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A PRELIMINARY STUDY OF THE RADIATIVE PROPERTIES OF TOWN GAS DIFFUSION FLAMES

by

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

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SUMMARY

The methods used for finding the emissivity and temperature of a luminous flame were reviewed. The radiative properties of town gas flames burning in the open from a 30 x 30 cm porous burner were found using the Schmidt and Kurlbaum methods. The absorption coefficient of the flame was .005 cm^{-1} and its temperature was 1454°K. Large errors were found in thermocouple readings of flame temperature due to losses by radiation to the cold surroundings.

The construction of a partial wall around the burner reduced the temperature and absorption coefficient of the flame. An asbestos crib placed above the burner increased the flame temperature and absorption coefficient. There were changes in the shape of the flame in both cases.

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1. Introduction

The rate of spread of a fire is largely controlled by radiation from its luminous flames to the combustible surroundings. The amount of thermal radiation falling on a particular element removed from the flame is

$\sigma \psi \epsilon_f T_f^4$, where σ is the Stefan-Boltzmann constant ($= 1.36 \times 10^{-12}$ cal cm^{-2}s^{-1} ^{o}K^{-4})

ψ is the geometrical configuration factor (dimensionless)

ϵ_f is the emissivity of the flame (dimensionless)

T_f is the absolute temperature of the flame (^{o}K)

The geometrical view factor, ψ, is the fraction of energy radiated by the fire which is intercepted by the combustible element. It is a function of the geometrical shape and size of the fire and its position with respect to the element. Values of various configuration factors are given in the literature [1-5] in the form of tables, graphs and equations and will not be discussed here.

This report deals with the emissivities and temperatures of flames. It reviews some of the methods used for temperature and emissivity measurement and the factors affecting their magnitude. It also describes some preliminary experiments on the radiative properties of town gas flames.

2. Theory

2.1. Emissivity of Luminous Flames

A luminous flame consists of gaseous combustion products (mostly CO_2, H_2O, N_2 and excess air) and a dispersion of soot particles of sizes ranging between .006μ and 200μ depending on the type of fuel[4]. Flames of heavy residual oils contain particles having a size comparable with the original oil-drop size of 50-200μ. Powdered coal flames contain soot particles with an average size of 20μ. Gaseous fuels produce particles ranging in size from .006 - .06μ. The smaller particles are formed initially but they agglomerate into larger filamentary particles as they travel downstream with the flame. These particles assume the temperature of their surroundings quickly[6] and emit continuous thermal radiation which usually exceeds the band emission of the heteropolar gas gaseous molecules (CO_2 and H_2O) present in the combustion products.

The emissivity of the gaseous products, ϵ_g, can be found using the method described by Hottel[4]. The emissivity due to soot particles is difficult to estimate theoretically because of its dependence on particle size and concentration, both of which are functions of the type of fuel, the rate of fuel mixing with air, the amount and type of diluents and flame temperature.

The emissivity due to soot particles, ϵ_s, is usually given by

$$\epsilon_s = 1 - e^{-kd} \qquad (1)$$

where k = an absorption or extinction coefficient (cm^{-1})

d = a characteristic thickness of the flame (cm)

If it is assumed that the flame is homogeneous, that Kirchoff's Law applies (i.e. $\epsilon_g = \alpha_g$) and that the particles have no reflectivity (i.e. transmissivity $\tau_g = 1 - \alpha_g = 1 - \epsilon_g$) then

$$\epsilon_f = 1 - e^{-kd} (1 - \epsilon_g) \qquad (2)$$

These assumptions do not always hold. Powdered coal particles and the coke particles in oil flames are sufficiently large to be substantially opaque to incident radiation, whereas the soot particles in a luminous gaseous fuel flame (.006-.06μ) are smaller than the wavelengths at which thermal radiation is transmitted (0.3-50μ) and consequently interact with thermal radiation like semitransparent or scattering bodies.

For large opaque soot particles it can be shown[7] that

$$k = \frac{3}{4} \frac{v}{V} \cdot \frac{1}{r} = N_o \pi r^2 \qquad (3)$$

where v = total volume of fuel particles

V = gas volume

r = radius of particle

N_o = number of particles per unit volume of gas

Blokh[8] considered the interaction of electromagnetic waves with a dispersed turbid medium in which the diameter of the soot particles was much smaller than the radiation wavelength. He derived the following expression for k

$$k = \eta\,(1.56 \times 10^{-3}T - .64)\,\frac{C}{\rho} \qquad (4)$$

where η = a constant

T = temperature (^{o}K)

C = concentration of soot

ρ = specific gravity of soot

Based on the work of Mie[9] other expressions have been derived relating the absorption coefficient k (cm^{-1}), the radius of soot particles r (μ), their number density, N (particles/cm^3) and the wavelength λ (μ). One of these was that derived by Yagi[10]

$$k = 39.5\,\frac{r^3}{\lambda}\,N\left[1 - 15\left(\frac{r}{\lambda}\right)^2\right] \qquad (5)$$

All such equations are difficult to use when one tries to predict the value of k because r and N have to be found experimentally for that particular flame and one could just as easily measure the emissivity of the flame by one of the methods described below.

2.2. Problems in Measuring the Emissivity of Fires

Several methods have been employed for the measurement of the emissivity of homogeneous luminous flames. However, most of these methods give highly erratic results when the flame flickers or when there are large temperature gradients within the flame.

The flame of a slow burning fire consists of globules or cells containing a cold mixture of entrained air, combustible gases and combustion products. A thin shell surrounds these cells where combustion takes place basically by molecular diffusion even though the cells are in a state of continuous movement. For larger fires, these globules accelerate and break up into filaments with cooler air entrapped in between. Flickering causes large high frequency and amplitude fluctuations in thermocouple and pyrometer readings. In addition to the flickering of fires, there is always pulsation due to the "gulping" process of air entrainment which adds to the difficulty in obtaining accurate temperature and radiometric measurements. Thermocouple readings are further complicated by errors due to loss of heat by radiation to the cold surroundings through the flames. The errors could be very large, particularly for thin flames with low emissivities. These errors are discussed in the Appendix.

2.3. Methods for Measuring the Total Emissivity of Luminous Flames

2.3.1. The Schmidt Method

A total radiation pyrometer is sighted through the flame onto a cold black target to give a reading σR_1 (cal cm^{-2}s^{-1}). It is then sighted through the flame on a hot background wall to give a reading σR_2. Finally, it is sighted on the hot background alone to give σR_3. Now

$$\sigma R_2 = \sigma R_1 + \sigma R_3 \tau_f \qquad (6)$$

where τ_f = the transmissivity of the flame

$$R_1 = \sigma \epsilon_f T_f^4 \qquad (7)$$

When there is little difference between the hot background and flame temperatures

$$\tau_f = 1 - \epsilon_f$$

Combining this with equation (6) gives

$$\epsilon_f = \frac{R_1 + R_3 - R_2}{R_3} \qquad (8)$$

$$T_f = \left(\frac{R_1}{\epsilon_f}\right)^{\frac{1}{4}} \qquad (9)$$

2.3.2. The Kurlbaum[12] Method

If the hot background temperature could be changed until the pyrometer gave the same reading with and without the flame interposed (i.e. $\sigma R_2 = \sigma R_3$), then the flame temperature would be equal to the black body temperature of the background. Usually, it is inconvenient to adjust background furnace temperatures to give particular readings. Instead, several arbitrary steady state readings are made and a plot of σR_2 against σR_3 is prepared. The resulting curve is interpolated or extrapolated to find the point where $\sigma R_2 = \sigma R_3$ from which value the flame temperature can be calculated.

2.3.3. The Two Path Method

In order to obtain the monochromatic emissivity of a flame an optical pyrometer is sighted on the flame with and without a mirror in the background. If a filament pyrometer is used, then it will read two temperatures: T_{r1} for one flame thickness and T_{r2} when the pyrometer receives radiation from the flame and from its reflection in the mirror.

Using Wien's Law

$$c_1 \lambda^{-5} e^{-c_2/\lambda T_{r1}} = \epsilon_{\lambda,f}\, c_1 \lambda^{-5} e^{-c_2/\lambda T_f} \tag{10}$$

$$c_1 \lambda^{-5} e^{-c_2/\lambda T_{r2}} = \epsilon_{\lambda f}\, c_1 \lambda^{-5} e^{-c_2/\lambda T_f}(1 - \tau_{\lambda f}\rho_m) \tag{11}$$

where C_1 = Planck's first constant

C_2 = 1.4387 cm °K

λ = the dominant wavelength for the optical pyrometer, usually red (.6651 x 10^{-4}cm)

$\epsilon_{\lambda,f}$ = the flame emissivity at that wavelength

$\tau_{\lambda,f}$ = the flame transmissivity at that wavelength

ρ_M = the mirror reflectivity

T_f = flame temperature

Equations (10) and (11) can be solved for $\epsilon_{\lambda f}$ and T_f

$$\epsilon_{\lambda,f} = 1 - \frac{e^{-\frac{c_2}{\lambda}\left(\frac{1}{T_{r2}} - \frac{1}{T_{r1}}\right)} - 1}{\rho_m} \tag{12}$$

$$T_f = \frac{1}{\frac{1}{T_{r1}} + \frac{\lambda \ln \epsilon_{\lambda,f}}{c_2}} \tag{13}$$

2.3.4. Hottel and Broughton's[13] Method

In order to obtain the total emissivity one needs ϵ_λ as a function of λ because :

$$\epsilon_f = \frac{\int_0^\infty \epsilon_\lambda \, R(\lambda T) \, d\lambda}{\int_0^\infty R(\lambda T) \, d\lambda} \qquad (14)$$

where

$$R(\lambda T) = c_1 \lambda^{-5} e^{-c_2/\lambda T}$$

Hottel and Broughton[13] found that ϵ_λ for a luminous flame can be written in the form

$$\epsilon_\lambda = 1 - e^{-kd/\lambda^n} \qquad (15)$$

where $n = .95$ for $\lambda > .8\ \mu$

$n = 1.39$ for $\lambda < .8\ \mu$

since $\epsilon_\lambda R(\lambda T) = R(\lambda T_\lambda) = C_1 \lambda^{-5} e^{-C_2/\lambda T_\lambda} = \epsilon_\lambda C_1 \lambda^{-5} e^{-C_2/\lambda T_f}$

where T_λ is the brightness temperature

then $$\frac{1}{T_f} - \frac{1}{T_\lambda} = \frac{\lambda}{C_2} \ln \left\{1 - e^{-kd/\lambda^n}\right\} \qquad (16)$$

From one measurement of T_λ with an optical pyrometer and a knowledge of T_f, one can obtain kd from which ϵ_f can be evaluated by equation (14). Hottel[4] gives the integration in the form of curves.

2.3.5. Two Colour Method

If an optical pyrometer is sighted at the flame with two colour filters such as red and green interposed individually between it and the flame, two different temperatures will be read T_r and T_g respectively.

From equation (16)

$$\frac{1}{T_f} - \frac{1}{T_r} = \frac{\lambda_r \ln \epsilon_r}{C_2} \qquad (17)$$

$$\frac{1}{T_f} - \frac{1}{T_g} = \frac{\lambda_g \ln \epsilon_g}{C_2} \qquad (18)$$

Combining these two relationships with equation (15) one can solve for kd and T_f and eventually obtain ϵ_f from equation (14). The tedious work involved is eliminated by using the graphs of Hottel[4].

2.3.6. Method of Daws and Thring[14]

This method is quite similar to the two colour method. It involves taking two radiation intensity readings again. One is made with an optical pyrometer while another is obtained with a total radiation pyrometer. Two graphs are then used to obtain T_f and ϵ_f.

3. Experimental Results and Discussion

Town gas* was burned at the rate of 4 l/s in a 30 cm square porous burner placed horizontally and the radiative properties of the resulting flame were studied at a height of about 35 cm from the surface of the burner. Eleven S.W.G. 40 Chromel-Alumel thermocouples were stretched horizontally parallel to the burner surface at a height of 35 cm and were spaced at 3.8 cm intervals. A 30 cm diameter furnace having a 4 cm opening served as a black body source. A variable transformer was

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*The composition of the town gas employed was approximately

CO_2 = 5%, O_2 = 1.5%, C_nH_{2n+2} = 14.5%, C_nH_{2n} = 4.5%

H_2 = 44%, CO = 20.5%, N_2 = 10%

used to change the furnace temperature. Four Pt/Pt 13 per cent Rh thermocouples protruding about 0.5 cm into the furnace gave the temperature of the furnace. The narrow angle total radiation pyrometer and the furnace opening were aligned at a height of 32 cm above the burner. A diagram of the apparatus is shown in Figure 1.

3.1. Emissivity of Open Town Gas Flames

The Schmidt and Kurlbaum methods were used to evaluate the flame emissivity and temperature. A narrow angle total radiation pyrometer was sighted at the spherical furnace aperture with and without the flame interposed and at the flame with a water cooled blackened target in the background. Values of the emissivity at different hot background temperatures (T_b) were valculated using equation (8) and are given in Table 1.

Table 1

Emissivity of the Flame as Calculated by the Schmidt Method

T_b (°C)	R_1 (°K^4)	R_2 (°K^4)	R_3 (°K^4)	ϵ_f
733	.535 x 10^{12}	1.150 x 10^{12}	.860 x 10^{12}	.285
771	.661	1.480	1.025	.201
830	.585	1.570	1.292	.238
870	.585	1.787	1.465	.180
888	.576	1.920	1.557	.137
945	.585	2.240	1.944	.149
973	.556	2.390	2.108	.130
1013	.585	2.675	2.412	.133
1046	.576	2.860	2.635	.133
1069	.640	3.085	2.815	.131

The calculated flame emissivities were high at low background temperatures but decreased to a steady level of about .132 as the temperature of the background source approached the temperature of the flame. A flame temperature of 1454°K (1181°C) was calculated from equation (9).

Figure 2 is a plot of R_3 against R_2. The point at which $R_3 = R_2$ was found by linear extrapolation. It gave about the same temperature as that calculated by Schmidt's method (viz. 1454°K). The black body furnace temperature could not be raised to this value in order to check its accuracy.

The average radiative flame temperature = $\sqrt[4]{\frac{\int_0^d T^4 dx}{d}}$ was found to be 1014°K, from the profile recorded by the thermocouples. The flame thickness, d, was arbitrarily defined as the distance between the two horizontal points in the flame where the temperature was 300°C. The maximum temperature read by the thermocouples was 1223°K. Theoretically, a temperature of 1241°K was calculated for a thermocouple placed at the axis of a cylindrical flame having properties similar to those of the town gas flame employed in this study. (See Appendix).

The flame absorption coefficient was found to be .005 cm^{-1} with the flame thickness, d, as defined above.

3.2. Effect of Enclosing the Fire

Experiments were conducted in which a wall was built around three sides of the burner. Temperature profiles taken at the same level from the burner surface are shown in Figure 3 for different wall heights. It is seen that the flame temperature is reduced and that the flame shifts towards the back wall. The emissivity was also calculated by the Schmidt method and is given in Table 2. The emissivity and absorption coefficient of enclosed flames were lower than those obtained for flames in the open and their values decreased with increasing wall height. This could be attributed to the decrease in k with the decrease in temperature as given by equation (4).

Table 2

Effect of Partially Enclosing the Flame with Side Walls on the Radiative Properties of the Flame

Wall Ht. (cm)	Flame Depth (cm)	Max. Temp. (°K)	ϵ_f	k(cm^{-1})
0	28.4	1223	.132	.00500
5.1	24.7	1158	.100	.00425
7.6	23.1	1038	.086	.00389
12.7	21.3	958	.067	.00325

A least square fit of k against maximum temperature (Figure 4) gave the relation

$$k = 6.03 \times 10^{-6} T - .0025 \qquad (19)$$

This equation can be changed into the form of equation (4) assuming a constant soot concentration:

$$k = .00391 \ (1.542 \times 10^{-3} T - .64) \qquad (20)$$

It is interesting to note that the coefficient of T is quite close to that predicted theoretically by Blokh (viz. 1.56×10^{-3}).

3.3. Crib Effect

A crib consisting of layers of seven asbestos wood rods of rectangular cross section (1 cm x 2.5 cm x 30 cm) was built above the burner. The spacing between the rods was 3.8 cm. Cribs of one, two and three layers were employed and the temperature profiles found with the thermocouples laid out in a line parallel and perpendicular to the direction of the rods in the top layer of the crib. These profiles are shown in Figure 5 and 6. There was a marked difference between the profiles taken in the two thermocouple orientations. Visually, the shapes of the flames viewed in both directions were also different and are sketched in Figure 7. The effect of the crib was to make the flame thinner in the direction parallel to the top layer and thicker in the direction perpendicular to the top layer. It is difficult to say from the reported data (Table 3) whether the thinning of the flame in one direction and thickening in another was related to the orientation of the sticks in the top layer, or to the predominance of sticks orientated in one direction in the whole crib. The optical pyrometer gave a higher reading when sighted perpendicular to the top layer of the crib than when it was parallel to it, because of the difference in flame depth.

The Schmidt method was used to calculate the emissivities of some of these flames and the results are given in Table 3. This investigation was terminated because of the failure of the background black body furnace.

Table 3

Radiative Properties of Crib Flames

	Orientation of thermocouples w.r.t. top layer	ϵ_f	k (cm^{-1})	Flame width (cm)	Equivalent black body temperature of the flame measured by Optical Pyrometer °C
No crib	-	.132	.005	28.4	827
One layer	$\perp$			40.6	850
	$\parallel$	.114	.00582	20.8	825
Two layer crib	$\perp$	.128	.00612	22.4	755
Three layer crib	$\perp$			28.2	725
	$\parallel$	.094	.00525	17.3	712

4. Conclusions and Recommendations

1. Diffusion town gas flames burning in the open above a 30 x 30 cm square burner have an emissivity of 0.132, a temperature of 1454°K, and an absorption coefficient of .005 cm^{-1}. These values were found by the Schmidt method. The Kurlbaum method confirmed the calculated temperature.

2. Large errors are always present when thermocouples are used to measure temperatures of thin flames of low emissivity. A town gas flame should begin to behave as a black body (ϵ_f.95) when its thickness is greater than 600 cm. Only then will thermocouple errors be small.

3. The construction of a partial wall around a fire decreased the temperature of the flames and tilted the flames toward the wall.. The emissivity and absorption coefficient at a particular level of the flame were decreased.

4. The presence of a crib above the burner increased the absorption coefficient and the average temperature of the flame. The orientation of the sticks in the crib seemed to influence the shape and temperature profile of the flame.

5. Further studies are recommended to investigate the dependence of the absorption coefficient on temperature. This could be done using the same apparatus but with emissivity and temperature profiles measured at different heights above the burner.

6. The absorption coefficients of the flames from wood cribs of varying bulk density should be found by the Schmidt method. These values would be useful in making predictions of radiation from large scale flames.

7. In order to complete the picture of the radiative properties of luminous flames, a thorough study of soot concentration and particle size in fires and the factors affecting them is necessary.

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APPENDIX

Thermocouple Error

A thermocouple immersed in a luminous flame will receive heat by radiation and convection from the surrounding hot gases and lose heat by radiation through the partially transparent flames to the cold surroundings. Its reading will thus be lower than the flame temperature. A heat balance on a thermocouple placed in a gray flame gives

$$hA\,(T_f - T_c) + \sigma\,\epsilon_f \alpha_c\,A\,T_f^{\,4} + \sigma\,A\,(1-\epsilon_f)\alpha_c\,T_a^{\,4} = \sigma\,\epsilon_c\,A\,T_c^{\,4} \qquad \text{(A-1)}$$

where h = heat transfer coefficient by convection (cal $cm^{-2}s^{-1}\,{}^{o}C^{-1}$)

A = area of thermocouple (cm^2)

T_f = flame temperature (${}^{o}K$)

T_c = thermocouple reading (${}^{o}K$)

ϵ_f = emissivity of the flame

$\epsilon_c = \alpha_c$ = emissivity and absorptivity of the thermocouple

T_a = ambient temperature (${}^{o}K$)

A theoretical estimate of a thermocouple reading was made for the town gas flame employed in this study. The thermocouple (S.W.G. No. 40) was assumed to have a diameter at the junction of twice the wire diameter. The calculation was made for a thermocouple placed at the axis of a cylindrical flame having the same size, radiative properties and temperature as of the flame used (i.e. $d = 28.6$ cm, $k = .005\ cm^{-1}$, $T_f = 1454\ {}^{o}K$). The velocity of combustion products in these flames is of the order of 100 cm/sec. Assuming that the properties of the combustion gases were those of air at $1454^{o}K$, a Reynolds number of 1.1 was calculated.

For $1 < Re < 4$, the heat transfer coefficient h can be estimated from

$$\frac{hD}{K} = .891\ Re^{.33} \qquad \text{(A-2)}$$

where D = wire diameter

K = thermal conductivity of the gas

Re = Reynolds number

Equation (A-2) gave a value of $h = 0.0104$ cal $cm^{-2}s^{-1}{}^{o}C^{-1}$

The beam length in a cylinder radiating to a point at its base varies between 0.77 and 0.9 of the diameter[16]. Since the emissivity of 0.132 was measured across a flame thickness of 28.4 cm (See Table 2) the appropriate beam length between the cylindrical flame and the thermocouple at the axis would be about 23.6 cm. With the absorption coefficient calculated previously ($k = .005$ cm^{-1}) and this beam length a flame emissivity of 0.113 was found. Substituting these values into equation (A-1) and using $\alpha_c = 0.87$ and $T_a = 300^oK$ gave a theoretical thermocouple temperature of 1241^oK.

This means that an error of 213^oC was possible in the thermocouple reading.

Actually, the calculation had been simplified a great deal because flames are usually non-cylindrical and their emissivity, absorptivity and transmissivity are functions of the path of radiation within the flame and thus the thermocouple position in the flame.

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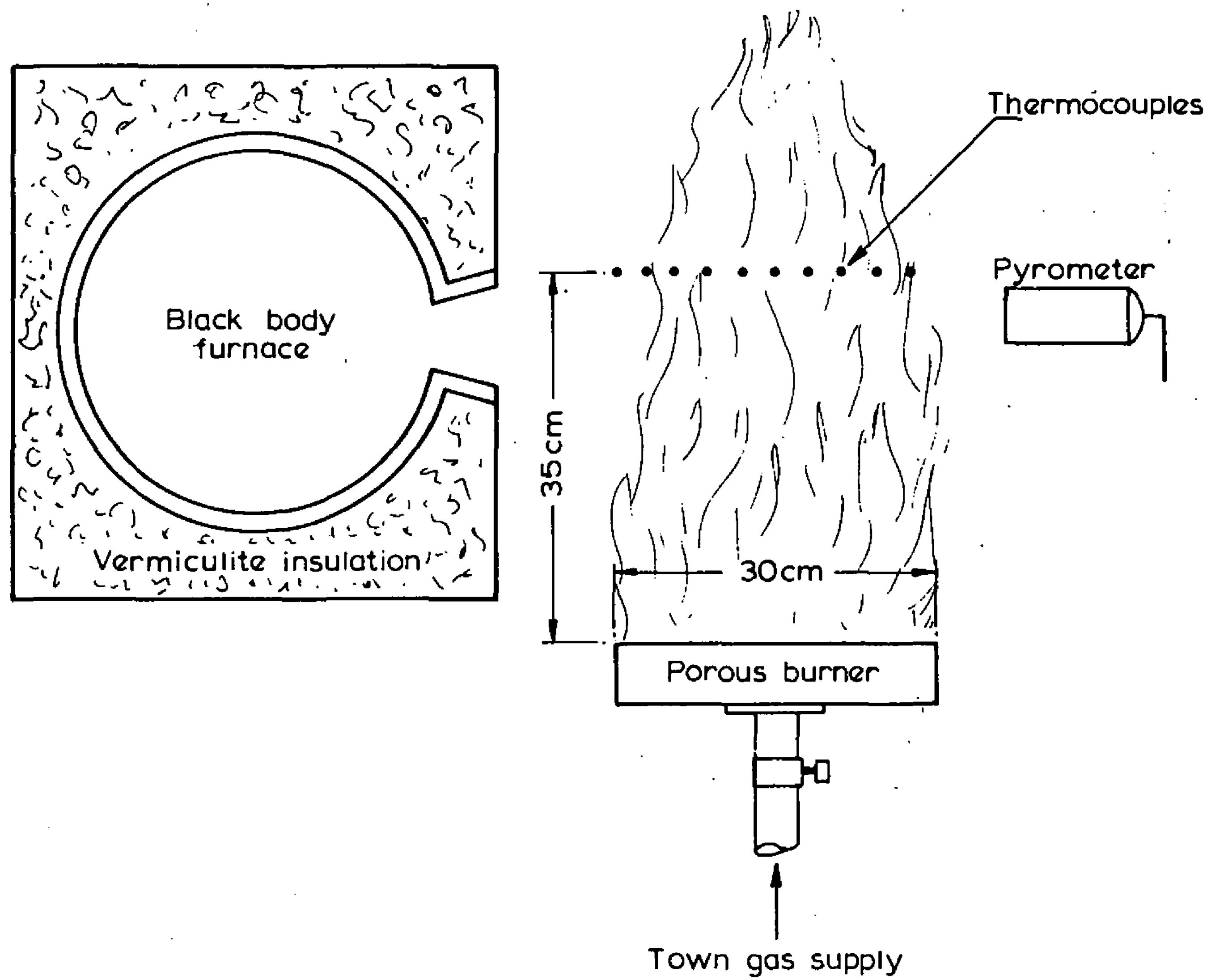

FIG. 1. APPARATUS FOR STUDYING RADIATIVE PROPERTIES OF FLAMES

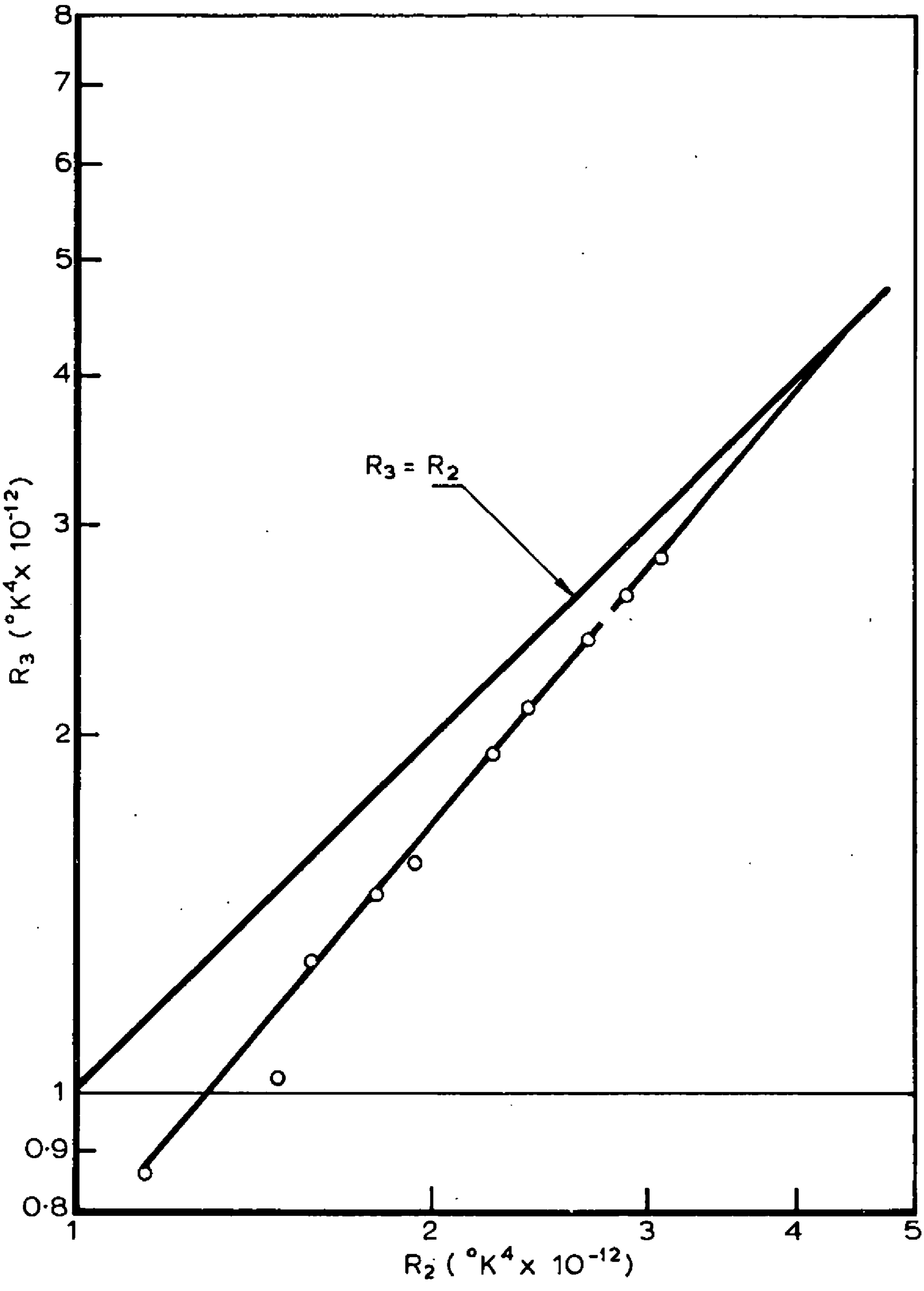

FIG. 2. CALCULATION OF FLAME TEMPERATURE BY KURLBAUM'S METHOD

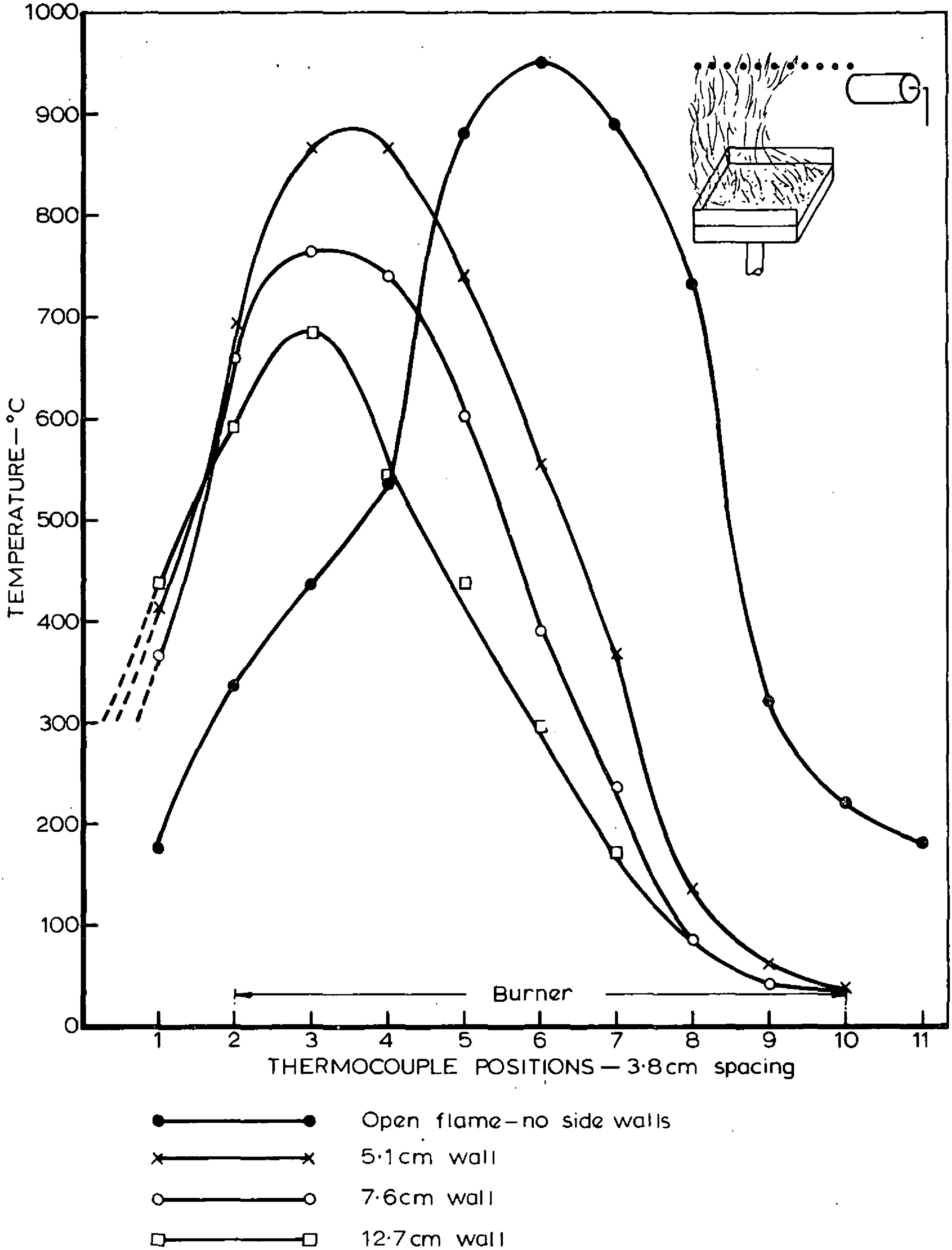

FIG. 3. EFFECT OF THREE SIDE WALLS OF DIFFERENT HEIGHTS ON THE TEMPERATURE PROFILE

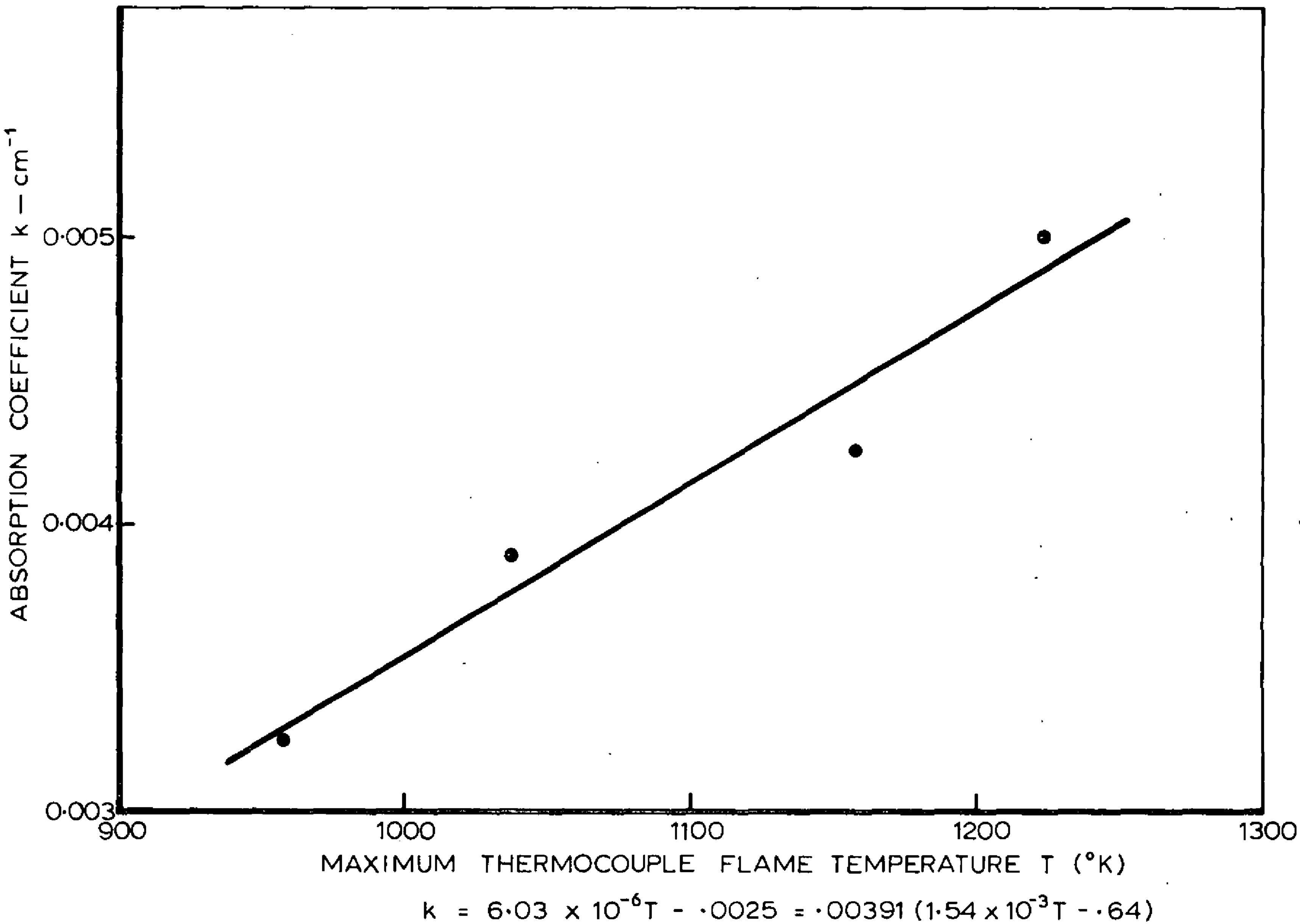

FIG. 4. EFFECT OF FLAME TEMPERATURE ON ABSORPTION COEFFICIENT

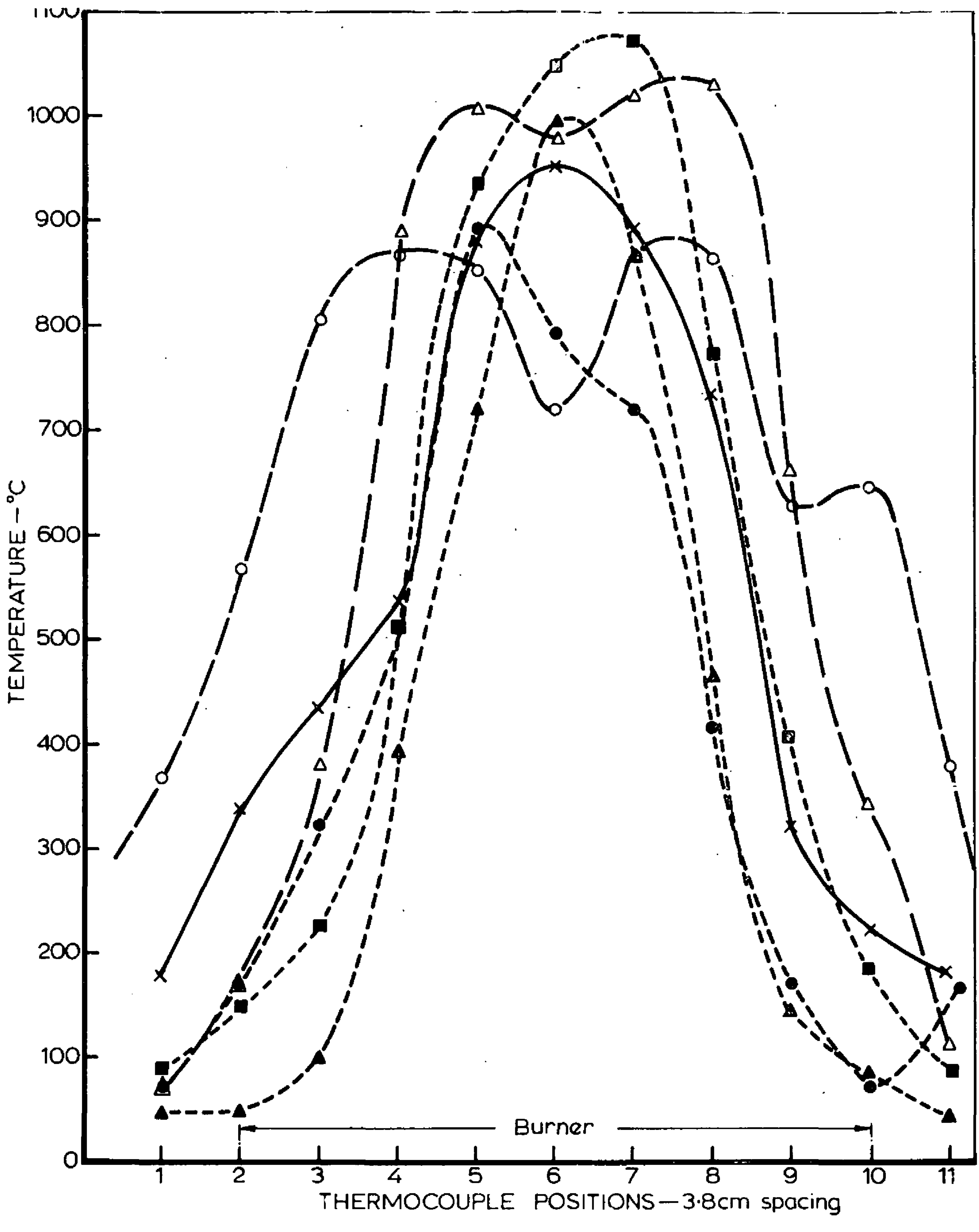

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FIG. 5. TEMPERATURE PROFILES ABOVE THE BURNER WITH AND WITHOUT CRIBS. THERMOCOUPLES WERE PLACED PARALLEL AND PERPENDICULAR TO THE TOP CRIB LAYER

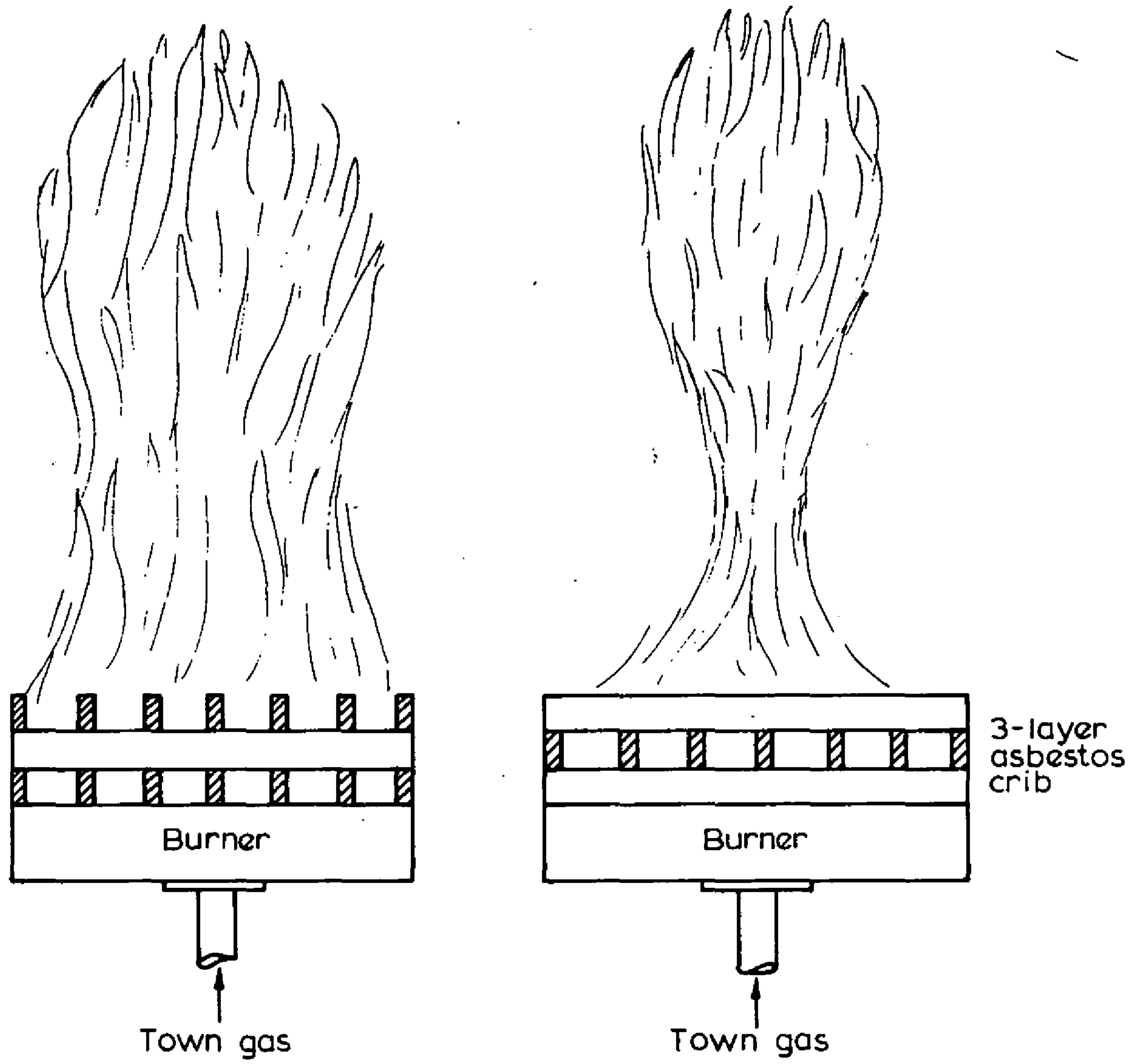

FIG. 6. TYPICAL SHAPE OF THE FLAME WITH A CRIB OF THREE LAYERS VIEWED PARALLEL AND PERPENDICULAR TO THE TOP LAYER

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