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THE EVAPORATION OF WATER DROPS IN A BUNSEN FLAME

by

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Summary

A study has been made of the evaporation in a bunsen flame of water drops suspended on quartz fibres. It was found that in the range of drop sizes investigated, 1.3 - 2.3 mm, the contribution of radiation to heat transfer was negligible in comparison with the contribution of convection, and that the heat transfer agreed with that calculated from Ranz and Marshall's law (3), if the calculated value of the heat transfer were multiplied by a constant factor of 0.63. An approximate formula has been developed to calculate the heat transfer by convection to water drops in a flame at a temperature different from that of a bunsen flame.

List of symbols

A	constant	
B	constant	
D	drop diameter	cm
D <sub>v</sub>	volumetric diffusivity	cm <sup>2</sup> /sec
F	$\frac{\rho \lambda}{4k \Delta T}$	
G	$0.3 \text{ Pr}^{\frac{1}{3}} \sqrt{\frac{\nu \rho}{\mu}}$	
H	heat transfer	cal/(cm <sup>2</sup> )(sec)
H <sub>c</sub>	heat transfer by convection	cal/(cm <sup>2</sup> )(sec)
H <sub>r</sub>	heat transfer by radiation	cal/(cm <sup>2</sup> )(sec)
K	constant	
L	latent heat of vaporization	cal/g
M	molecular weight of diffusing vapour	
P	total pressure	atm
R	gas constant	= 82 (atm)(cm <sup>3</sup> )/(°K)(mole)
T	absolute temperature	°K
T <sub>av</sub>	average film temperature	°K
ΔT	difference between gas temperature and	°C

a, b	drop dimensions	
$b_{g,w}$	molecular mass diffusivity $\frac{PM}{M'_{av}}$	$D_v$ g/(cm)(sec)
$C_p$	specific heat of gas at constant pressure	cal/(g)(°C)
h	heat transfer coefficient for convection	cal/(sec)(cm <sup>2</sup> )(°C)
k	thermal conductivity (subscript a and v for air and vapour respectively)	cal/(sec)(cm)(°C)
m	quantity of material vaporized	g
t	time	sec
v	gas velocity	cm/sec
y	$1 + G \sqrt{D}$	
$\lambda$	total heat of vaporization	cal/g
$\rho$	gas density	g/cm <sup>3</sup>
$\rho_l$	liquid density	g/cm <sup>3</sup>
$\mu$	gas viscosity	g/(sec)(cm)
Nu	Nusselt number for heat transfer	$\frac{h_c D}{k \Delta T}$ or $\frac{h D}{k}$
Pr	Prandtl number	$\frac{\mu C_p}{k}$
Re	Reynolds number	$\frac{v D \rho}{\mu}$
Sc	Schmidt number	$\frac{\mu}{b_{g,w}}$

Introduction

Work on the efficiency of water sprays in extinguishing liquid fires has indicated that heat transfer between flames and the water drops may be an important factor in determining the efficiency of the spray (1). In order to estimate this factor it is necessary to have some knowledge of the mechanism of heat transfer from flames to water drops and the laws which govern the heat transfer rate.

The total rate of heat transfer to a drop in a flame is due to a combination of radiation and convection. The radiation may be estimated from known laws if the temperature and emissivity of the flame and the emissivity and the absorbing factor of the drop are known. There is difficulty as a rule, however, in estimating the emissivity of the flame, especially if it is luminous. The convection will depend on the properties of the gases in the flame, the temperature difference between the drop and the flame and the relative velocity between the drop and the flame gases. Although the formula governing the evaporation of a drop into a moving air stream at room temperature has been well established by Frössling (2), work on heat transfer to evaporating drops at higher temperatures is scanty. Ranz and Marshall (3) have found that the following law, which is very similar to Frössling's law, governs the evaporation of water drops into air of temperatures up to 220°C and in a Reynolds number range of 0 - 200.

$$Nu = \frac{h D}{k} = 2.0 + 0.60 Pr^{\frac{1}{3}} Re^{\frac{1}{2}} \dots \dots \dots (1)$$

(for nomenclature see list of symbols on p. 1 - 2)

In equation 1,  $h$  is the heat transfer coefficient,  $(\text{cal}/(\text{cm}^2)(\text{sec})(^\circ\text{C}))$  and it will be noted that it does not depend directly on the temperature difference since the latter does not come into the equation. Gohrbrandt<sup>(4)</sup> however, who has worked on the evaporation of camphor balls in air at temperatures up to  $760^\circ\text{C}$  and at Reynolds numbers between 100 and 2,000 found that at the higher temperatures the heat transfer coefficient decreased with increase in temperature difference. This he ascribed to an increase in the width of the boundary layer due to the presence of diffusing camphor vapour. Gohrbrandt has given an equation which may be reduced to

$$\text{Nu} = \frac{\lambda}{\lambda + C_p \Delta T} K \text{Re}^{\frac{1}{2}} \dots\dots\dots(2)$$

where  $K$  is a constant varying from 0.58 - 0.66 for camphor vapour. This equation is similar to that which equation 1 would reduce to at high Reynolds number except that a factor has been introduced which reduces the value of the Nusselt number ( $\text{Nu}$ ) as the temperature difference ( $\Delta T$ ) increases. It may be noted that at the highest air temperature at which Ranz and Marshall worked, they obtained Nusselt numbers somewhat lower than those predicted from equation 1.

Ingebo<sup>(5)</sup> has studied the evaporation from a cork sphere of a series of liquids into air at temperatures between  $30 - 500^\circ\text{C}$  and a range of Reynolds numbers of 1000 - 6000. Ingebo expressed his results as follows

$$\text{Nu} = \frac{h D}{k_a} = \left( \frac{k_a}{k_v} \right)^{0.5} \cdot \left[ 2 + 0.303 (\text{Re Sc})^{0.6} \right] \dots\dots(3)$$

The theoretical background to this equation is obscure and it cannot be easily compared with the equations of the other authors. The Schmidt number ( $\text{Sc}$ ) is the ratio of molecular momentum transfer to molecular mass transfer and is usually used in conjunction with the Nusselt number for mass transfer, not heat transfer as in equation 3. The conductivity ratio  $\frac{k_a}{k_v}$  was introduced to compensate for difference in conductivity in the boundary layer due to the outward flow of vapour. Within the range  $30 - 500^\circ\text{C}$  the outward mass flow of vapour from a volatile liquid drop will vary over a wide range, yet this is not taken into account in this correction.

A calculation on Ingebo's data for water, benzene and methanol into air shows that the Nusselt number predicted from equation (1) of Ranz and Marshall was about 50 - 80% of that obtained by Ingebo which indicates that the experimental results of the two authors do not agree. The fact that Ingebo used a cork sphere from which to evaporate the liquids may have introduced a roughness factor which increased the turbulence and therefore the heat transfer rate. On the other hand, for nitrobenzene, the Ranz and Marshall equation predicts a heat transfer rate approximately the same as that obtained experimentally by Ingebo. This may be explained by Ingebo having neglected the sensible heat required to heat the liquid to its evaporating temperature at the surface. Although this would be justified for liquids of low boiling point or high latent heat, it would not be equally justified with a liquid such as nitrobenzene which is of high boiling point and low latent heat, and the error due to this factor may have cancelled the roughness error. The use of Ingebo's equation to calculate heat transfer from flames to evaporating water drops would be difficult, since information is required on the diffusion of water vapour into flame gases; this information is not available.

It may be concluded that in the region below  $500^\circ\text{C}$ , there is a divergence of opinion on the equation to be used to calculate heat transfer by convection to evaporating drops, although the equation of Ranz and Marshall appears to be the most accurate. At flame temperatures there is practically no information available. In order to obtain an estimate of the heat transfer between flames and drops a study has been made on the evaporation of water drops in a bunsen flame.

## Experimental

The apparatus used is shown in fig. 1. The bunsen burner A was 9 mm internal diameter and burnt a mixture of coal gas and air; these gases were fed to the burner at constant rates of 43.6 and 106 cc/second respectively. The composition of the coal gas was

	% by volume
Carbon monoxide	- 18.55
Unsaturated hydrocarbons	- 2.9
Saturated "	- 18.6
Hydrogen	- 49.5
Oxygen	- 0.65
Nitrogen	- 6.95
Carbon dioxide	- 2.85

The height of the flame was 13 cm and the height of the blue cone 3.0 cm. The lower part of the flame and the upper part of the burner were surrounded with a pyrex glass shield S to steady the flame.

A water drop suspended on a quartz fibre B could be swung from a position C, where its dimensions could be measured in a projecting system D, to a point E on the axis of the flame 9 cm above the rim of the burner. The flame at this level had a diameter of 2.0 cm. In the experiments a drop was placed on the quartz fibre by means of a fine pipette. The drop was placed in position C where its dimensions were measured. It was swung gently into point E in the flame and the time for its evaporation taken with the stop watch. The end point of the evaporation was made more easily visible by coating the fibre with a silicone paint. This caused the fibre to glow brightly as soon as the drop evaporated.

It was found in the initial tests that a drop when placed on a fibre was not quite spherical, the dimensions  $b$  on the axis along the fibre being greater than the dimension  $a$  on an axis perpendicular to the fibre. Moreover, the deviation from sphericity,  $\frac{b}{a}$  increased as the drop evaporated as shown in fig. 2. It was found, however, that  $\frac{b}{a}$  decreased, i.e. the drops became more spherical as the fibre diameter decreased. It was difficult, however, to use very fine fibres since the drops which could be supported on them evaporated too quickly for a sufficiently accurate measurement of the time and also the fibres curled up very easily in the flame. In the main series of tests, therefore, drops were evaporated on fibres of three thicknesses 0.60, 0.30 and 0.16 mm respectively, so that extrapolation could be made to a fibre of zero thickness. On each of these fibres the time for evaporation of ten drops of each of three initial sizes were recorded.

## Results

The results for the three fibres are shown by curves (i) (ii) and (iii) of fig. 3. Along the ordinate is plotted the equivalent spherical diameter, i.e. the diameter of a sphere which would have the same volume as the drop on the fibre, and along the abscissae the time for evaporation. In calculating the equivalent spherical diameter the shape of the drop on the fibre was assumed to be ellipsoidal and allowance was made for the volume of the fibre contained by the drop. Each point plotted for each fibre is the mean of the ten readings taken.

It will be seen that there is a difference in the time taken for a given size drop to evaporate on the different fibres. This was due to two factors, the difference in surface area of the drops due to deviations from sphericity, and the different amounts of heat conducted along its fibres due to different

fibre thicknesses. A correction for both these factors was made by plotting the time taken for evaporation of drops of given equivalent spherical diameter against fibre thickness and extrapolating to zero thickness of fibre. This procedure gave curve (iv) in fig. 3 which was regarded as representing the time which it would take spherical drops to evaporate in a bunsen flame.

Calculations

Experimental values of heat transfer. If the heat transferred to a drop is equated to the heat required for vaporization then

$$H \pi D^2 = \lambda \frac{dm}{dt} = \lambda \frac{d(\frac{\pi}{6} D^3)}{dt} = \frac{\lambda \pi D^2}{2} \cdot \frac{dD}{dt}$$

and  $H = \frac{\lambda \pi}{2} \cdot \frac{dD}{dt} \dots\dots\dots(4)$

Thus from the slope of curve (iv) in fig. 3 at any diameter the heat transfer at that diameter may be calculated. Heat transfer values calculated in this manner, taking  $\lambda$  as 620 cal/g., are shown in column 2 of Table 1.

Calculated heat transfer values. It was assumed that in that part of the flame in which the drop was situated complete combustion of the coal gas had taken place with the theoretical quantity of air, i.e. the gases moving past the drop consisted entirely of carbon dioxide, water vapour and nitrogen. The temperatures in the flame at the point where the drop was inserted was taken as 1700°C from a map of the temperature in a bunsen flame given by Barret (6).

To calculate the convection, the surface of the drop was assumed to be at 100°C. Actually its temperature would be the wet bulb temperature, but the difference between this and 100°C under the prevailing conditions would be very small compared with the difference between the temperature of the surface of the drop and the flame. The velocity of the gas was calculated assuming that all the combustion products were passing in turbulent flow through the measured cross section of the flame (2 cm diameter). The value for velocity obtained in this way was in fair agreement with that which could be predicted from work carried out by Lewis and Von Elbe (7) on the velocity in natural gas - air flames. Estimates of the viscosity, density and conductivity of the gas at the mean of the temperatures of the gas and the drop surface (900°C) were made from the composition of the gas and the properties of the individual gases at this temperature. By substitution in the Ranz and Marshall equation the heat transfer due to convection at a few drop sizes were calculated and are shown in column 4, Table 1. Further details of these calculations are given in Appendix I.

To calculate radiation the whole of the flame was considered to consist of carbon dioxide, water vapour and nitrogen in the same proportions as that moving past the drop, and the temperature of the flame was taken as 1700°C. The radiation was considered entirely due to the carbon dioxide and water vapour present, and from the partial pressures of these constituents and the dimensions of the flame an emissivity of 0.007 was obtained (8). Taking the absorption factor of the drop as unity the radiation was found to be

$$H_r = 0.007 \times 1.37 \times 10^{-12} \times (1970)^4 = 0.14 \text{ cal}/(\text{cm}^2)(\text{sec})$$

This value is independent of drop size.

Table 1. Theoretical and experimental values for heat transfer

Drop size cm	Experimental value of heat transfer H. cal/(cm <sup>2</sup> )(sec)	Calculated Radiation heat transfer H <sub>r</sub> cal/(cm <sup>2</sup> )(sec)	Calculated Convection heat transfer H <sub>c</sub> cal/(cm <sup>2</sup> )(sec)	H <sub>c</sub> — H
0.125	8.9	0.14	13.7	1.54
0.175	6.8	0.14	10.9	1.61
0.225	5.8	0.14	9.3	1.60

It will be seen that the calculated value for Hr is considerably less than either the calculated value of Hc or the experimental value of H and may therefore be neglected. The heat transfer to the drop may be considered, therefore, as entirely due to convection. The calculated value of Hc follows the experimental value but it is consistently about 60% higher (column 5 Table 1).

Calculation of time for evaporation of drops. Equation 4 may be integrated to give the time for evaporation of a drop as long as the dependence of H on D is known.

$$t = \frac{\lambda \rho}{2} \int_D^0 \frac{dD}{H} \dots\dots\dots(5)$$

In the Ranz and Marshall equation the dependence of H on D is such as to give an exact integral to equation 5 as follows (see appendix II)

$$t = \frac{2F}{G^4} \left\{ \frac{y^3}{3} - \frac{3y^2}{2} + 3y - \log_e y - \frac{11}{6} \right\} \dots\dots\dots(6)$$

Where  $G = 0.3 \text{ Pr}^{\frac{1}{3}} \sqrt{\frac{\nu}{\lambda}}$

$$F = \frac{R \lambda}{4k \Delta T}$$

$$y = 1 + G \sqrt{D}$$

The calculated times for evaporation of drops of 1 - 2.5 mm diameter in the bunsen flame is shown as curve (v) of fig. 3 and by the straight line (ii) on the logarithmic plot on fig. 4. It will be seen that the times actually obtained were consistently about 60% greater than those calculated. It will be noted in fig. 4 that the slope of the straight line (ii) representing the calculated values is practically the same as that (i) representing the experimental values.

Discussion

The calculations show that the heat transfer by convection to a water drop in a bunsen flame may be represented by Ranz and Marshall's equation if a constant factor of 0.63 is introduced.

$$\frac{hd}{k} = 0.63 \left( 2 + 0.60 \text{ Pr}^{\frac{1}{3}} \text{ Re}^{\frac{1}{2}} \right) \dots\dots\dots(7)$$

A number of assumptions have been made in the calculations by which this conclusion has been reached. Probably the major assumption is that the values of the properties of the gas which were inserted in the Ranz and Marshall equation have been taken to be those of the gas at the mean temperature between the surface temperature of the drop and the flame temperature. The most important property of the gas in calculating the heat transfer is the thermal conductivity since it will be seen from equation 7 that assuming a constant Prandtl number the heat transfer coefficient varies with the first power of the thermal conductivity, whereas even at high Reynolds numbers it will only vary with the square root of viscosity, density and velocity of the gas. Available information (8) indicates that in the range of temperature from 100 - 1700°C the thermal conductivity of the flame gases in the tests would be approximately directly proportional to the absolute temperature. Thus the mean conductivity of the flame gases occurs approximately at the mean temperature. The factor of 0.63 in equation 7 may therefore be tentatively accepted as representing a real deviation from Ranz and Marshall's equation. That this factor is necessary may be expected from the

results of Gohrbrandt (4).

The object of the experimental work was to obtain if possible a relationship by which the heat transfer by convection from flames of burning materials to water drops may be calculated. These flames are usually luminous diffusion flames of lower temperature than that of a bunsen flame, and therefore, it is unlikely that the same correction factor of 0.63 will apply. It was difficult to extend the experimental technique to these flames, firstly because it was very difficult to maintain the diffusion flames steady, and secondly because of the deposition of soot on to the drop during the time which the drop had to remain in the flame to evaporate completely. An estimation of the correction factor to use for these flames may, however, be made by considering the mechanism by which heat transfer takes place by convection. The heat is transferred from the flames to the drop by conductivity across a boundary layer. In the opposite direction to the heat flow, there is a mass flow of water vapour which will acquire sensible heat as it passes through the boundary layer. It may therefore be assumed that the correction factor A will have a dependence on temperature as follows

$$A = \frac{\lambda}{\lambda + B \Delta T} \dots\dots\dots(8)$$

BΔT represents the heat carried away as sensible heat by the vapour. If all the water vapour coming from the drop were heated to the temperature of the flame within the boundary layer then it would be expected that the factor B would be equal to the average specific heat of the water vapour within the boundary layer. However, probably only a fraction of the heat is transferred to the water vapour in the boundary layer; the rest of the heat is transferred by mixing of water vapour with the flame after the vapour is carried away into the wake of the drop. Therefore, it would be expected that B would be less than the specific heat of the water vapour; substitution in equation 8 shows B is equal to 0.23 (N.B. the specific heat of water vapour at 900°C is 0.56 cal/(g)(°C). From the fact that A is a constant over the range of Reynolds numbers used during the tests (40 - 80) it follows that B is a constant too. As a first approximation, therefore, equation 9 may be used to calculate heat transfer by convection to evaporating water drops from flames, at Reynolds numbers of 40 - 80.

$$Nu = \frac{\lambda}{\lambda + 0.23 T} (2 + 0.6 Pr^{\frac{1}{3}} Re^{\frac{1}{2}}) \dots\dots\dots(9)$$

References

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(2) N. Frössling. "Über die Verdunstung fallender Tropfen". Gerlands Beitr. z. Geophysik. 1938, 52 170 - 216.

(3) W. E. Ranz and W. R. Marshall. Chemical Engineering Progress 1952. 48 p. 141 - 6, 173 - 180.

(4) W. Gohrbrandt. "The Evaporation of Spheres in a Hot Air Stream." N.G.T.E. Memo. No. M.110, 1951.

(5) R. D. Ingebo. "Vaporization Rates and Heat Transfer Coefficients for Pure Liquid drops." Nat. Amer. Committee on Aeronautics. Tech. Note 2368.

(6) P. Barret. "La Mesure des Temperatureurs de Flamme." Publ. Science et Tech. du Ministere de L'air. Tech. Note No. 33, 1950.

(7) B. Lewis and G. von Elbe. "Combustion, Flames and Explosives." Academic Press, New York, 1951.

(8) M. Fiskenden and O.A.Saunders. "Introduction to Heat Transfer." Oxford University Press. 1950.

## Appendix I

### Calculations of Physical Properties of the Flame Gases

(1) Composition of flame gases, assuming complete combustion

From the composition of the coal gas, the oxygen required for complete combustion, and the carbon dioxide and water vapour produced was calculated. The nitrogen present was calculated assuming the air contained 21 per cent oxygen and 79 per cent nitrogen.

% Composition of gas		Oxygen for combustion	Combustion products	
			Carbon dioxide	Water vapour
Carbon monoxide	18.55	9.28	18.55	
Unsat Hydrocarbons	2.9	8.70	5.8	5.8
Methane	18.6	37.20	18.6	37.2
Hydrogen	49.5	29.80		49.5
Oxygen	0.65	-.65		
Nitrogen	6.95			
Carbon dioxide	2.85		2.85	
Total	100	84.33	45.8	92.5
Total Nitrogen		321.4		

Thus 100 vol. gas gives 462.7 vol. combustion products, composed of 70.1 per cent nitrogen, 9.9 per cent carbon dioxide and 20.0 per cent water vapour.

(ii) Velocity of flame gases

Rate of coal gas flow through burner = 43.6 ccs/sec.

Therefore rate of flow of combustion products at 1700°C =  $\frac{462.7 \times 0.436 \times 1973}{293}$

and average velocity of flame at point of insertion of drop, flame diameter 2 cm.

$$= \frac{462.7 \times 0.436 \times 1973}{\pi \times 2^2}$$

$$= 435 \text{ cms per second.}$$

Therefore velocity at axis of flame, for turbulent flow, =  $1.2 \times 435 = 522 \text{ cm/sec.}$

(iii) Physical properties of flame gases

All properties below are calculated at atmospheric pressure, and at the mean temperature of the gases, 900°C, from data in Fishenden and Saunders. Direct proportionality of properties with composition is assumed.



Appendix 1 (Contd)

Density p

Contribution of Nitrogen =  $0.000304 \times 0.701 = 0.000213$   
 " " Carbon Dioxide =  $0.000464 \times 0.099 = 0.0000460$   
 " " Water =  $0.000184 \times 0.200 = 0.0000368$

Therefore density of flame gases =  $0.000296 \text{ gm/cc}$

Viscosity

Nitrogen =  $0.000464 \times 0.701 = 0.000325$   
 Carbon dioxide =  $0.000446 \times 0.099 = 0.000045$   
 Water =  $0.000392 \times 0.200 = 0.0000783$

Therefore viscosity of flame gases =  $0.000448 \text{ gm/(cm)(sec)}$

Thermal conductivity, k

Nitrogen =  $0.000174 \times 0.701 = 0.000122$   
 Carbon dioxide =  $0.000184 \times 0.099 = 0.0000182$   
 Water =  $0.000254 \times 0.200 = 0.0000508$

Therefore thermal conductivity of flame gases =  $0.000191$

(iv) Heat transfer calculations

Convection (Ranz and Marshall)

$$\frac{H_c D}{\Delta T} = Nu = 2 + 0.6 Pr^{\frac{1}{3}} Re^{\frac{1}{2}}$$

$Pr = 0.767$  for flame gases. (8)

$$\text{Therefore } H_c = \frac{0.00019 \times 1600}{D} \left\{ 2 + 0.6 \times 0.915 \left( \frac{522 \times 0.0003 \times D}{0.00045} \right)^{\frac{1}{2}} \right\}$$

$$= \frac{0.305}{D} (2 + 10.26D^{\frac{1}{2}})$$

Appendix II

The time of evaporation of a drop by convection

Integration of Ranz and Marshall equation

We have

$$Nu = 2 + 0.6(Gr)^{1/2} Re^{1/4} \dots\dots\dots(1)$$

and

$$t = \frac{\lambda \rho}{2k} \int_D^0 \frac{D}{H} \dots\dots\dots(5)$$

Combining (1) and (5)

$$t = \frac{\rho \lambda}{4k \Delta T} \int_D^0 \frac{1}{1 + 0.3 Pr^{1/3} Re^{1/2}} D, dD.$$

Writing  $F = \frac{\rho \lambda}{4k \Delta T}$  and  $G = 0.3 Pr^{1/3} \sqrt{\frac{v \rho}{\lambda}}$ , this becomes

$$t = F \int_D^0 \frac{D dD}{1 + G D}$$

Putting  $y = 1 + G \sqrt{D}$ , and differentiating

$$dD = \frac{2}{G} \left( \frac{y-1}{2} \right) dy = \frac{2(y-1)}{G^2} dy$$

and, when  $D = 0$ ,  $y = 1$ .

and, therefore,

$$t = \frac{2F}{G^4} \int_{y_D}^1 \frac{y^3 - 3y^2 + 3y - 1}{y} dy$$

$$= \frac{2F}{G^4} \left[ \frac{y^3}{3} - \frac{3}{2} y^2 + 3y - \text{Log}_e y \right]_{y_D}^1$$

and, finally

$$t = \frac{2F}{G^4} \left( \frac{y^3}{3} - \frac{3y^2}{2} + 3y - \text{log}_e y - \frac{11}{6} \right)$$

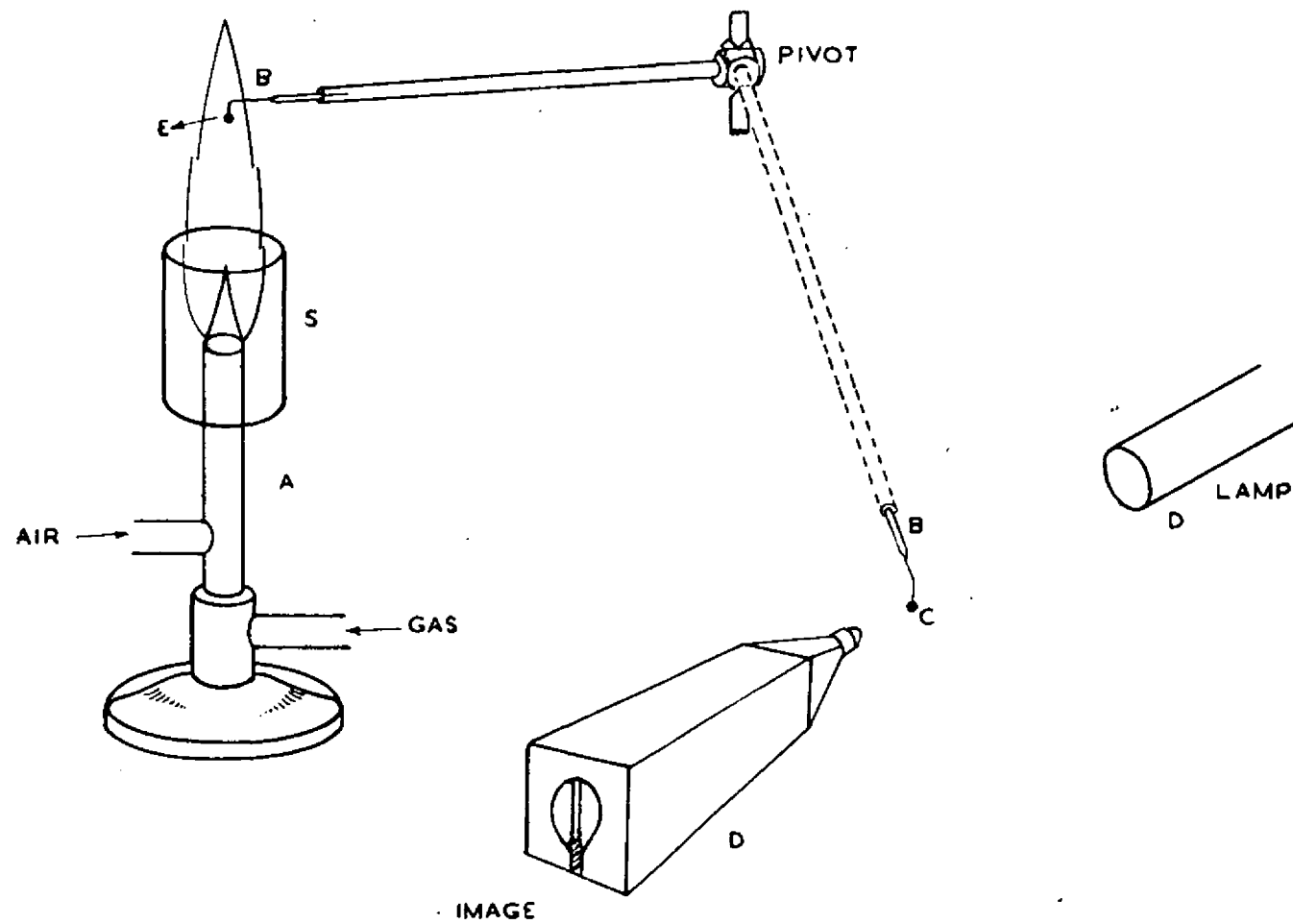


FIG. 1. GENERAL ARRANGEMENT OF APPARATUS.

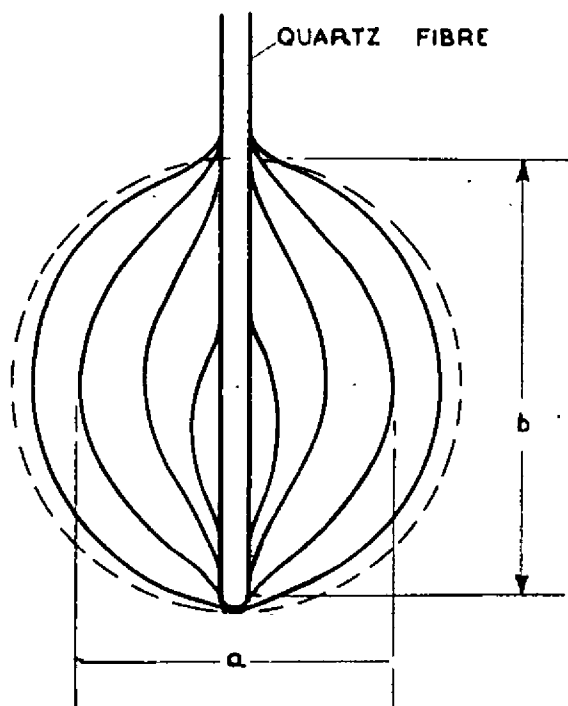


FIG. 2. THE SHAPE OF AN EVAPORATING WATER DROP.

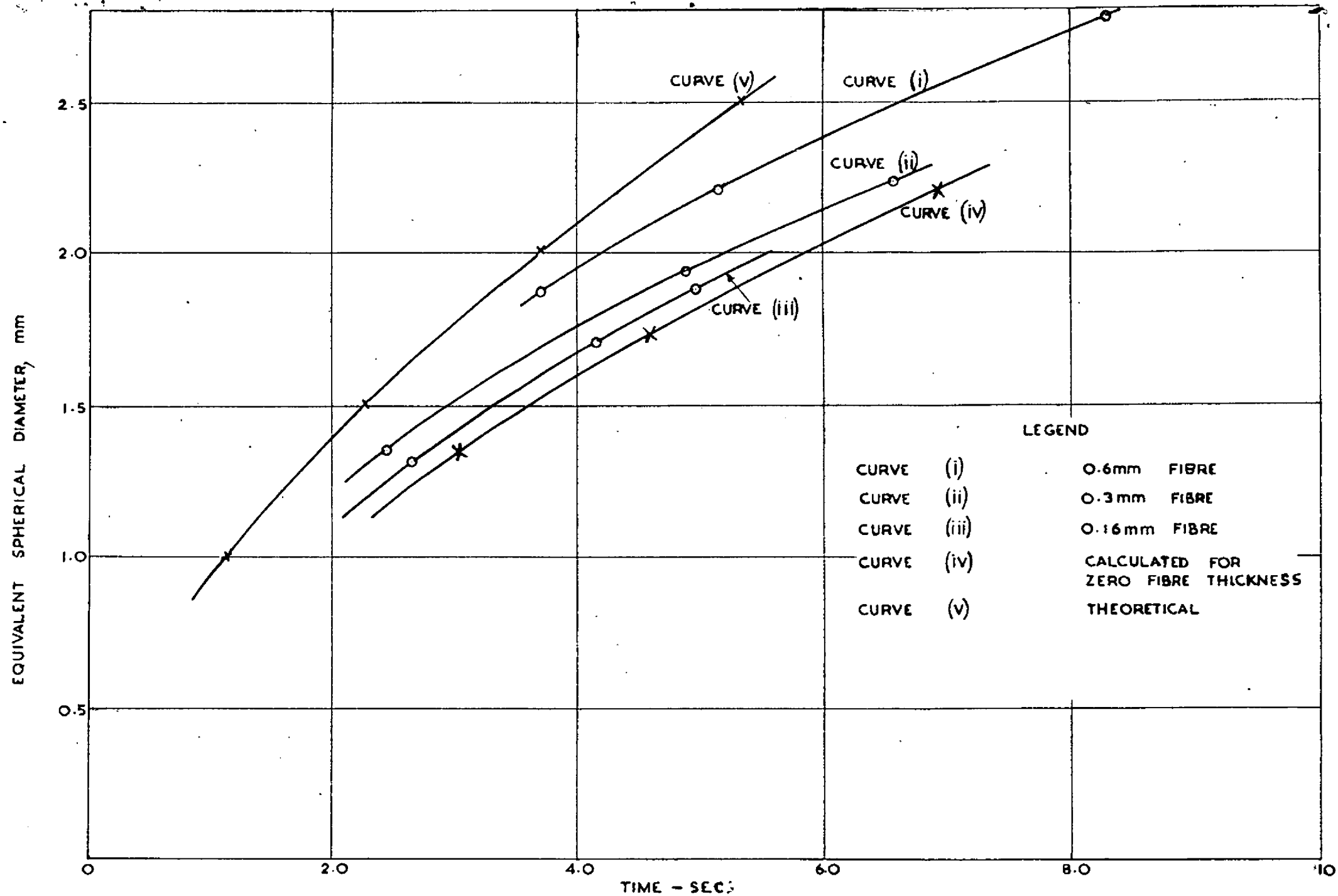


FIG. 3. EVAPORATION OF DROPS IN A BUNSEN FLAME.

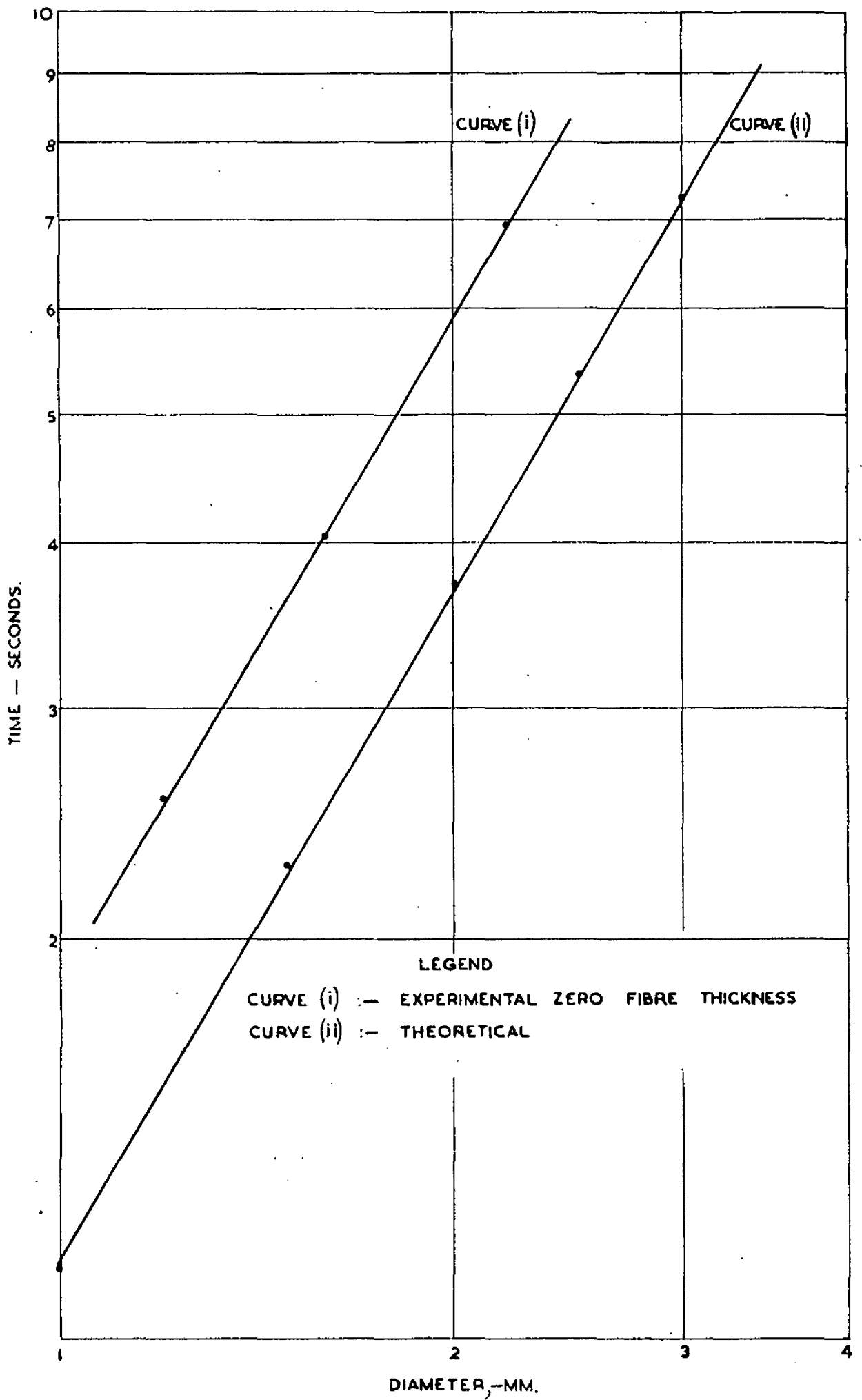


FIG. 4. EVAPORATION OF DROPS IN A BUNSEN FLAME.