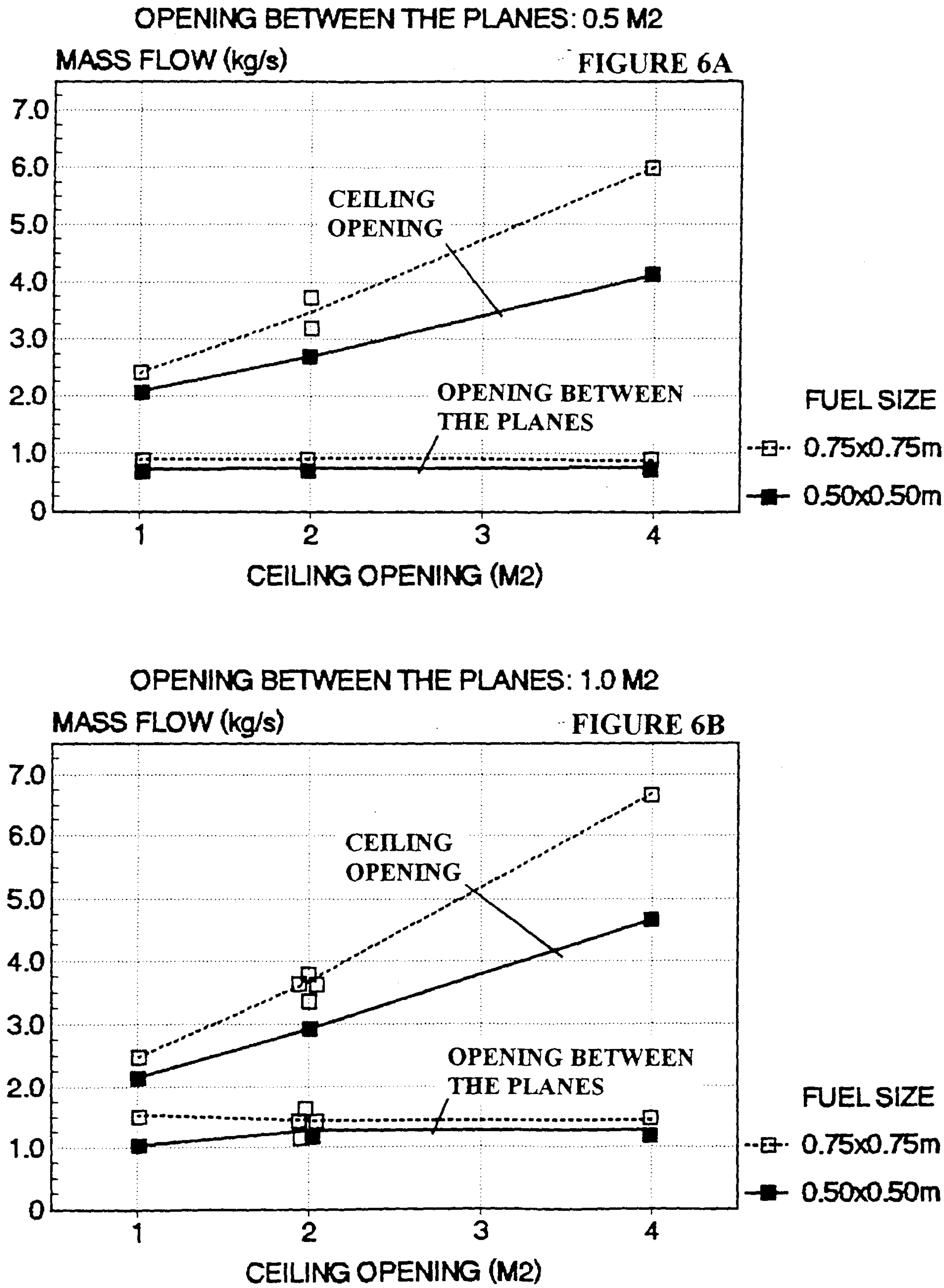


Figure 6A-B. Calculated mass flow values through horizontal openings based on velocity values measured centrally at the openings. The flow coefficient is assumed to be 0.6.

CALCULATED DATA – ZONE MODEL

UPPER PLANE

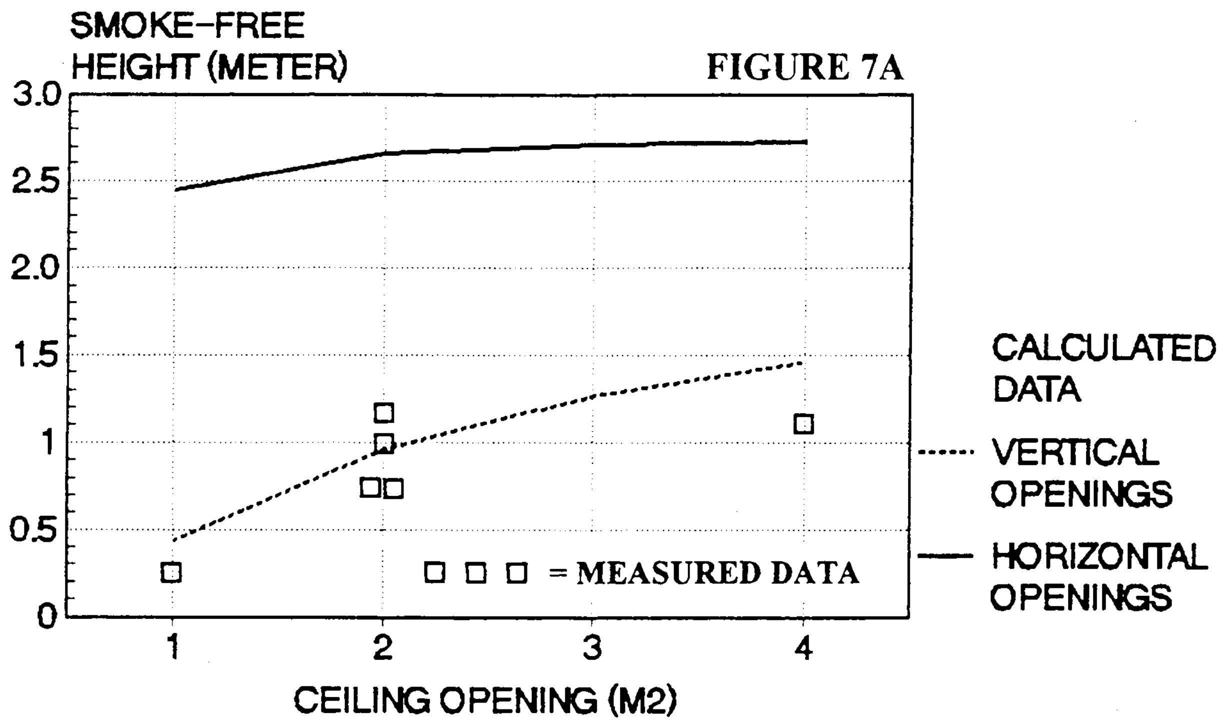


FIGURE 7A

LOWER PLANE

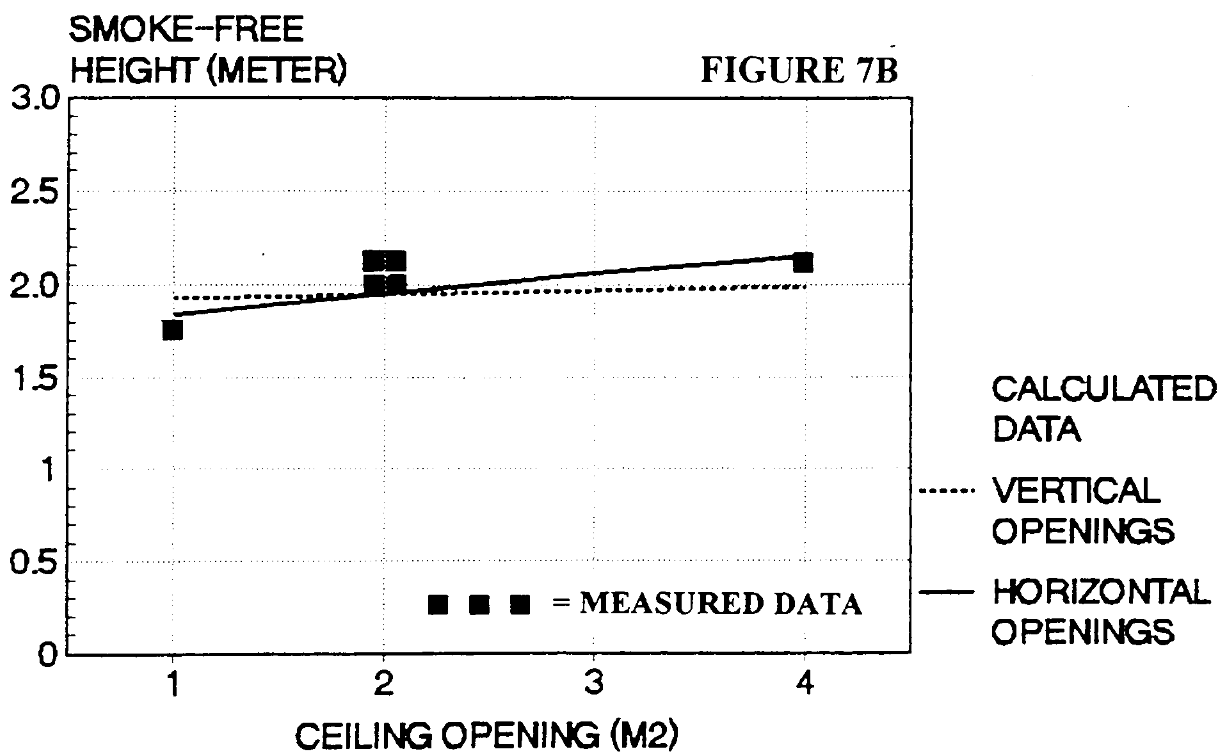
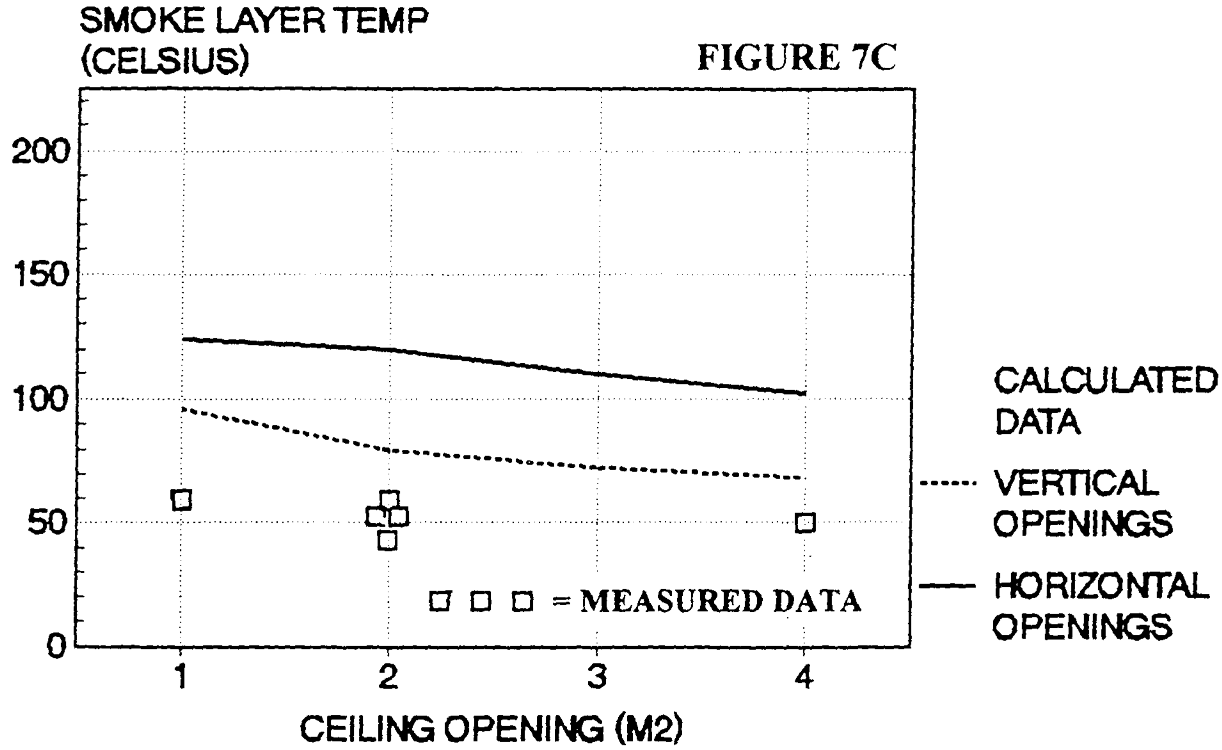


FIGURE 7B

UPPER PLANE

FIGURE 7C



LOWER PLANE

FIGURE 7D

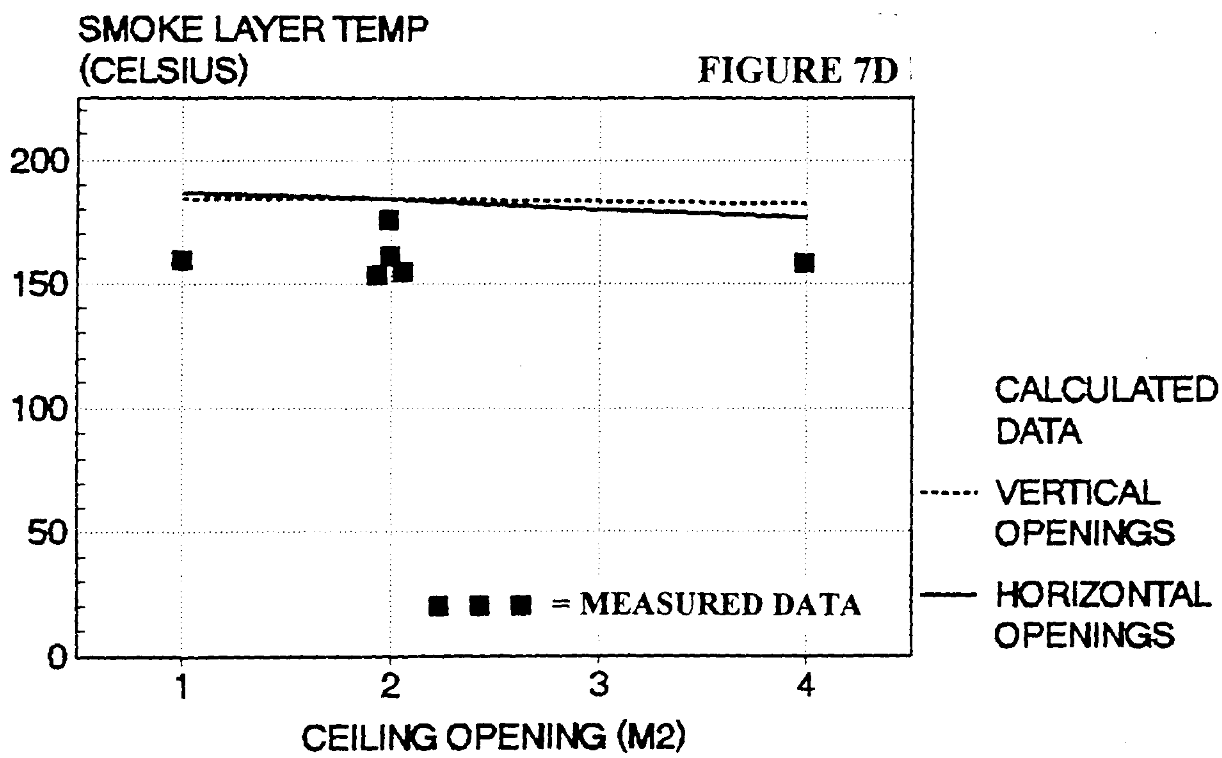
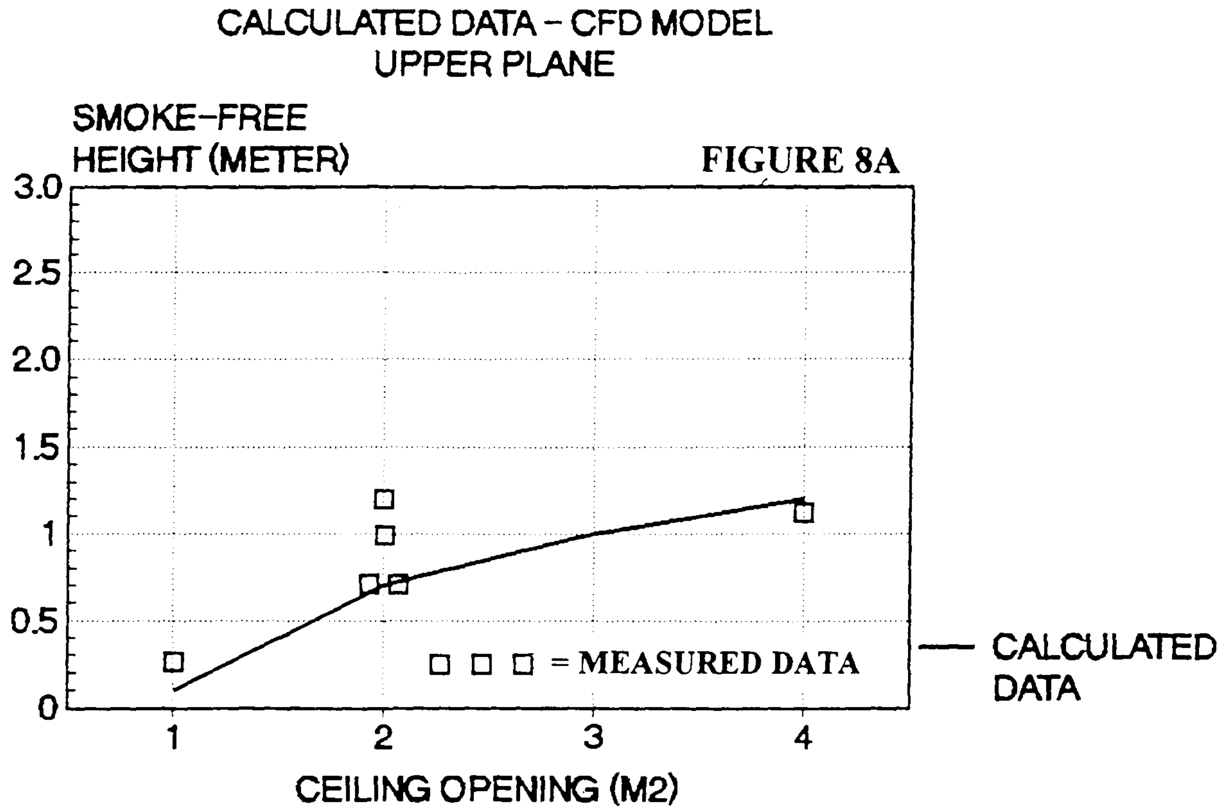


Figure 7A-D. Calculated data by zone model are compared with measured data. The quantities compared are the smoke-free height and average smoke layer temperature.



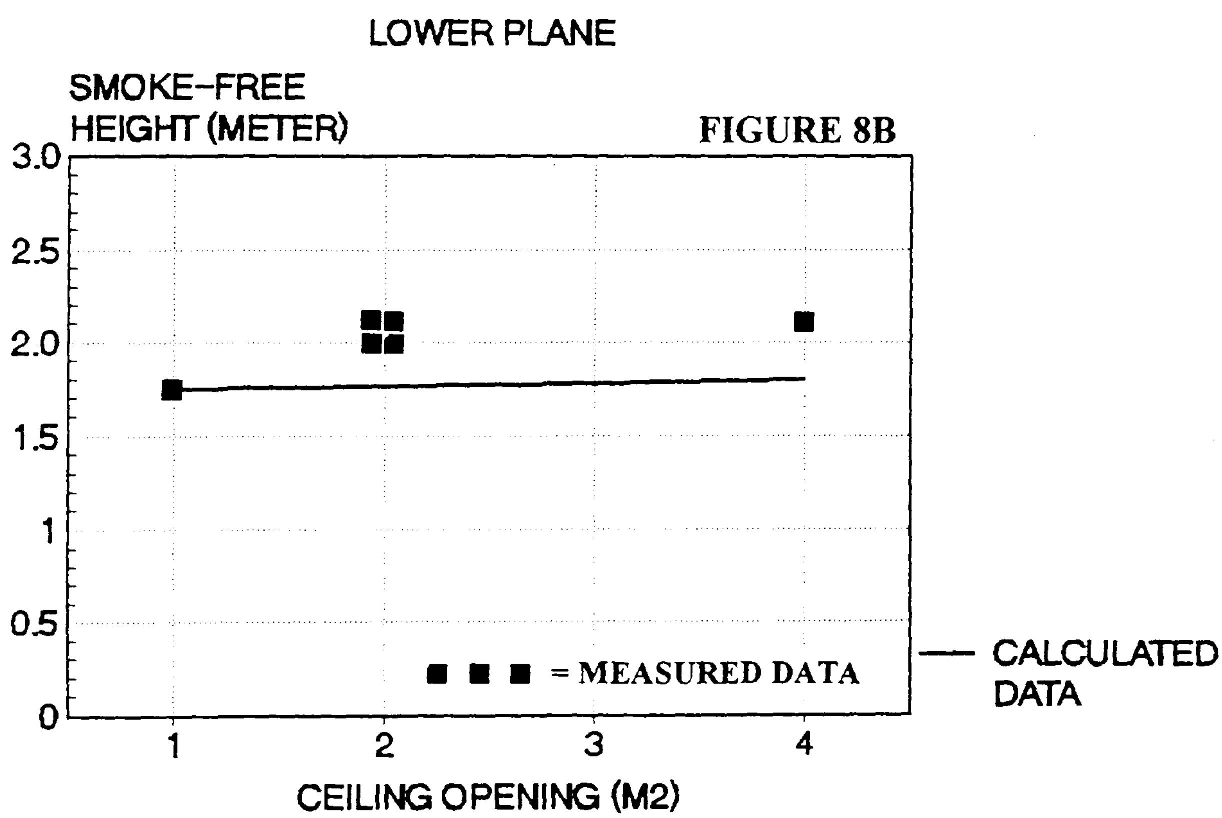


Figure 8A-B. Calculated data by CFD model are compared with measured data. The quantitiy compared is the smoke-free height.

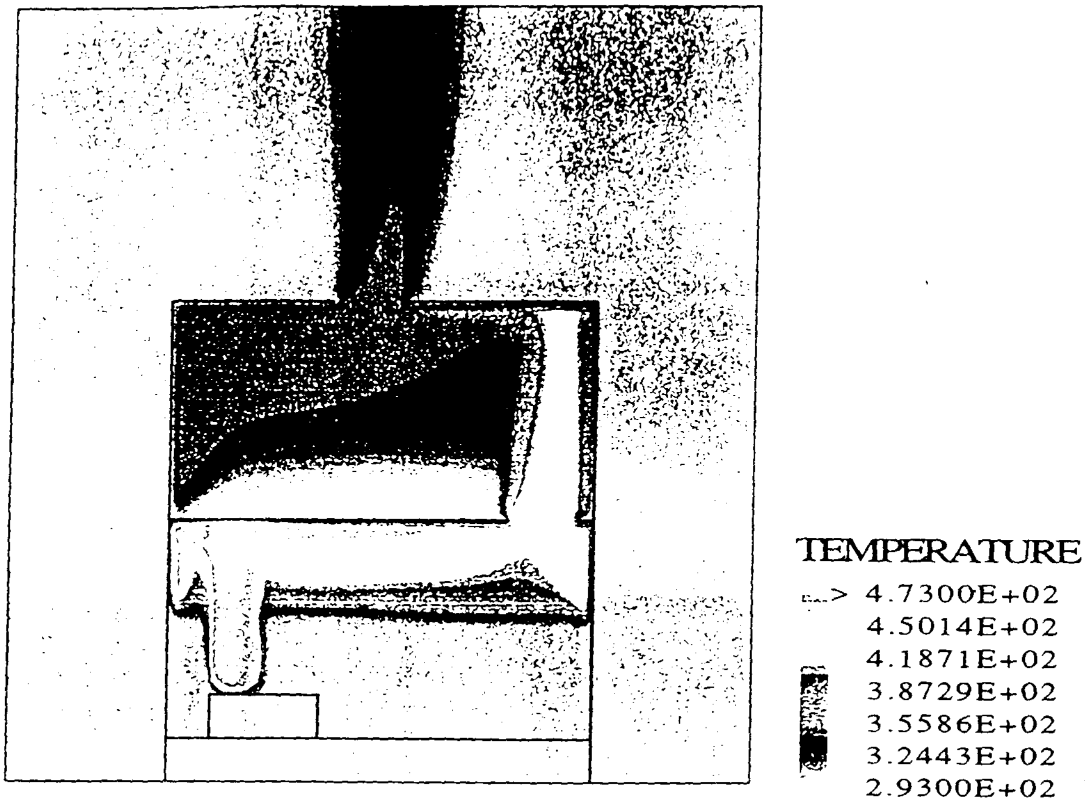


Figure 9A. Calculated temperature values plotted along the central plane of the test configuration. The ceiling opening is 2 m^2. The temperature is given in Kelvin (473 K = 200 ^{0}C).

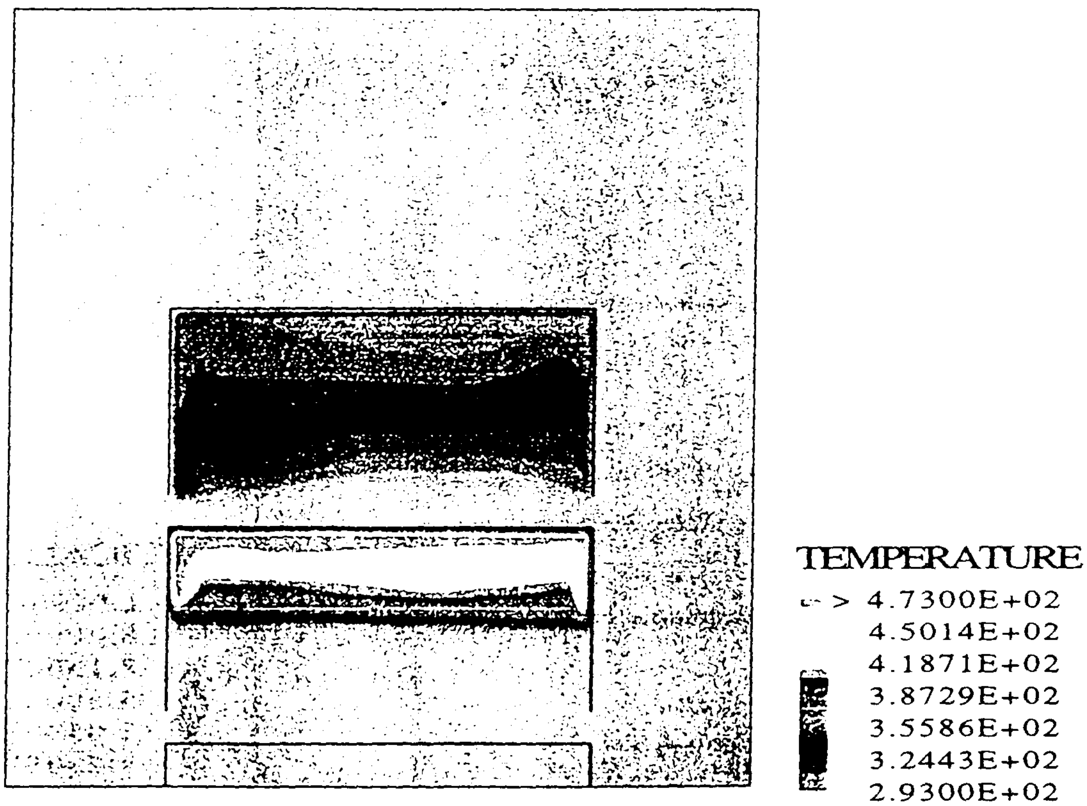


Figure 9B. Calculated temperature values plotted along the plane of 1.5 meter from the wall. The ceiling opening is 2 m^2.

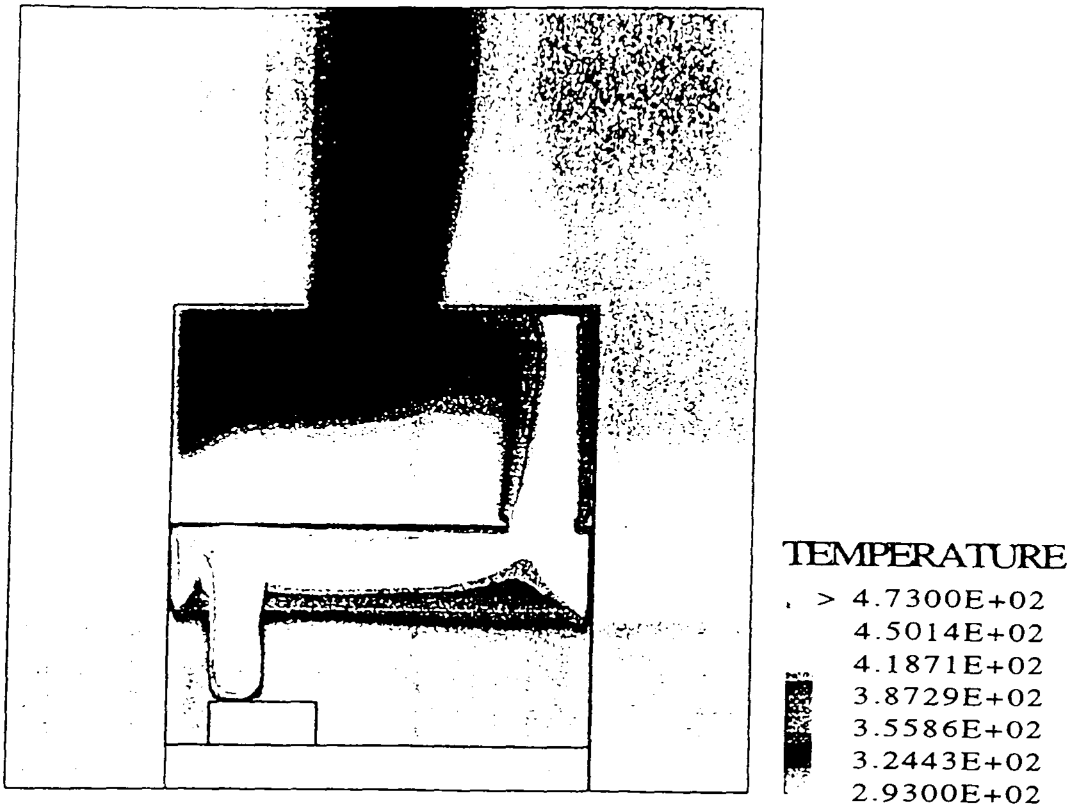


Figure 10A. Calculated temperature values plotted along the central plane of the test configuration. The ceiling opening is 4 m^2. The temperature is given in Kelvin (473 K = 200 ^0C).

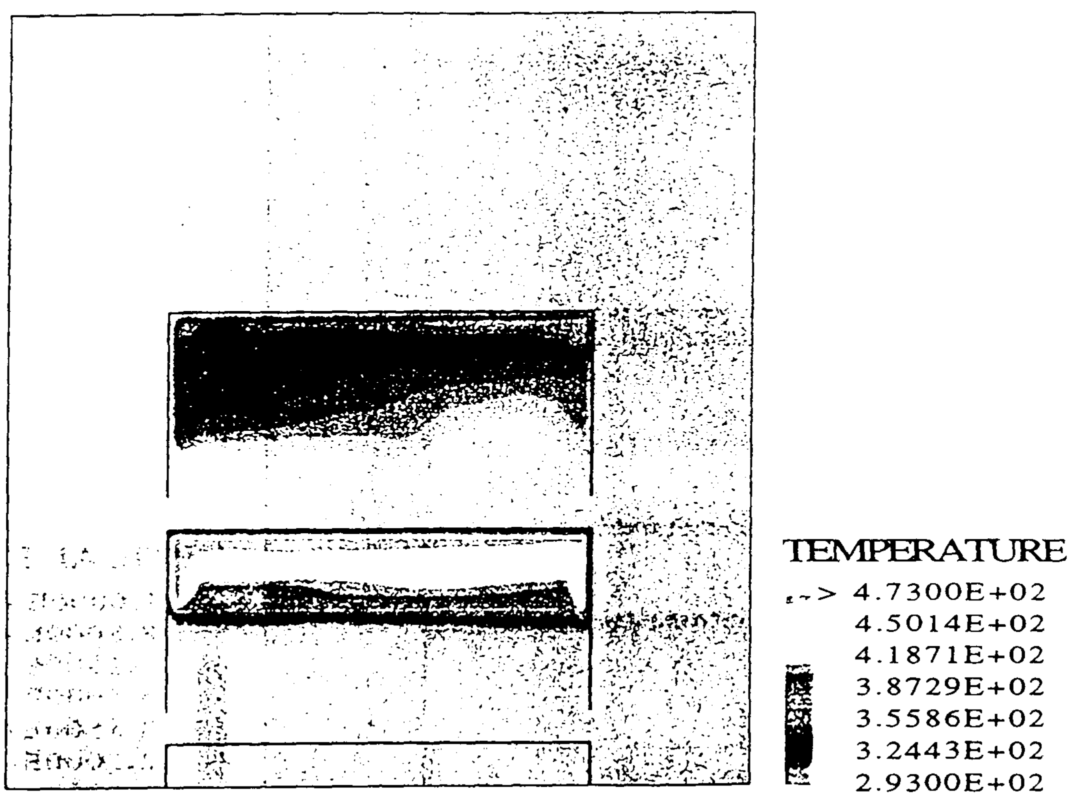


Figure 10B. Calculated temperature values plotted along the plane of 1.5 meter from the wall. The ceiling opening is 4 m^2.