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FULLY DEVELOPED FIRES IN A SINGLE COMPARTMENT. PART I. APPARATUS AND MEASUREMENT METHODS FOR EXPERIMENTS WITH TOWN GAS FUEL

by

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SUMMARY

Descriptions are given of the apparatus and methods of measuring the important variables in experiments on the behaviour of a fire in a single compartment in which town gas was burned.

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1. INTRODUCTION

A knowledge of the behaviour of a fire in an enclosing compartment, in particular the variation with time of the temperature, or the heat transfer within the compartment, is necessary before the fire resistance required for containing walls, ceilings etc. can be properly specified. Two kinds of approach to this problem have been adopted at the Fire Research Station; in the first, information is being sought on factors affecting the rate of growth, intensity and duration of fires by experiments in which wood fuel is burned in model compartments of various scales. In the second, described in this series of reports, the more important factors, particularly those which control the rate of combustion, are being studied in more detail.

The most common fuel involved in fire is wood, or other cellulosic material such as paper, cardboard, or certain fabrics. It is difficult, however, in experiments with wood fuel to obtain sufficient variation in burning rate to enable the variation of other factors with burning rate to be observed, and in any case the burning rate can only be altered by changing another variable as well, such as the design of the fuel bed. The most important period of the fire in determining fire resistance requirements is that in which gaseous fuel is being evolved from the wood by pyrolysis and is burning in a diffusion flame. Thus the problem can be treated largely as one of mixing and combustion in gases, and the decomposition of the solid fuel dealt with separately.

In these experiments wood fuel was therefore replaced by a burner through which gaseous fuel (town gas) was injected into a compartment and burned. Since the total burning rate was no longer controlled by the fire itself, factors such as heat transfer, flow pattern of gases, and heat losses could be measured and studied more easily, and over a wider range of burning rates.

This report is concerned with the apparatus and methods of measuring these and other important quantities. Various intruments and methods had to be devised and these are described in Section 4.

2. COMPARTMENT

The compartment used for these experiments measured internally 72 cm high, 79 cm wide and 91 cm deep, Fig 1. The back, side walls, and bottom were of 1.3 cm thick asbestos wood covered on the outside with $1\frac{1}{2}$ mm mild steel sheet, and secured in a heavy angle-metal frame. Sheets of 1.3 cm thick asbestos wood were bolted on to the open front to give the required window opening. In order that any inadvertent explosion within the box would be vented, the roof was constructed of small pieces of asbestos millboard 5 mm thick laid, without attachment, on asbestos padding to give a reasonably gas-tight seal. As leaks developed during the series of experiments they were caulked with asbestos wool. Asbestos millboard has, at least at low temperatures, a thermal conductivity about half that of asbestos wood so that the thermal insulation of the roof was of the same order as that of the walls, Three 13 cm square holes, closed with mica windows, were made in one side to allow the flame to be seen from outside the compartment. Holes were cut in the steel sheet and asbestos wood in one side and in the back wall, and pieces of asbestos wood to which thermocouples were attached were inserted to fill the holes. A similar piece was inserted into a hole in the ceiling.

Town gas entered the compartment through a burner measuring 51 cm x 63.5 cm, Fig 1. Previous experiments(1) had shown that this burner was suitable since at low flows town gas emerged fairly evenly from the whole surface.

3. FUEL GAS

The fuel gas used was mains town gas, an average analysis for the period of most of the experiments being given in Table 1(2). Over this period the composition was fairly constant and it is unlikely that its combustion properties varied significantly, although in a few measurements made later on (e.g. the air flow measurements of Section 4.2) the gas composition was found to be slightly different and the stoichiometric air/fuel ratio and combustion products were specially recalculated.

Table 1

Town gas composition

Constituent	Per cent by volume	Per cent by weight
CO	22	40
CH_4	16	17
N_2	6	11
CO_2	4	11
Unsaturated hydrocarbons, assumed C_4H_8	3	11
H_2	47	6
C_2H_6	1	2
O_2	1	2

Average combustion data for the dry gas, calculated from data supplied by the Eastern Gas Board, are given in Table 2.

Table 2

Town gas combustion data (average for the period of most of the experiments)

Density	0.69 g/l at N.T.P.		
Calorific value (net, water uncondensed)	4,200 cal/l at N.T.P. 6,400 cal/g		
Mean specific heat* between 0°C and t°C cal g^{-1} deg C^{-1}	t	Town gas	Stoichiometric combustion products (wet)
	0	0.51	0.26
	200	0.55	0.27
	400	0.58	0.28
	600	0.61	0.29
	800	0.64	0.29
	1000	0.67	0.30
Stoichiometric air requirement	4.1 vols dry air/vol dry town gas		
	8.2 g dry air/g dry town gas		
Stoichiometric combustion products	Constituent	Vols/vol dry unburned gas	Per cent by volume
	CO_2	0.56	12
	Water vapour	0.94	19
	N_2	3.34	69

*Taking values quoted by Spiers(3) for coal gas produced in continuous vertical retorts (steaming), which has a similar average composition.

4. MEASUREMENTS

The principal measurements made were:-

(1) Fuel gas flow

(2) Air flow into window opening

(3) Heat transfer to points within the compartment, and its components.

(4) Heat flow through the walls

(5) Temperature of gases leaving the compartment

(6) Radiation from window opening

(7) Position of the tip of the flame emerging from the window opening.

4.1 Fuel gas flow

The fuel gas flow was measured by means of orifice plates and pressure tappings in the supply line in an installation conforming to British Standard 1042(4). The differential pressure across the orifice plate was measured by means of an inclined-tube water manometer. It was found possible to calibrate the manometer absolutely by filling it with mercury and comparing with a water-filled U-gauge of suitable range. Four interchangeable orifice plates enabled a wide range of gas flow to be measured.

4.2 Air flow into window opening

An attempt was made to measure air flow directly with a compensated hot-wire anemometer(5). It was found that the reading of an anemometer placed low down in the plane of the window opening in the region where air was entering the compartment fluctuated too much to enable reliable velocity measurements to be made, apparently because of draughts in the laboratory and fluctuations in the lower boundary of the emerging flame.

However, an indirect measurement of an air flow was obtained for a town gas flow producing a flame just contained within the model, so that the combustion of the town gas was completed within the compartment. Determinations of the O_2, CO_2 and CO content of the effluent gas in the plane of the window opening and a knowledge of the town gas flow and composition enabled the inlet air flow to be found, as described more fully in Appendix 1.

The method cannot yet be extended to determine air flows when the flame is emerging from the opening since this would require a simple means of analysing all the constituents of unburned town gas as well as its combustion products. The air flow given by this method was 32.4 g/s for a window opening 19 cm high and 79 cm wide, and a town gas flow of 2.1 g/s.

The air flowing into a compartment can also be calculated by the method described by Kawagoe(6) in which the compartment is assumed to be full of hot stagnant gas so that the flow of air in and gases out of the compartment is caused by pressure differences. This assumption is most nearly true for small window openings though it is not yet known how large a window opening may be before the assumption is invalid. It will not necessarily be even approximately true for window openings which are large in relation to the size of the compartment, for example in cubical compartments with the window opening occupying the whole of one side.

With this assumption the air flow (M) into the compartment can be shown to be:-

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

where M = mass rate of air flow into compartment

R = mass rate of fuel flow

a = discharge coefficient of opening, taken as 0.7(6).

ρ_0 = density of ambient air

ρ_1 = density of hot gases within the compartment

A = window opening area

H = window height

In wood fires with compartments with a small window the mass air flow is several times the fuel flow and the density of the gases within and leaving the compartment can be assumed to be equal to that of air at the same temperature. The density ratios in equation (1) can then be replaced by the inverse ratios of the absolute temperatures. In some cases, however, this assumption is unjustified, e.g., in the present experiments at the highest town gas flows where the mass air flow is about the same as the mass flow of town gas and the specific gravity of the fuel gas is about 0.5.

The above equation gives 32.0 g/s in the situation described above which agrees closely with the experimental value of 32.4 g/s. It is reasonable to assume that provided the conditions (e.g. window size, flame shape etc.) are not too different from those obtaining during the experimental verification of equation (1) the air flow into the model can be calculated with sufficient accuracy for other town gas flows.

The air flow measurements were made with a window area of 4 per cent of the total area of the compartment and the agreement between air flow calculated by the method of Kawagoe and that measured lends support to the suggestion of Thomas and Hinkley(7) that the small window regime will apply to fully developed fires in compartments having an area of openings up to at least 5 per cent of the total area of the compartment (corresponding to about $\frac{1}{3}$ of the area of one side of a cube). Although the pressure within the compartment was not measured the satisfactory use of the above equation implies that the pressure differences calculated during the course of its derivation can also be regarded as correct.

4.3 Heat transfer

Two instruments have been developed to measure heat transfer within the compartment.

The first(8) measured total heat flux from the temperature rise of water flowing through a receiver. The instrument was mounted on the end of a 4 ft long probe so that it could be placed in various positions and point in various directions in the compartment.

The second(9) was developed to separate the convection and radiation components of heat flux. The receiver mounted on the end of a probe was a similar size and shape to the total heat-flux meter but consisted of two separated segments of copper, one gold plated and one blackened.* The receiver was placed in the model and a shield covering the receiver was removed. From the rate of rise of temperature of the segments the convection and radiation components were obtained.

It was found possible to make use of the small time constant (about 1.4 s) of the total heat-flux meter to separate flame and wall radiation.(8) The output from the heat-flux meter was proportional to total heat transfer and was recorded continuously on a pen recorder during the period immediately before and after abruptly turning off the fuel gas supply. The traces obtained were of the form shown in Fig 2. The sharp increase in the heat transfer just after turning off the town gas supply in Fig 2 (b) was due to the flame falling back past the heat-flow meter. Apart from convection transfer from heated air, which was shown by the convection/radiation heat-flux meter to be small (about 0.04 cal cm^{-2} s^{-1} for town gas flows of 4.5 and 12 g/s, and 0.01 cal cm^{-2} s^{-1} for a flow of 21 g/s) the radiation from the walls was given by a very simple numerical extrapolation to the time of turning off the town gas flow (Appendix III). The transient effect of the flame dying away lasted less than 2 s and was ignored. The reading before turning the town gas supply off was made up of radiation from the flames both directly and after reflection from the walls, radiation from the walls after absorption in the flame, and convective transfer from the flame.

With the flame established the total heat flow Q, to the meter is

$$Q = R_F + R_W(1 - a_F) + C \qquad \text{..........} (2)$$

where R_F is the flame radiation component

R_W the wall radiation component

a_F the effective absorptivity of the flame

and C the convective heat transfer component.

Since Q, R_W and C can be measured R_F can be found if a_F is known. a_F could not be directly measured under the conditions of the experiment but the emissivity of town gas flames in the open has been measured(1) by two methods(10, 11) and values found in the range 0.1 to 0.15 for a 30 cm flame thickness, which is about the thickness of flame in the model compartment.

The flame and wall radiation values obtained (Table 3) depend, to some extent, on the value taken for flame absorptivity and because of this uncertainty are only approximate. These results will be discussed in part II of this series of reports.

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*The reflectivity of the gold segment was separately measured.

Table 3

Dependence of heat transfer components on the value taken for flame absorptivity

Heat transfer component cal cm^{-2} s^{-1}	Town gas flow g/s								
	4.5			12			21		
	Absorptivity (a)			Absorptivity (a)			Absorptivity (a)		
	0.05	0.1	0.2	0.05	0.1	0.2	0.05	0.1	0.2
R_W	1.75	1.75	1.75	0.75	0.75	0.75	0.4	0.4	0.4
C	0.25	0.25	0.25	0.2	0.2	0.2	0.2	0.2	0.2
$(1 - a)R_W$	1.7	1.6	1.4	0.7	0.7	0.6	0.4	0.35	0.3
R_F	0.6	0.7	0.9	0.25	0.25	0.35	0.05	0.1	0.15
Total	2.55			1.15			0.65		
Measured total	2.6			1.0 to 1.1			0.6		

4.4 Heat flow through the walls

The heat flow through the asbestos wood pieces inserted into the walls and ceiling was estimated by means of standard heat loss formulae(3) from the exterior surface temperature, this being measured by thermocouples cemented into grooves in the surface with "Autostic" high-temperature cement.

The heat flow per unit area through the pieces was slightly higher than that through the walls since the steel sheet and air gap increased the wall insulation, but it was more reproducible since the steel sheet buckled when it became hot and the air gap did not remain constant. This did not apply to the ceiling heat flow block since the ceiling was not covered with steel sheet.

The heat flow through the whole of the walls ceiling and floor was obtained from the heat flows through the wall or ceiling blocks by making a small correction for the extra insulation of the steel sheet and air gap, assuming that the average heat flow over a wall or ceiling was the same as the heat flow at its centre. An allowance was made for the heat lost through the mica windows.

4.5 Temperature of exit gases

An estimate of the temperature of the exit gases was obtained with four 28 s.w.g. (0.4 mm dia.) chromel-alumel thermocouples mounted in the plane of the window opening, 1.9 cm apart in a vertical line in the centre of the window (Fig 1). The wires near the thermojunctions ran horizontally in the window plane. The thermocouples read low by an amount probably not exceeding 270 deg C (Appendix II). A more accurate method, depending on a heated-shield suction pyrometer, is being developed.

4.6 Radiation from window opening

The radiation passing through the window opening, was measured by setting up the total heat-flux meter with its receiver in the plane of the window opening, in the region where air was entering.

4.7 Flame trajectory

The position of the tip of the flame emerging from the window opening was estimated by eye from the side, against a grid of 1 ft squares, allowance being made for parallax error.

5. ACKNOWLEDGEMENTS

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APPENDIX I

Measurement of air flow into the window opening by analysis of the effluent gas

Samples were extracted from the effluent gases at a number of points in the plane of the window opening by means of a water-cooled probe, and subsequently analysed with an Orsat apparatus. No carbon monoxide was found although the Orsat apparatus could have detected the presence of 0.2 per cent, and the combustion was therefore assumed to be complete.

From the composition of the town gas used in these experiments it was calculated that 1 litre burned stoichiometrically with 4.60 litres air, produced 0.99 litres water vapour, 0.625 litres CO_2 and 3.69 litres nitrogen.

Thus if the ratio of volumetric air flow into the window opening to volumetric town gas flow was A, the constituents of the effluent gas were in the following volumetric proportions:-

Water vapour	0.99
CO_2	0.625
N_2	$3.69 + (A - 4.60)\ 0.79$
O_2	$0.21\ (A - 4.60)$

The mean concentrations of oxygen and carbon dioxide were:-

$$(\bar{O}_2) = 21\ \frac{(A - 4.60)}{(A + 0.705)}$$

$$(\overline{CO}_2) = \frac{62.5}{A + 0.705}$$

$$\text{Thus} \qquad A = \frac{0.705\ (\bar{O}_2) + 96.6}{21 - (\bar{O}_2)}$$

$$\text{and} \qquad A = \frac{62.5 - 0.705\ (\overline{CO}_2)}{(\overline{CO}_2)}$$

The concentrations of both oxygen and carbon dioxide were used to obtain independent estimates of A, and hence the rate of flow of air into the window opening was found since the town gas flow was known.

The Orsat apparatus effectively measured the concentration of constituents in the dried gas and in order to find the actual concentration in the effluent gases, an allowance for the water vapour contained in them was necessary.

There was some stratification in temperature, in O_2 and CO_2 concentrations, and in velocity so that it was necessary to weight the concentration values accordingly before a mean concentration could be obtained.

APPENDIX II

Error in the measurement of the exit gas temperature

The order of magnitude of the error in the exit gas temperature measured by means of 28 s.w.g. chromel-alumel thermocouples can be found from the heat balance for the thermojunction, neglecting conduction along the wires since they lie along isotherms:-

$$I\psi\, 2\pi r a \quad + \quad 2\pi r h\ (T^1 - T) \quad = \quad 2\pi r \sigma \epsilon T^4 \qquad \ldots\ldots\ldots\ (3)$$

Radiation absorbed by thermojuction	Convection transfer to thermojunction	Radiation emitted by thermojunction

where r is the radius of thermojunction, assumed to be a long horizontal cylinder at right angles to the direction of gas flow

ϵ is the emissivity of thermojunction

a is the absorptivity of thermojunction

h is the convection transfer coefficient

T is the absolute temperature of thermojunction

T^1 is the absolute gas temperature

I is the intensity of radiation in the window plane

ψ is the configuration factor

Then the error in the measured gas temperature is

$$T^1 - T = \frac{\sigma \epsilon T^4 - I\psi a}{h}$$

I has been assumed to be equal to the intensity measured low down in the plane of the window opening (Section 4.6). h was calculated(12) for nitrogen, since this was the major constituent of the effluent gases.

Taking

$\psi = \frac{1}{2}$

$r = 0.04$ cm

$h = 0.0036$ cal cm^{-2} s^{-1} (12)

$\sigma = 1.36 \times 10^{-12}$ cal cm^{-2} s^{-1} deg C^{-4}

$a = \epsilon = 1$

we obtain the values of $T^1 - T$ given in Table 4.

Table 4

Error in effluent gas temperature measurement

Town gas flow g/s	Radiation intensity in plane of window opening cal cm^{-2} s^{-1}	Mean temperature of thermo-couples in plane of window opening °C	T^1-T deg C
4.5	1.6	735	170
9	1.1	755	270
25	0.7	535	60

The values of (T^1-T) in Table 4 are upper limits to the error since the true intensity of radiation at the thermojunction is somewhat higher than that in the lower part of the window opening, because of the configuration of the flame.

APPENDIX III

Estimation of wall radiation

To a first approximation the radiative heat transfer from the walls (Q_t) was found to vary linearly with the square root of time (t) after turning off the gas, so that the heat transfer at zero time (Q_o) was given by

$$Q_o = Q_t + at^{\frac{1}{2}} \qquad \text{..........} (4)$$

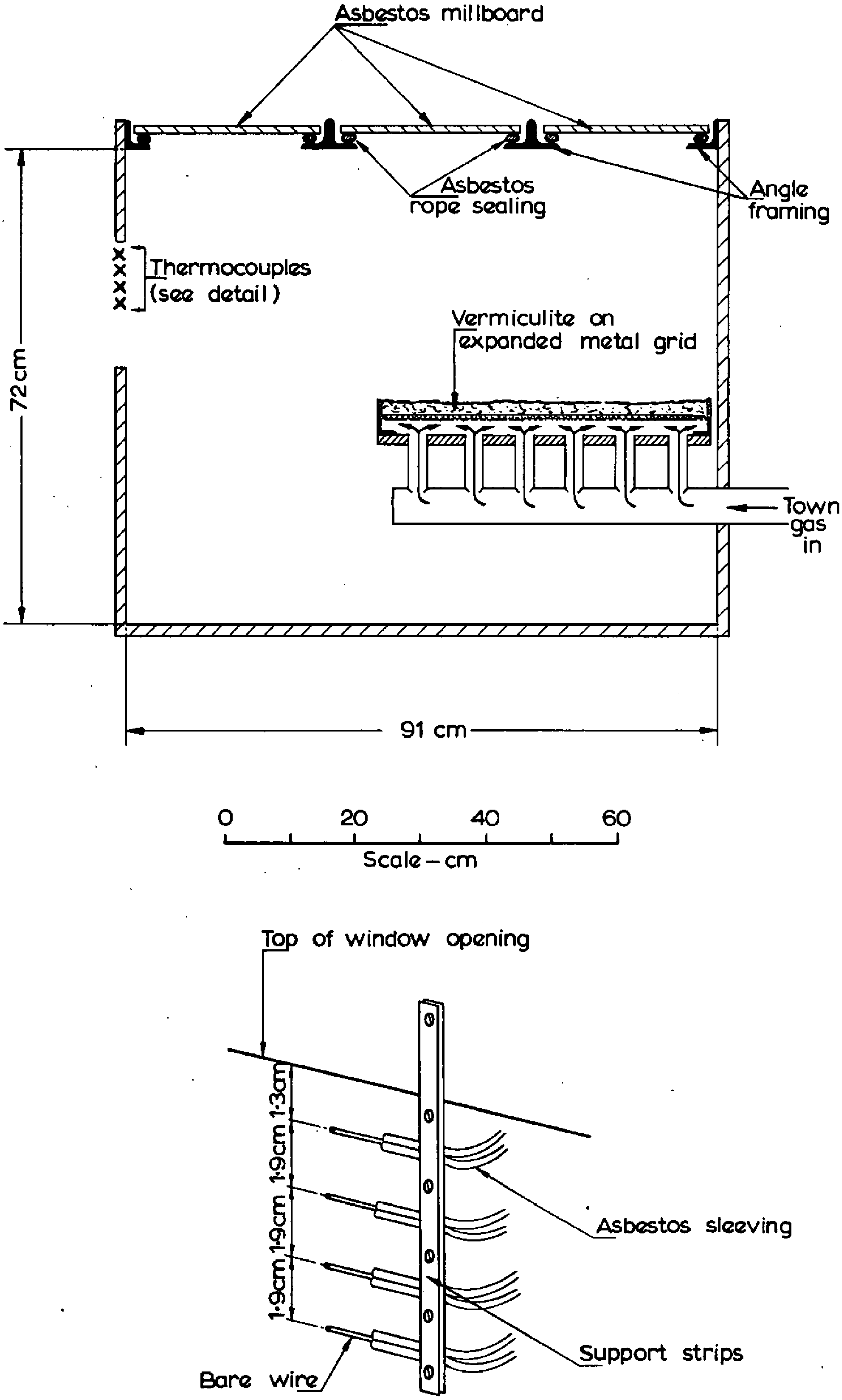
where a is a constant

Then, at t_1, $$Q_o = Q_1 + at_1^{\frac{1}{2}} \qquad \text{..........} (5)$$

and at $t_2 = 4t_1$, $$Q_o = Q_2 + 2at_1^{\frac{1}{2}} \qquad \text{..........} (6)$$

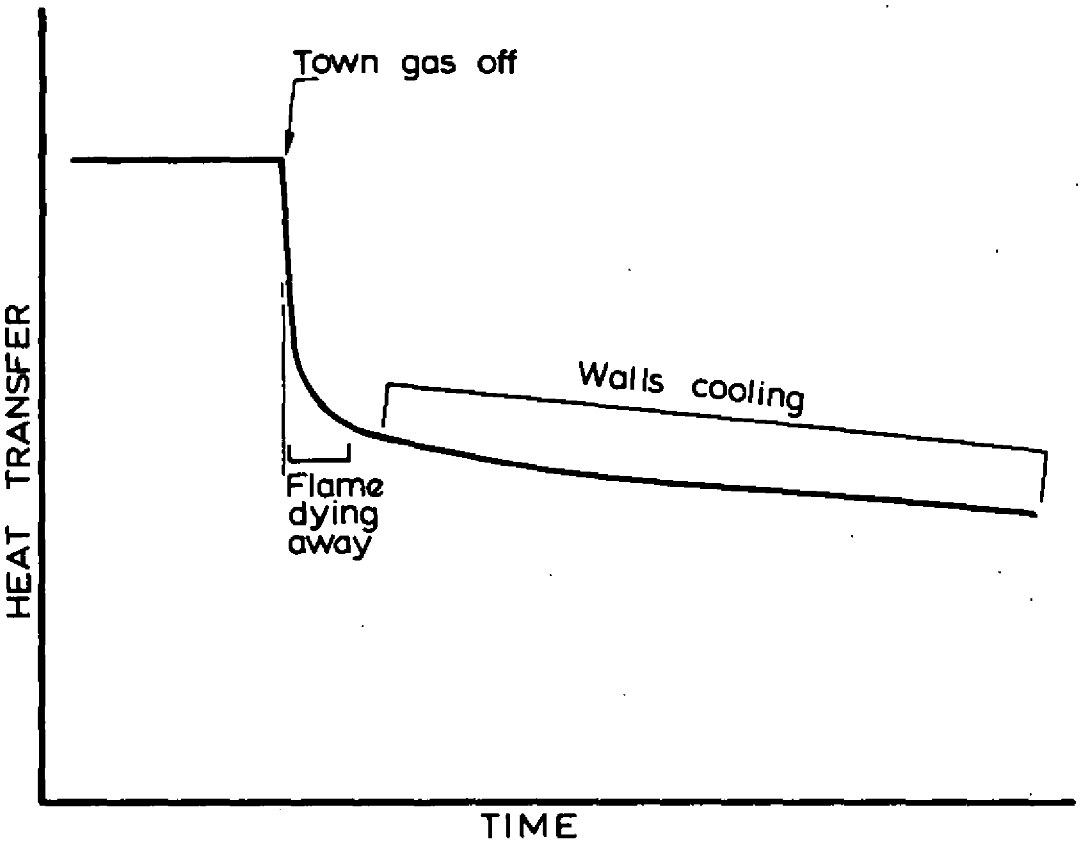
Thus from (5 and 6) $Q_o = 2Q_1 - Q_2 = Q_1 + (Q_1 - Q_2)$

Thus the heat transfer at zero time could be found by adding to the heat transfer at say 2.5 s the difference between the heat transfers at 2.5 and at 10 s.

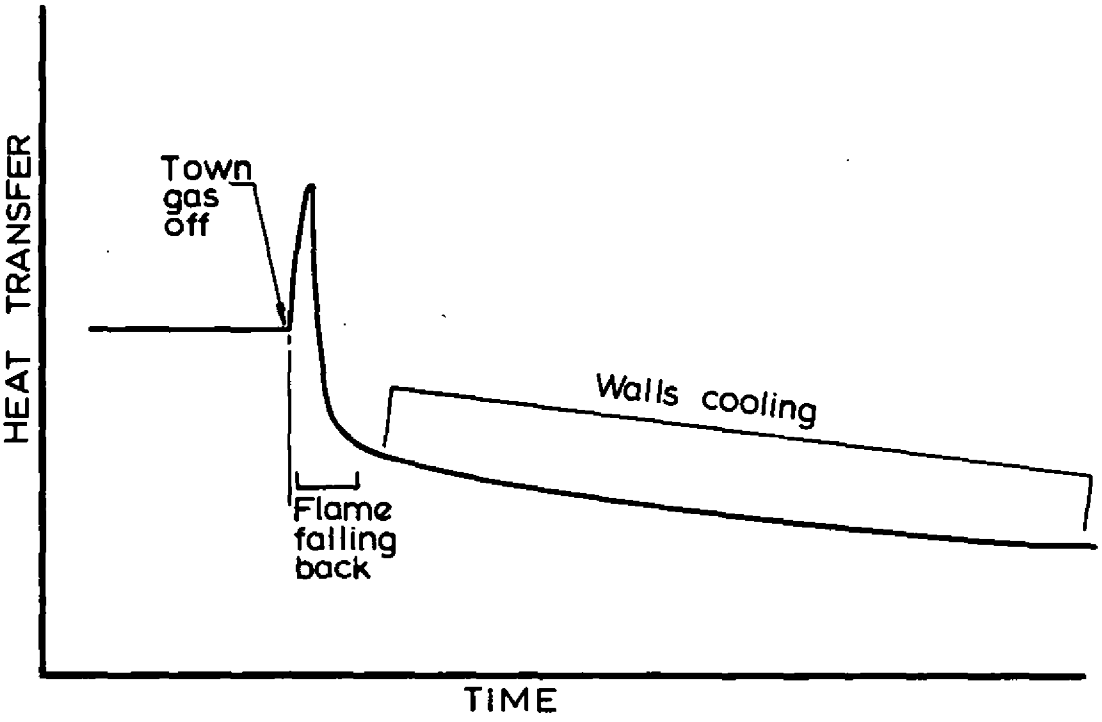


DETAIL OF THERMOCOUPLES

FIG. 1. SCHEMATIC SECTION OF THE MODEL COMPARTMENT IN A PLANE PERPENDICULAR TO THE PLANE OF THE WINDOW OPENING



(a) Town gas flow 4·5 g/s. Flame mainly inside compartment



(b) Town gas flow 21 g/s. Flame mainly outside compartment

FIG. 2. VARIATIONS IN HEAT TRANSFER AFTER TURNING OFF THE TOWN GAS SUPPLY