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MEASUREMENTS OF THE FLOW OF COMBUSTION GASES
FROM VENTILATED COMPARTMENTS

by

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SUMMARY

Measurements of the composition of combustion gases, withdrawn from different points of a vent at the top of one face of a 0.9 m cubical compartment, have shown that the gases withdrawn from the centre of the vent and 2 cm below the ceiling of the compartment have about the same composition as the average composition of all the evolved combustion gases for a fire disposed centrally on the floor of the compartment.

Comparison with calculated rates of evolution of combustion gases from data obtained from the above sampling position, by mass balance and heat balance methods, has shown that the rate of flow may be estimated with good accuracy by the use of a simplified form of the equation proposed by Kawagoe, provided that a discharge coefficient of 0.9 is incorporated in the equation.

Errors in measurement introduced by neglect of water vapour formed during combustion are small.

Key words; Burning rate, Combustion products, Compartment, Flow, Measurement, Ventilation.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

The velocity and rate of flow of combustion gases from fires in ventilated compartments are often required for calculations concerned with the amounts and rates of flow of toxic components, and with the decomposition of the fuels. In many experiments it is impracticable to measure gas velocity, and hence rate of flow, directly. However, a method of calculating such velocities and rates was presented by Kawagoe[1]. This note presents the results of some tests made at the Fire Research Station to assess the accuracy of such calculations for a particular form of combustion compartment.

EXPERIMENTAL

APPARATUS

The combustion compartment used for these experiments is shown in Fig. 1. It was a cube of 0.9 m side constructed of sheet steel, with a hinged front wall having a sliding panel which could be lowered to form a ventilation slot at the top of the compartment, of the full width of the compartment and pre-determined depths of 5 and 15 cm. The interior of the compartment was lined with 13 mm thick asbestos board. Propane was burnt in a rake burner having 12 burner tubes of 13 mm dia. and 45 cm long at 3.8 cm centre spacing on the floor of the compartment; a 60 cm square perforated steel plate was placed 15 cm above the burner to improve the uniformity of distribution of gases rising from the burner, Fig. 2. The burner was drilled with sufficient uniformly spaced holes to ensure that the fuel burnt with a smoke-free flame, with no tendency to lift-off from the burner, at the rates of flow used, 2.5 to 20 l/min. The compartment was fitted with three thermocouples at the positions indicated in Fig. 1, to measure the temperature of the gases within the compartment and emerging from the vent. Thermocouples were also fitted in one wall of the compartment to measure the temperature at the inner surface of the asbestos lining, at the space between the asbestos lining and the sheet steel case and on the outer surface of the sheet steel case, Fig. 3. Ambient temperature in the laboratory, in which the experiments were made, was measured by a mercury in glass thermometer. Samples of the gases emerging from the vent were withdrawn through a stainless steel sampling tube at

1 litre/min and passed through a train of gas burettes. Samples were collected at appropriate times by isolating a gas burette from the train, and were analysed subsequently by gas chromatography. The position of the gas sampling tube in the vent could be varied vertically and laterally.

Commercial propane was used for the experiments and was supplied to the burner from a cylinder of liquefied gas via a pressure reducing regulator and a flow meter. The rate of flow of gas was determined from the weight of propane consumed in a given time, a flow meter being used to indicate uniformity of rate of flow during tests.

TESTS

Two sets of experiments were made. In the first set the composition of the combustion gases was measured, at different points within the area of the vent, to discover a suitable single position of the sampling tube where the combustible gas collected would have the same composition as that of all the combustion gas passing through the vent at the time of sampling. Three samples of gas were analysed from each of the positions of the sampling tube during tests in which the rate of flow of fuel was kept constant. In the second set of tests, the samples of gas were collected from the position chosen after the first set of tests. The measured temperatures, gas compositions and rates of fuel flow during tests were used to calculate the rate of flow of combustion gases.
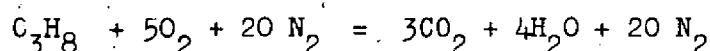
CALCULATION OF RATES OF FLOW OF COMBUSTION GASES

1. Mass balance method

The content of carbon dioxide in the combustion gases may be used to calculate the rate of flow through the vent.

The complete combustion of propane in air is represented approximately by

$$\text{Air}$$

$$C_3H_8 + 5O_2 + 20\ N_2 = 3CO_2 + 4H_2O + 20\ N_2$$

Thus one volume of propane gas produced 27 volumes of combustion gases containing 3 volumes (11.1 per cent) of carbon dioxide from combustion in 25 volumes of air. Therefore, if the collected combustion gases from the compartment contain X per cent of carbon dioxide when propane is burnt efficiently at

R 1/min, the rate of flow of combustion gases is

$$R = \frac{11.1}{X} \cdot 27 \text{ 1/min.} \tag{1}$$

2. Heat balance method.

The heat produced by the efficient burning of propane in the compartment under steady state conditions is lost in two ways; on the one hand through the walls of the compartment and on the other as sensible heat in the emerging combustion gases. The heat lost through the walls of the chamber was obtained from the equation

$$H(1/a + d_1/k_1 + d_2/k_2 + d_3/k_3 + 1/b) = T_a - T_b \tag{2}$$

Where H = heat transfer/unit area, time

d_1, d_2, d_3 = thickness of asbestos, air space and steel sheet respectively

k_1, k_2, k_3 = conductivity of asbestos, air and steel respectively

a = inner surface coefficient of heat transfer for the compartment

b = outer surface coefficient of heat transfer for the compartment

T_a = gas temperature within the compartment

T_b = temperature of air surrounding the compartment.

The value for d_2 was the only one not accurately determined, because distortion of the steel shell of the compartment had resulted in a widely variable space between the shell and asbestos lining. The mean value was estimated at 0.2 cm.

H was calculated for one test only from the conduction through the wall of the compartment, and the temperature of the inner and outer faces of the wall. The terms 1/a and 1/b were then evaluated from equation 2.

The U-value so obtained (the reciprocal of the terms within the brackets in equation (3)) was then applied to all tests. This simplification was made because (a) no allowance had been made for temperature gradients within the compartment, (b) it was assumed that all surfaces of the chamber lost heat at the same rate and (c) the thickness of the air space could not be known precisely all of which would lead to errors in heat transfer calculation precluding precise evaluation of the heat lost in the combustion gases. However, the heat transfer obtained as above should give a reasonable check on the other calculations.

The volume rate of flow of the combustion gases from the compartment was calculated from the estimated sensible heat loss, using a value for the specific heat of the gases calculated for mean composition of the combustion gases for all tests.

Buoyancy Method

The equation presented by Kawagoe can be written as

$$\frac{M}{\rho_0} = \frac{2^{\frac{2}{3}} \, a \, A \, H^{\frac{1}{2}} \, g^{\frac{1}{2}} \, (1 - \rho_1/\rho_0)^{\frac{1}{2}}}{3 \left[1 + (\rho_0/\rho_1)^{\frac{1}{3}} \cdot (1 + R/M)^{\frac{2}{3}} \right]^{3/2}}$$ (3)

Where M = mass flow rate of air into compartment
       a = discharge coefficient
       A = area of vent
       H = height of vent
       ρ_1 = density of gas in compartment
       ρ_0 = density of air entering compartment
       R = rate of burning

By making the assumptions that the gases are ideal and that the mean molecular weight of the combustion products does not differ from that of air, the equation may be written in the form

$$\frac{M}{\rho_0} = G \, A \, H^{\frac{1}{2}}$$ (4)

where G is a composite term, dependent on the temperature difference between the hot gases in the compartment and the air entering the compartment, and incorporating a, the discharge coefficient[3]. The values of G, taken from an earlier report, show a rapid increase for temperature differences of up to 100°C, but are practically constant for temperature differences greater than 200°C, Fig. 4. Because of the balance between the gases entering and leaving the compartment, equation 4 gives the equivalent volume flow of gases leaving the compartment at ambient temperature, provided the flow of fuel gas is small compared with the flow of air into the compartment. In the present tests, the flow of fuel gas did not exceed $1\frac{1}{2}$ per cent of the flow of air into the compartment, which always exceeded the stoichiometric rate.

Equation 4 applies for steady state conditions, the conditions under which the present tests were performed. However, it would not be expected to be greatly in error for non-steady states provided the changes in rate of burning take place slowly.

RESULTS

EFFECT OF SAMPLING POSITION

Tests were made in the compartment with vent depths of 5 cm and 15 cm, in which the position of the gas sampling tube was varied laterally and vertically. Three samples were taken at each position of the sampling tube. The mean value of carbon dioxide content and the range of values is plotted in Figs 5 and 6. The overall mean value for the relevant series of tests is also included in the Figures. The Figures indicate that a sampling position at the middle of the vent and 2 cm below the ceiling of the compartment gave a value for composition reasonably in accord with the overall mean. This sampling position was used for subsequent tests.

CALCULATION OF RATES OF FLOW

The calculation of gas flow from heat flow and mass flow data depend upon the complete combustion of the fuel for their accuracy. All gas samples collected were therefore analysed for carbon monoxide and methane as well as oxygen, nitrogen and carbon dioxide. No carbon monoxide or methane was detected in any of the tests and therefore combustion was assumed to be complete. This was confirmed by the absence of soot from the flames.

The date from individual tests used for the calculations are given in Table 1.

Table 1

TEST DATA

Test No.	Rate of flow Propane, 1/min	Depth of vent cm	Temperature, °C		Carbon dioxide, per cent	
			In compartment	At vent	Dry basis	Wet basis
J2	2.54	15	92.5	80.5	0.625	0.62
J3	2.92	5	145	130	3.17	3.03
J4	7.35	15	222	217	1.33	1.31
J5	8.6	15	228	214	1.50	1.47
J6	20.1	15	514	460	3.84	3.65

The heat of combustion of propane was taken as 20.3 kcal/1. Gas analyses were made on the dry basis and recalculated to wet basis. The rates of flow of propane were stable for all tests except J3. In this test the rate of flow increased but was stable during the last 45 minutes of test when the measurements included in the above table were made. The calculated specific heat for combustion gas of the mean composition for all tests was 0.327 cal/1.°C.

The rates of flow of combustion gases calculated by the three methods are given in Table 2

Table 2

Rates of flow of combustion gases, 1/sec, at 20°C

Test No.	Method of calculation			
	Mass Balance	Heat Balance	Buoyancy, (Eq.4.)	
			a = 0.7	a = 0.9
J2	20.5	22.1	15.2	19.5
J3	4.8	9.8	3.5	4.5
J4	28.0	25.8	19.5	25.1
J5	24.2	30.5	19.5	25.1
J6	27.2	28.8	20.2	26.0

calculations on the dry composition of gases. For calculations of rates of flow with other fuels, some of which might contain free moisture, a similar accuracy could only be attained if the gas analyses were made on the wet basis. However, the values for water content of gases from perfect stoichiometric combustion of the fuels that have been used in recent tests in ventilated compartments[2, 3] given in Table 3 indicate that no great error would be introduced by assuming that the water content of the gases was the same as for propane, 15 per cent.

.Table 3

Water vapour produced from the perfect stoichiometric combustion of fuels

Fuel	Approximate water content of combustion gases, per cent
Propane	15
Cellulose	17
Cellulose plus 20 per cent water	21
Wood	13
Wood plus 20 per cent water	17
Poly (vinyl chloride)*	7

* Poly (vinyl chloride) has been burnt together with similar weights of cellulosic matter[4].

For calculations of gas flow in connection with combustion experiments, due allowance must be made for the excess air in the combustion gases. Excess air can be estimated from the oxygen content of the combustion gases. Thus, the error introduced into estimation of gas flow by ignoring the water content of combustion gases would be 5 per cent or less for gases where the oxygen content was not less than 14 per cent, and 10 per cent or less where the oxygen content was not less than about 5 per cent. In a recent series of combustion experiments[4], the oxygen content of the combustion gases was reduced to 5 per cent only when the fire load was high and the ventilation low, and for many tests was of the order of 10 to 15 per cent.

DISCUSSION

Of the results given in Table 2, good agreement is shown between the values calculated from the mass balance and those calculated from the buoyancy equation, taking the value 0.9 for the discharge coefficient. The values calculated from the heat balance show good agreement with the other values, except for test J3. In this method of calculation, the flow of combustion gas is obtained from the difference between the thermal input from the burning propane and the heat lost through the walls. Errors in calculated gas flows would therefore be greatest when the differences between heat input and heat lost through the walls were the least, as for test J3, because the magnitude of error in the calculated values is transferred to a small residual value. The rate of flow calculated from the mass balance should be the least subject to error because of the high accuracy of (a) measurement of the rate of flow of propane, and (b) the analysis of combustion gases for carbon dioxide. Errors could be introduced into rates of flow determined by mass balance if the composition of the gas sample was not representative of the overall composition. However, the results of the first set of tests suggests that the samples taken were reasonably representative. The accuracy of rates of flow calculated from the buoyancy equation (4) is dependent upon the value selected for the principal indeterminate factor, the discharge coefficient, a. The rates of gas flow are in good agreement with those obtained from the mass balance method when the value 0.9 is taken.

It has been commonly found that, for simple discharge systems in which fluids issue from a plain orifice, the appropriate discharge coefficient is about 0.7. The larger discharge coefficient found appropriate in the present tests probably arises because of the position of the vent in relation to the compartment. Gases emerging from the vent are confined on the top and sides of the vent by the walls and ceiling of the compartment. Therefore the flow lines of the gases will probably be normal to the vent and parallel to these sides of the compartment, instead of converging on the vent as would occur if the walls were remote from the periphery of the vent. A discharge coefficient approaching unity would therefore be expected, because the only side of the rectangle of discharge not confined by a wall is the interface between the incoming air and the emergent combustion gases.

Although the analyses of gases were made on the dry basis for the above tests, the appropriate corrections were made for the water formed by the complete combustion of propane. It would be well to consider the magnitude of error in the rates of gas flow from the compartment that could be introduced by making

CONCLUSIONS

A sampling position, at the middle of a vent of between 5 and 15 cm depth, and 2 cm below the ceiling, of the 0.9 m cubical combustion compartment is suitable for the collection of representative samples of combustion gases from a crib fire of square section symmetrically placed on the floor of the compartment. The rates of flow of combustion gases can be determined by the use of the modified Kawagoe equation incorporating a discharge coefficient of 0.9. Errors introduced by the use of dry basis compositions of combustion gases are small, less than 10 per cent, except for some tests with large fire loads and restricted ventilation, and are unlikely to exceed 15 per cent except for tests with cellulosic fuel of high moisture content.

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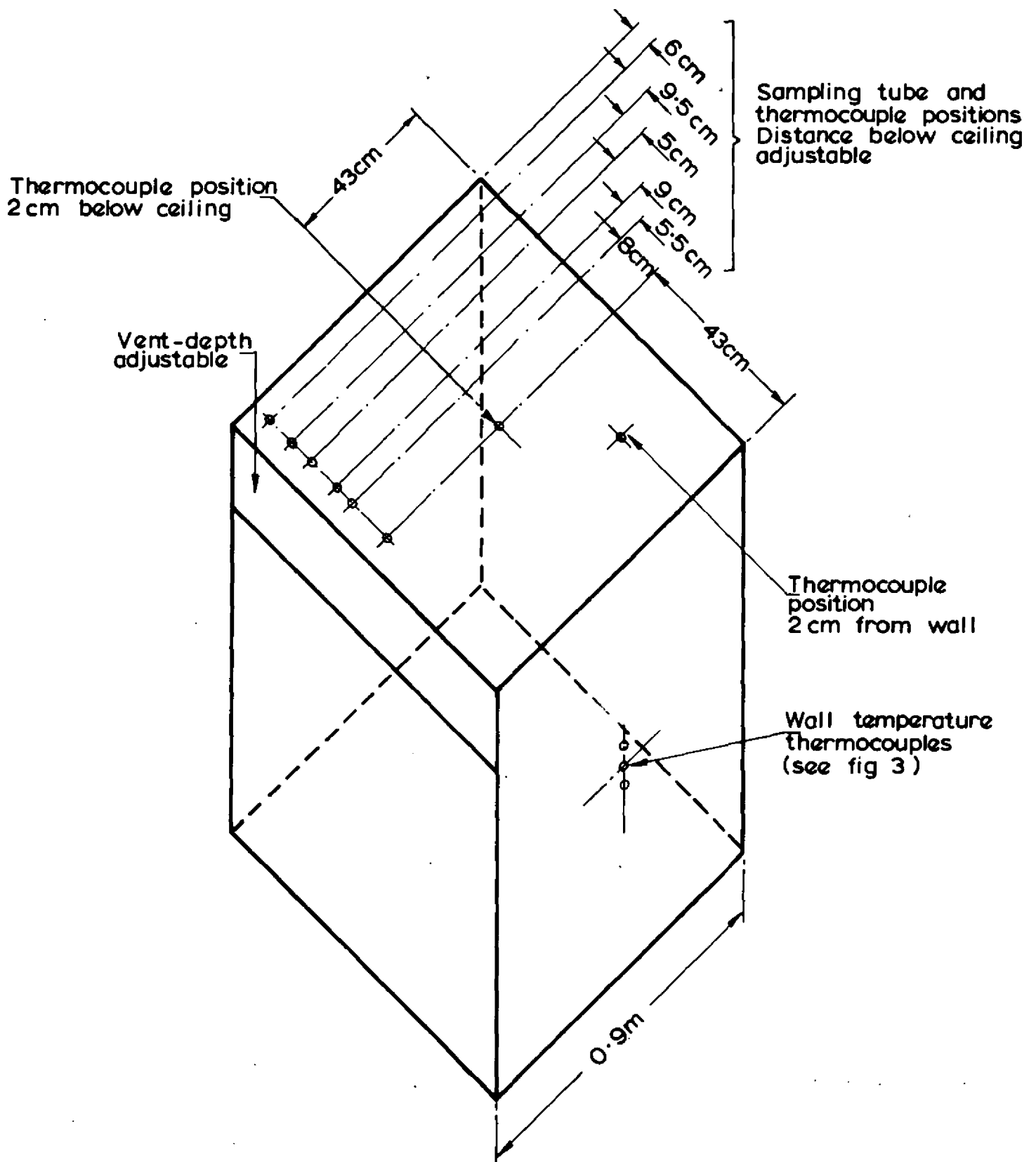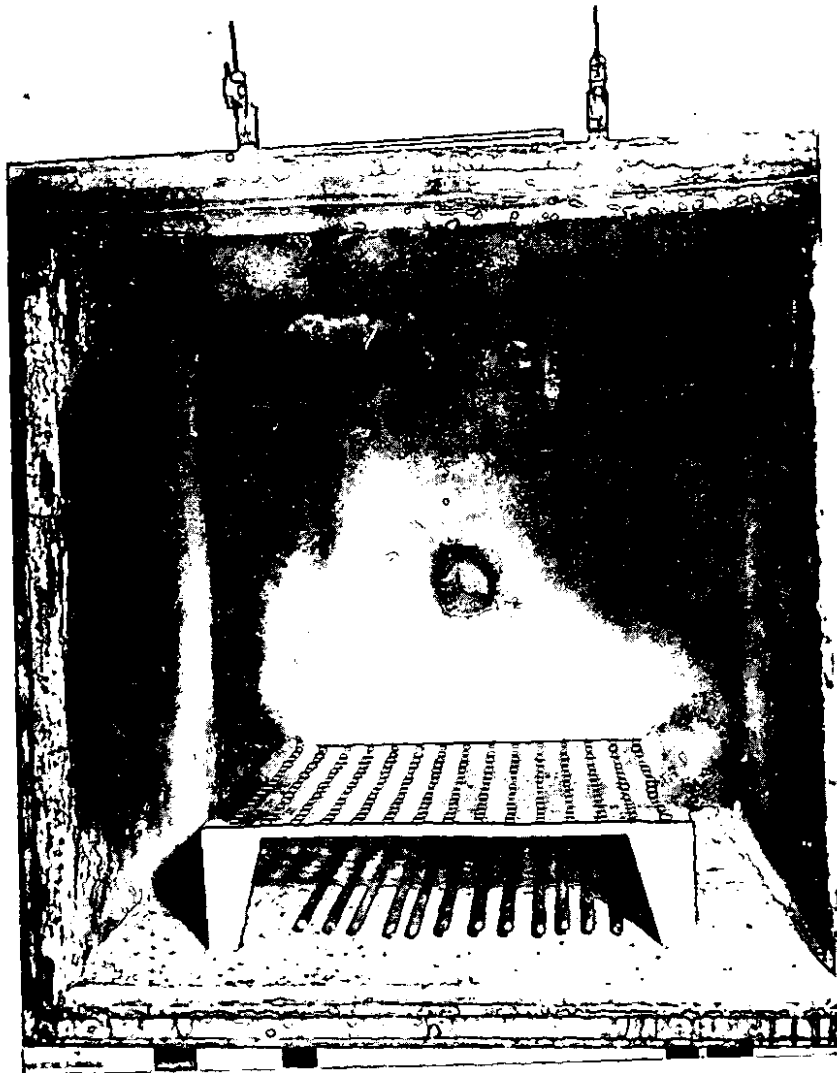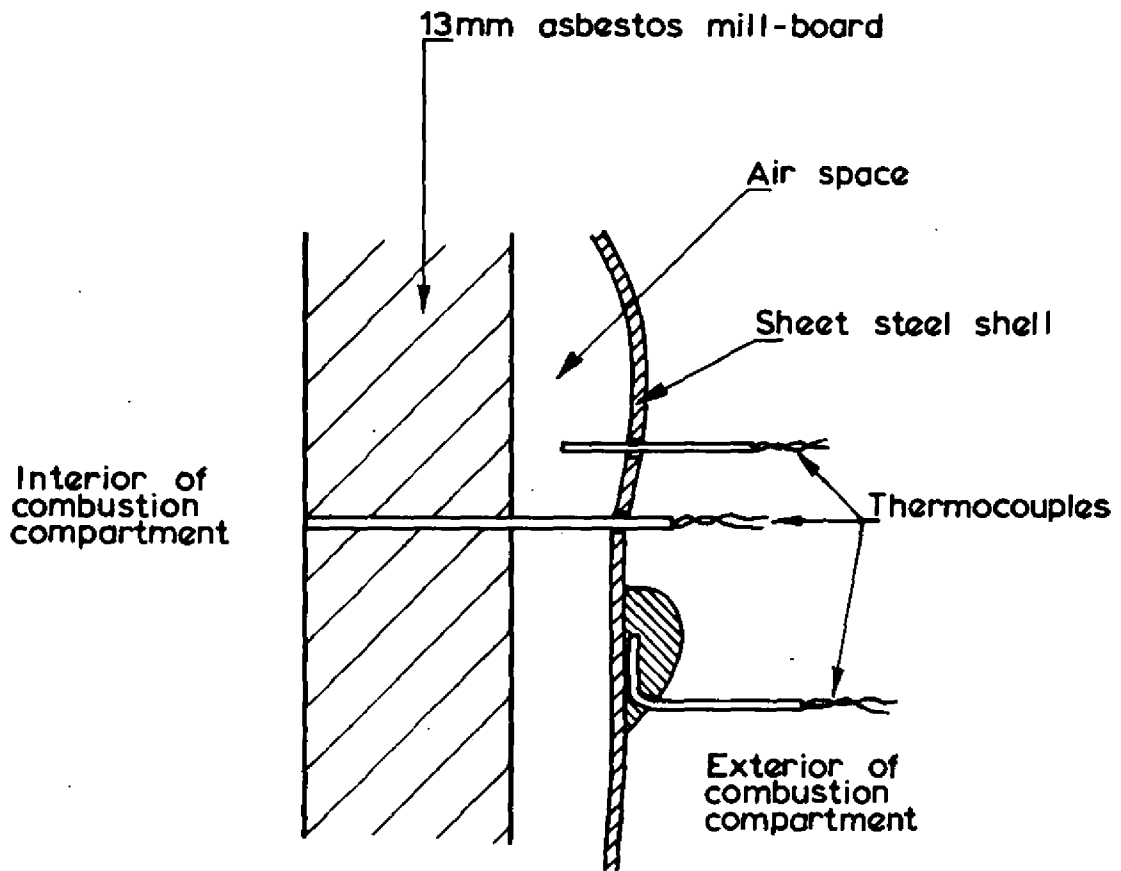
FIG. 1. CUBICAL COMBUSTION COMPARTMENT

FIG. 2. COMBUSTION COMPARTMENT SHOWING
RAKE BURNER AND BAFFLE PLATE

13mm asbestos mill-board

Air space

Sheet steel shell

Interior of
combustion
compartment

Thermocouples

Exterior of
combustion
compartment

Note :- Temperature outside combustion compartment
measured with mercury thermometer
Temperature inside combustion compartment
measured by thermocouples in gas space
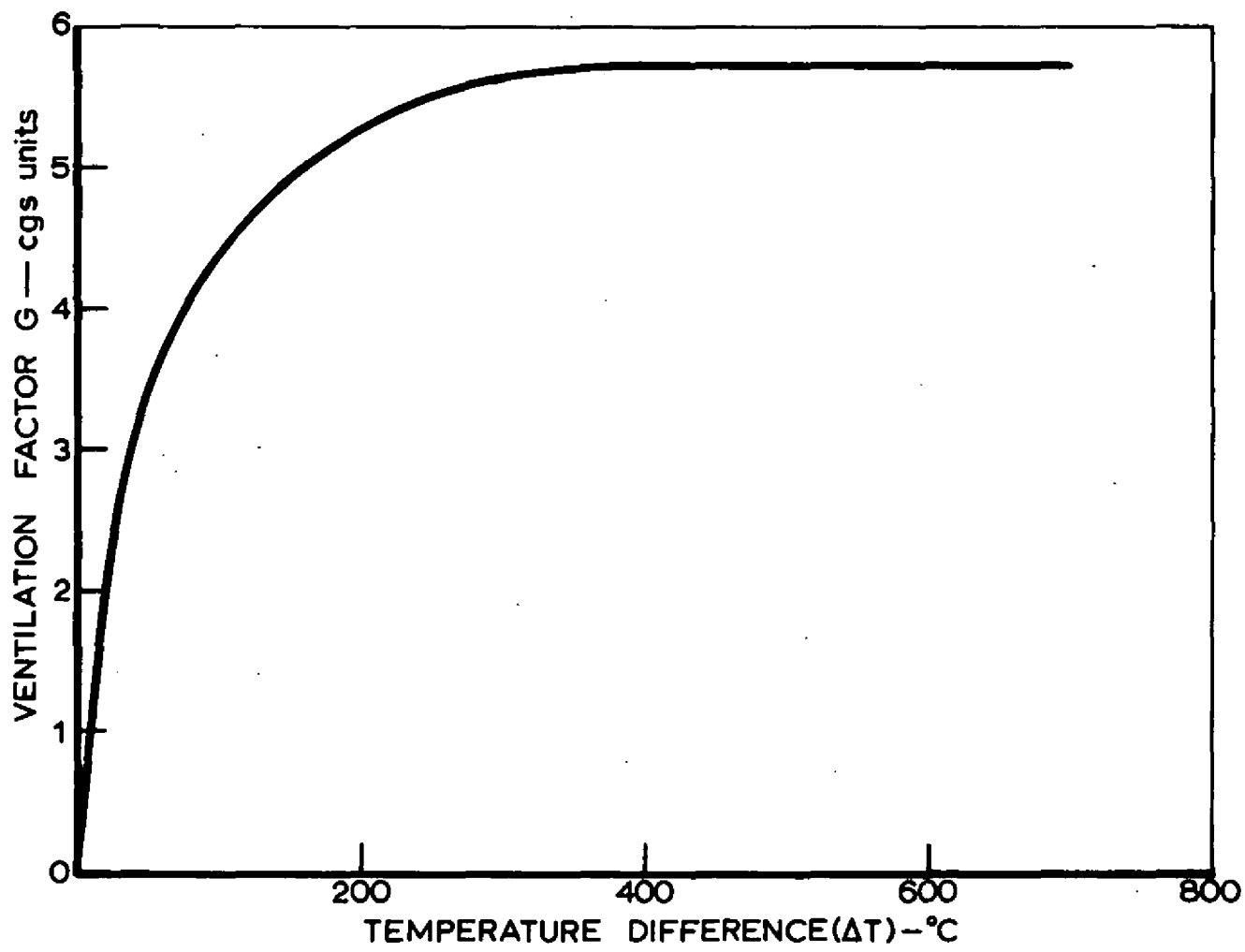
FIG. 3. WALL TEMPERATURE THERMOCOUPLES

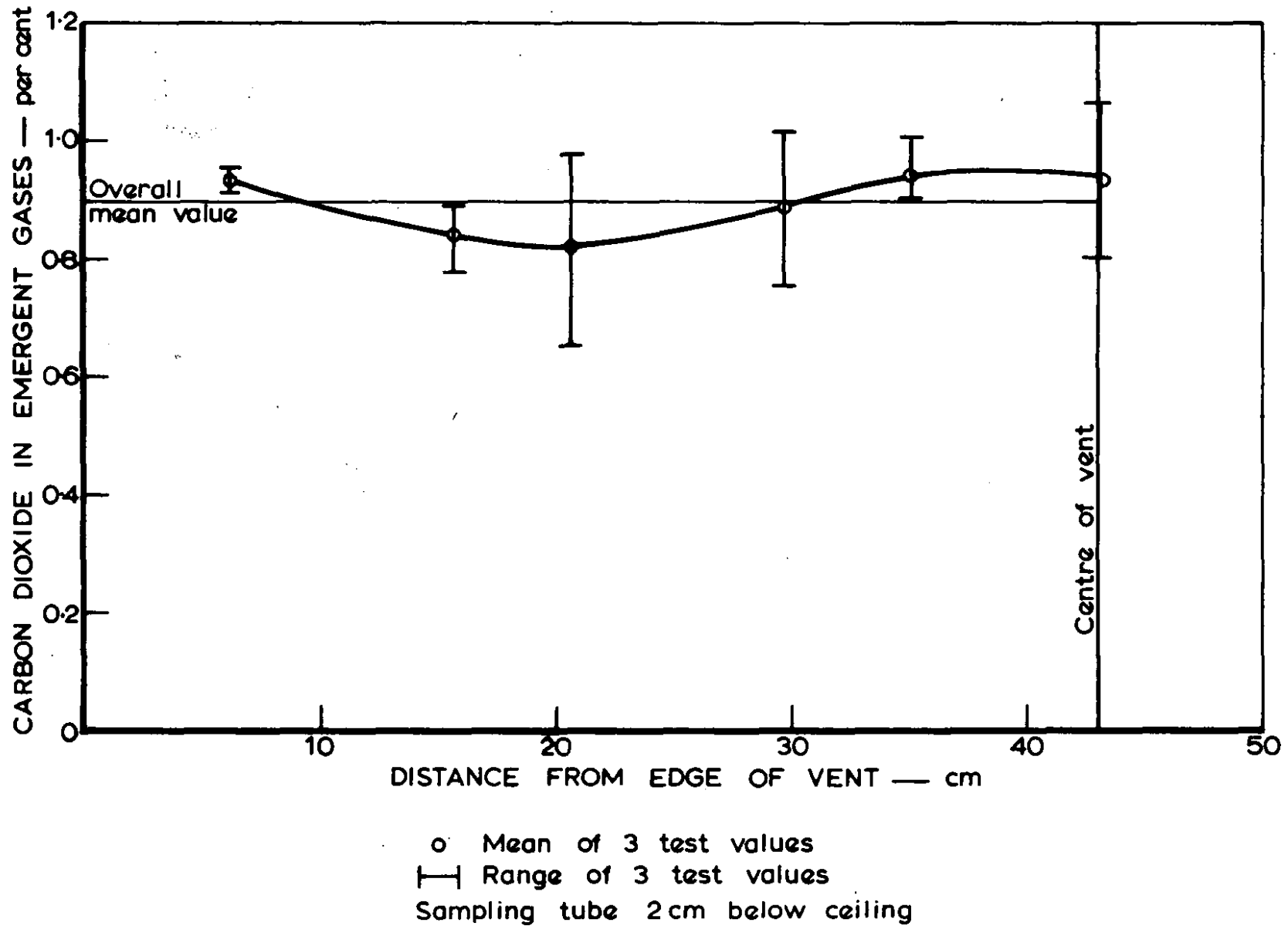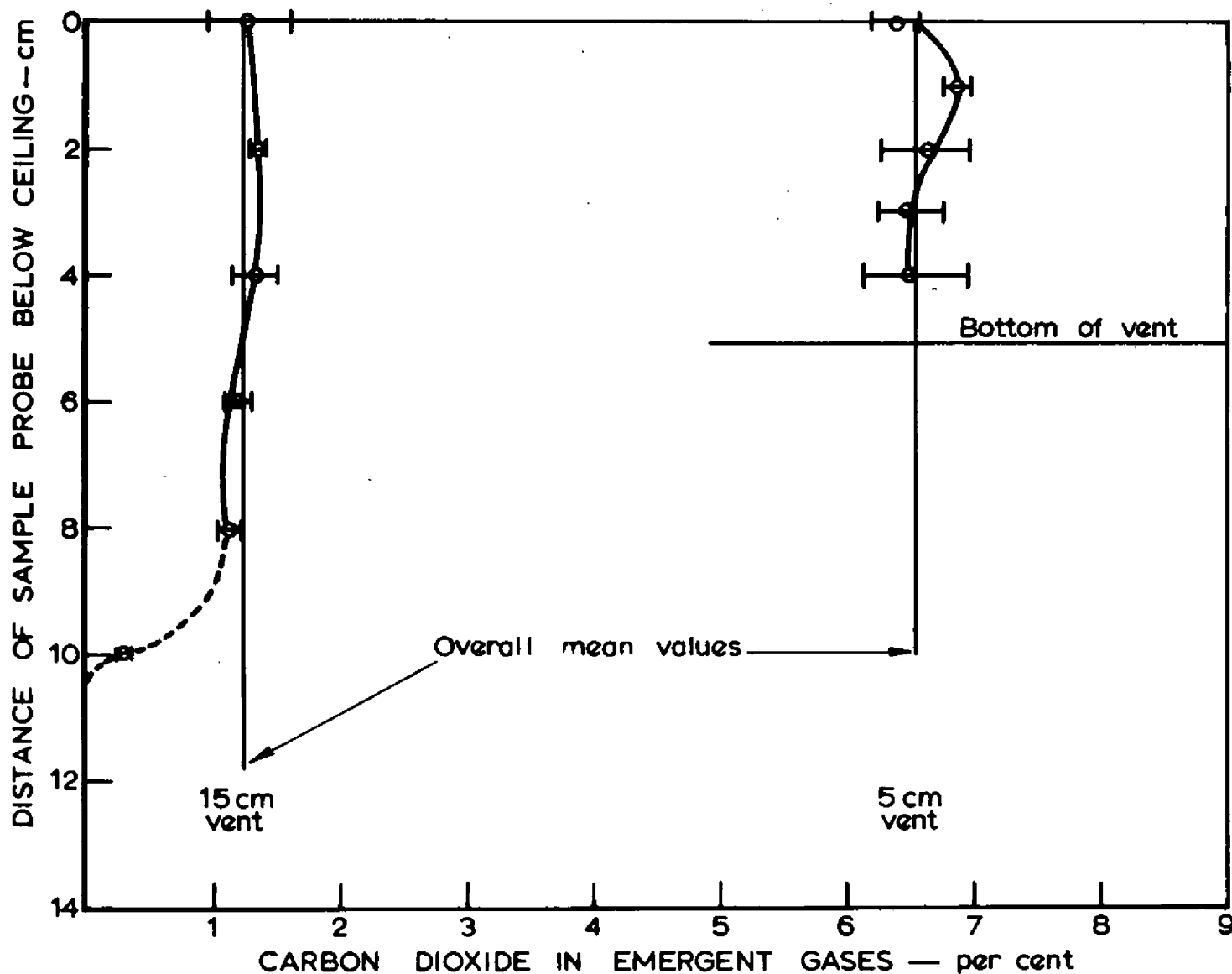FIG. 4. EFFECT OF TEMPERATURE ON PARAMETER G

FIG. 5. EFFECT OF LATERAL POSITION OF SAMPLING TUBE

FIG. 6. EFFECT OF VERTICAL DISTANCE OF SAMPLING TUBE BELOW CEILING