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THE RADIAL TEMPERATURE GRADIENT ACROSS THE WALLS OF CYLINDRICAL PIPES CONTAINING HEATED FLUIDS

by

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Summary

The loss of heat to the surroundings by radiation and convection from the outer surface of a cylindrical pipe containing a heated fluid is accompanied by a radial flow of heat from the inner to the outer surface of the pipe. This report describes a simple graphical method of evaluating the temperature difference between these surfaces when thermal equilibrium has been established.

Introduction

It is often necessary to know, in problems concerning the loss of heat from cylindrical pipes containing heated fluids, the radial temperature difference which exists across the wall of the pipe. This knowledge enables the engineer or physicist to compare the insulative effect of different thicknesses and materials of pipe walls and lagging, for certain temperatures of the contained fluid. It enables the architect or engineer to estimate the temperature of the external surface of a flue pipe conveying gases at a certain temperature and hence to calculate the nearest safe distance at which combustible material may be placed to the flue. The laws of heat transfer by radiation, conduction and convection enable this temperature difference to be calculated, but where many results have to be obtained, this method is tedious.

To avoid the necessity for calculation a set of four graphs has been drawn to provide a rapid method of evaluating the temperature difference. To use these graphs it is necessary to know the external diameter and wall thickness of the pipe, its external surface temperature, and the emissivity and conductivity of its material. The range of the graphs provides for external diameters from 2 inches to 9 inches, wall thicknesses from $^1/_{16}$ inch, to $\frac{1}{2}$ inch, emissivities from 0 - 100 per cent of black body emissivity, and thermal conductivities from 0.0001 to 1.0 calories/cm^2/sec/°C/cm. The emissivity and conductivity ranges include the values for all commonly-used pipe materials; a selection of these values is given in Appendix II. Where the temperature of the internal surface is known, but not the temperature of the external surface, the temperature difference should be obtained for values of the external surface temperature chosen to correspond to values of the internal surface temperature greater and less than the specified value. By interpolation, the value of the external surface temperature corresponding to the specified value of the internal surface temperature may then be estimated.

Description of graphs

In a state of thermal equilibrium the heat loss per unit area from a point on the surface of the flue-pipe by radiation and convection must equal the heat transfer through the pipe wall per unit area by conduction at that point. The curves provide a means of estimating the heat loss per unit area externally and, by equating this to the heat conducted through the pipe wall, of evaluating the difference of temperature between the two surfaces.

There are four families of curves.

The first (Figs. 1A, 1B, 1C,), which shows the relation between external surface temperature and heat lost to the surrounding atmosphere by radiation and convection, is drawn for different values of emissivity, varying from 0 - 100 per cent of black body emissivity, in steps of 20 per cent. This family has been drawn in three temperature ranges for greater accuracy, these being 0 - 250°C (1A), 250°C - 500°C (1B) and 500°C - 1,000°(1C).

The second family of curves (Fig 2) enables what may be termed the "equivalent thickness", p, of the pipe to be determined, knowing the external pipe diameter and wall thickness. The "equivalent thickness" is so called because it is equal to that thickness of plane slab of the material of the pipe which would permit the same rate of transfer of heat for the same temperature difference across it, as would the wall of the cylindrical pipe. The mathematical expression for "p" is derived in Appendix I.

The third family (Fig 3) shows the relation between radial heat transfer by conduction, and the product K.Δt, where K is the conductivity of the material of the pipe and Δt is the temperature difference between its inner and outer surfaces, the value of which it is required to determine.

The last family of curves (Fig 4) enables the value of Δt to be determined directly, knowing the conductivity of the pipe material and the value of the product K.Δt as previously found.

The equations from which all the curves have been drawn are given in Appendix I.

Sequence of operations

To find the temperature difference (Δt) between the inner and outer surfaces of a flue-pipe conveying hot gases where a condition of thermal equilibrium has been established, i.e. all the temperatures have reached their final values, the following procedure should be carried out.

(a) Select Figures 1A, 1B, or 1C according to the external surface temperature of the flue-pipe. Read off the heat lost per unit area by radiation and convection (H) corresponding to the external surface temperature and the emissivity appropriate to the material of the pipe.

(b) From Figure 2 ascertain the "equivalent thickness" (p) (see Appendix I), appropriate to the external diameter and wall thickness of the pipe.

(c) From Figure 3 obtain the product K.Δt appropriate to the value of H found in (a), and of p found in (b).

(d) Finally, from Figure 4 read off the required temperature difference (Δt) knowing the conductivity (K) of the material of the pipe, and the product K.Δt found in (c).

Example

The external surface of a $\frac{3}{8}$ in. thick asbestos cement flue-pipe of 6 in. external diameter must not rise above 150°C. It is required to know the maximum permissible inside surface temperature of the pipe. (Assume emissivity of asbestos cement = 90 per cent of black body, and conductivity = 0.93×10^{-3} calories/cm²/sec/°C/cm).

(a) Figure 1 shows the total external heat loss at 150°C to be 0.052 cal/cm²/sec. (interpolating between the curves for 80 per cent and 100 per cent black body radiation).

(b) Figure 2 gives the value of p as 1.01 cm.

(c) Figure 3 shows that for a heat transfer of 0.052 cal/cm²/sec the product K.Δt is 0.053 cal/cm²/sec/cm.

(d) Figure 4 gives the temperature difference as approximately 58°C.

Hence the maximum permissible temperature for the inner surface of the pipe is approximately 150°C + 58°C = 208°C.

Appendix I

Equations from which Figures 1 - 3 have been drawn

The curves of Fig.1 A, B, and C, for different values of the emissivity of the surface of the pipe, are drawn according to the equation:-

$$H = e(T_2^{\,4} - T_A^{\,4}) + c(T_2 - T_A)^{1.25} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where H = heat lost to the surroundings per unit area at a point on the surface of the pipe by radiation and convection (cals/cm²/sec.)

e = emissivity of the surface of the pipe (cals/cm²/sec/°K⁴)

c = convection coefficient (1) for a vertical cylinder

$= 4.7 \times 10^{-5}$ cals/cm²/sec/$°K^{1.25}$

T_2, = temperature of outside surface of pipe at the point concerned in °K.

T_A, = Ambient temperature, °K.

Figure 2.

The parameter p, which has been termed the "equivalent thickness" of the pipe, has been adopted for convenience to express the factor $\left(\frac{d}{2} \log \frac{d}{d - 2b}\right)$ in equation (3) below. Its value is obtained from Figure 2, which has been drawn using the logarithmic expansion of the expression to two terms:-

i.e.
$$p = \frac{d}{2} \log \frac{d}{d - 2b}$$

$$= \frac{d}{2} \log \left(1 - \frac{2b}{d}\right)^{-1}$$

$$= \frac{d}{2} \left(\frac{2b}{d} + \frac{4b^2}{2d^2} + \ldots\ldots\ldots\right)$$

$$= b + \frac{b^2}{d} \text{ approximately.}$$

Figure 2. therefore has been drawn from the equation:-

$$p = 2.54 \left(b + \frac{b^2}{d}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where p = "equivalent thickness" in cms.

b = thickness of pipe wall in ins.

d = external diameter of pipe wall in ins.

The mean value theorem shows that the error involved in taking only two terms of the logarithmic series is less than 10 per cent provided that $\frac{2b}{d}$ does not exceed 0.4.

The curves of Fig 3 are drawn, for different values of the "equivalent thickness", p, of the pipe (see below), from the equation:-

$$H^1 = K \frac{(t_1 - t_2)}{\frac{d}{2} \log \frac{d}{d - 2b}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where H^1 = heat transfer by conduction through the wall of the pipe = H in (1) in the steady state.

K = conductivity of the material of the pipe (cal/cm²/sec/°C/cm)

t_1 = temperature of inside surface of pipe, °C

t_2 = temperature of outside surface of pipe °C

(Hence $\Delta t = (t_1 - t_2)$)

d = external diameter of pipe (in.)

b = thickness of pipe wall (in.)

References:

(1) "The Efficient Use of Fuel" p.130. pub. H.M.S.O.

Appendix II

Values of emissivity and conductivity of typical surfaces and materials

(a) Emissivities

Material	Emissivity (% black body radiation)	Ref.
Black body	100	McAdams' "Heat Transmission"
Aluminium		
polished	4	
rough	5.5	
Aluminium paint	35	
Brass		
polished	9.6	
dull	22	
Copper		
polished	3	
oxidised	70	
Cast iron		
polished	21	
turned	43.5	
oxidised	95	
Wrought iron		
polished	28	
oxidised	94	
Steel		
polished	52	
rough	94	
Zinc		
polished	4.5	
Galvanised iron	25	
Asbestos	96	
Asbestos cement	90	
Lampblack	96	
Glazed porcelain	92.4	

(b) Conductivities

Material	Conductivity cals/cm^2/sec/$^\circ$C/cm	$^\circ$C	Ref.
Asbestos	0.25×10^{-3}	100	(2)
Asbestos cement	0.93×10^{-3}	50	(2)
Aluminium	0.49	100	(1)
Copper	0.91	100	(1)
Wrought iron	0.14	100	(1)
Cast iron	0.11	100	(1)
Steel	0.11	100	(1)
Portland cement	0.85×10^{-3}	90	(2)
Porcelain	2.5×10^{-3}	95	(2)
Brass	0.26	20	(1)
Zinc	0.26	100	(1)
Slag wool	0.12×10^{-3}	30	(2)

(1) Kaye and Laby. - "Physical and Chemical Constants"
(2) "International Critical Tables". published by McGraw-Hill & Co. Ltd.

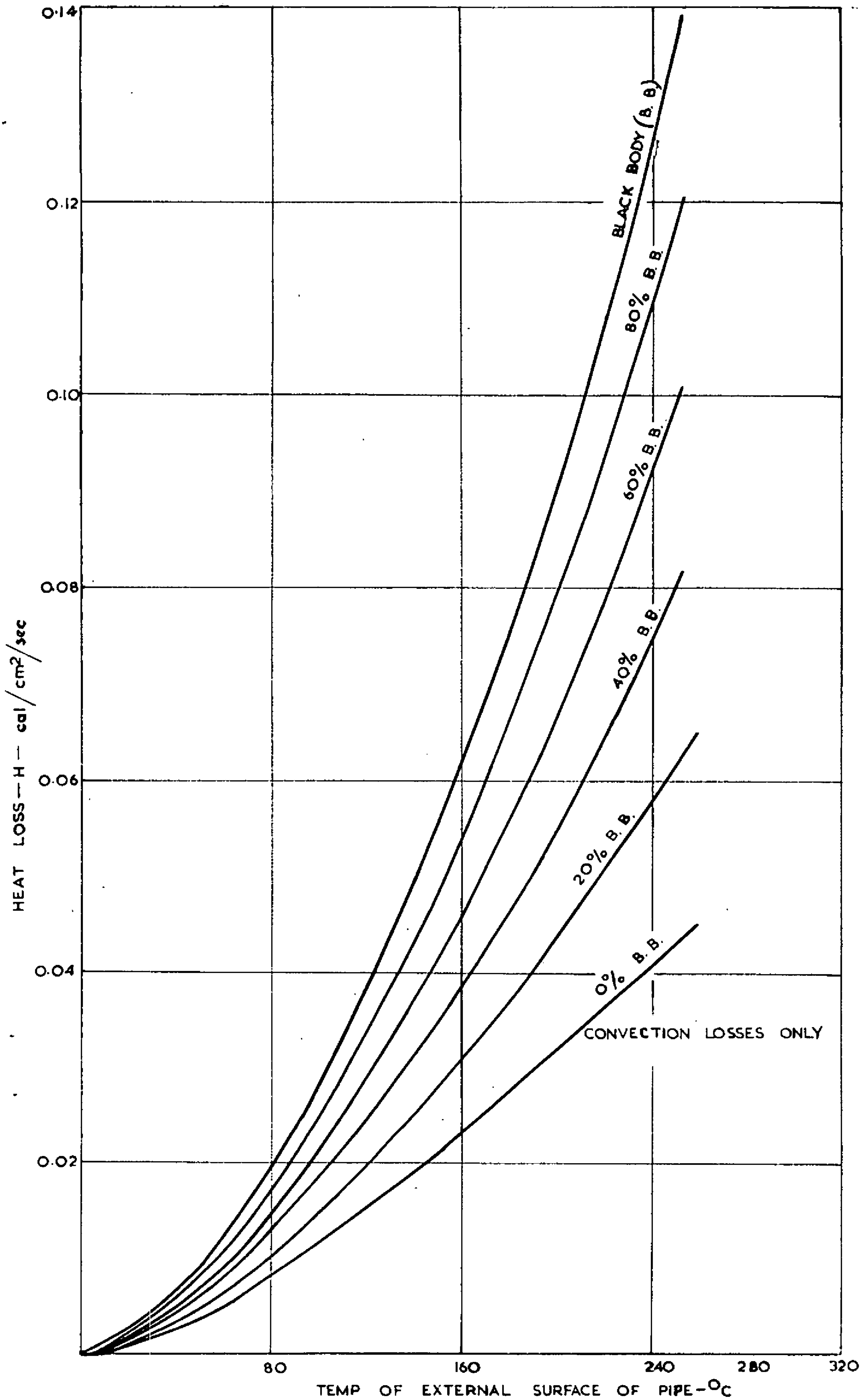


FIG. 1A. HEAT LOST BY RADIATION AND CONVECTION PER UNIT AREA FROM EXTERNAL SURFACE OF A VERTICAL CYLINDRICAL PIPE CONVEYING HOT GASES.

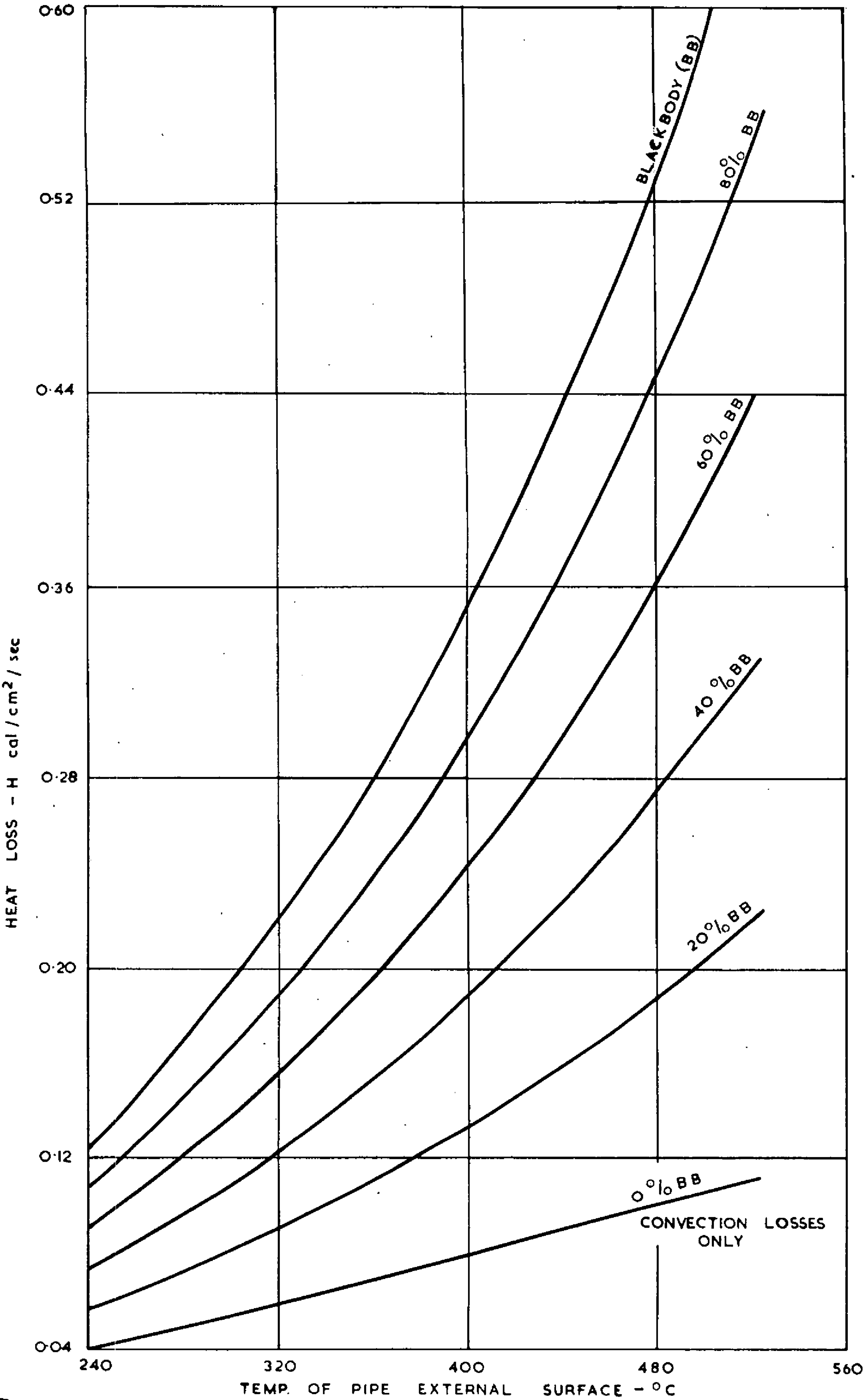
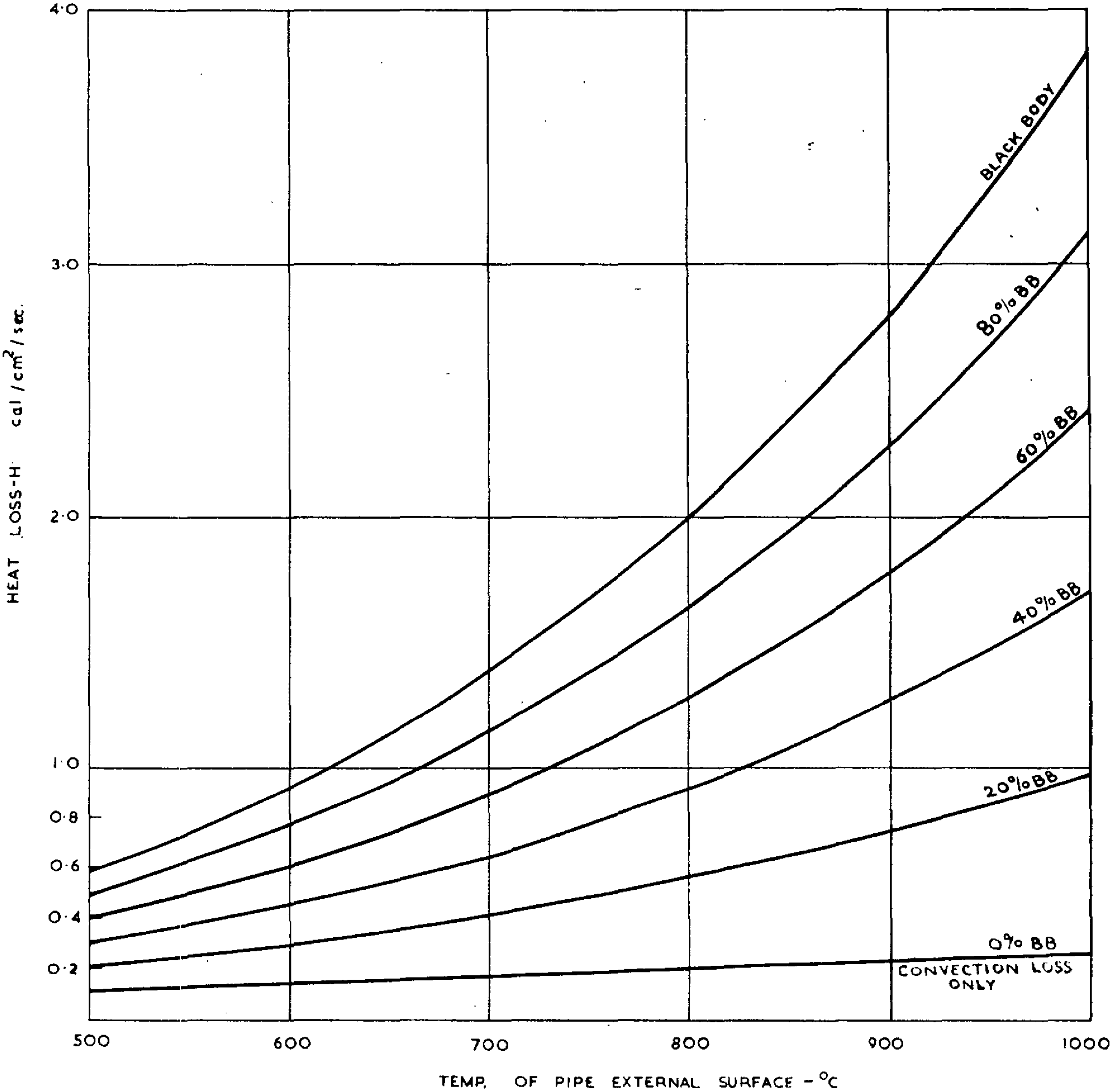


FIG. 1B

HEAT LOSS BY RADIATION AND CONVECTION PER UNIT AREA FROM EXTERNAL SURFACE OF A VERTICAL CYLINDRICAL PIPE CONVEYING HOT GASES.



HEAT LOSS BY RADIATION AND CONVECTION PER UNIT AREA FROM EXTERNAL SURFACE OF A VERTICAL CYLINDRICAL PIPE CONVEYING HOT GASES.

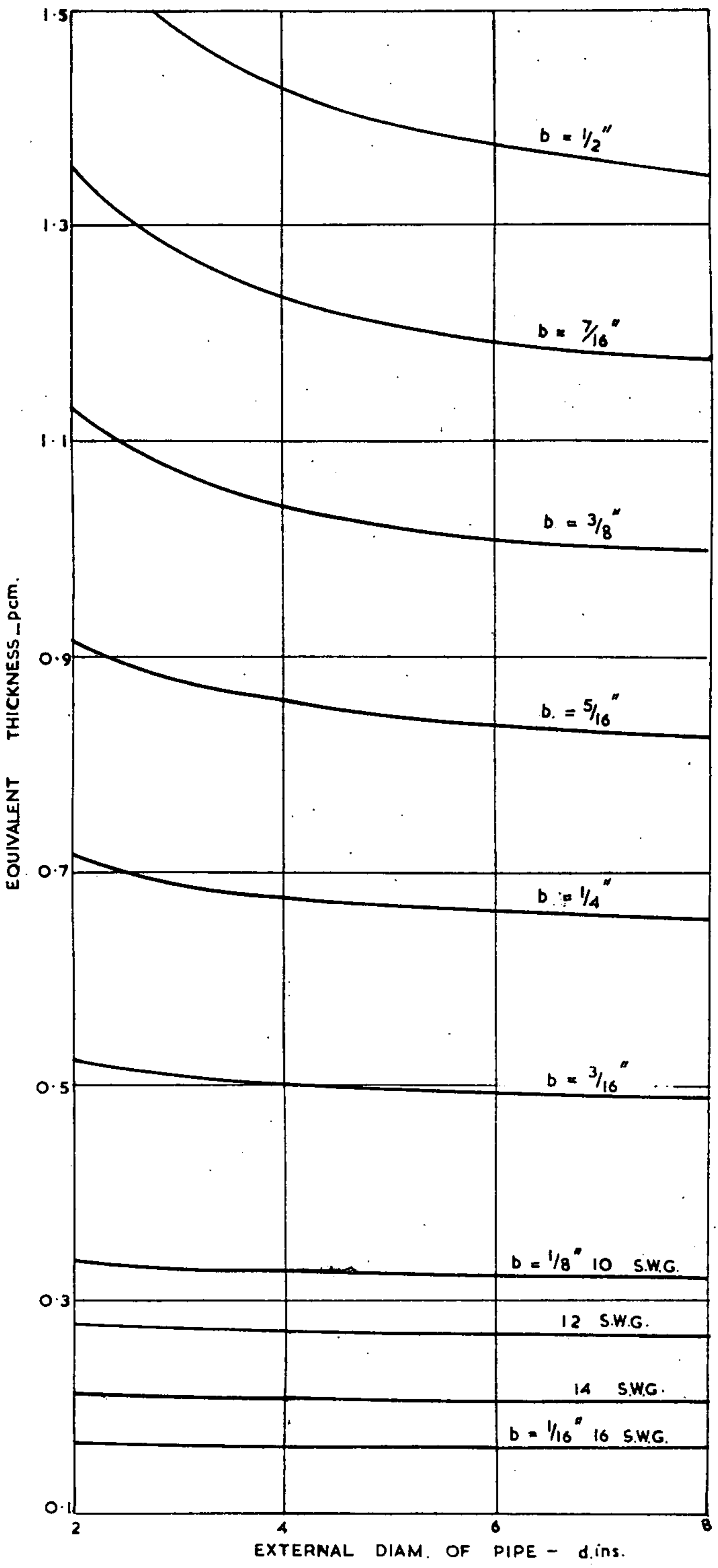


FIG. 2. THE "EQUIVALENT THICKNESS" OF A CYLINDRICAL PIPE.

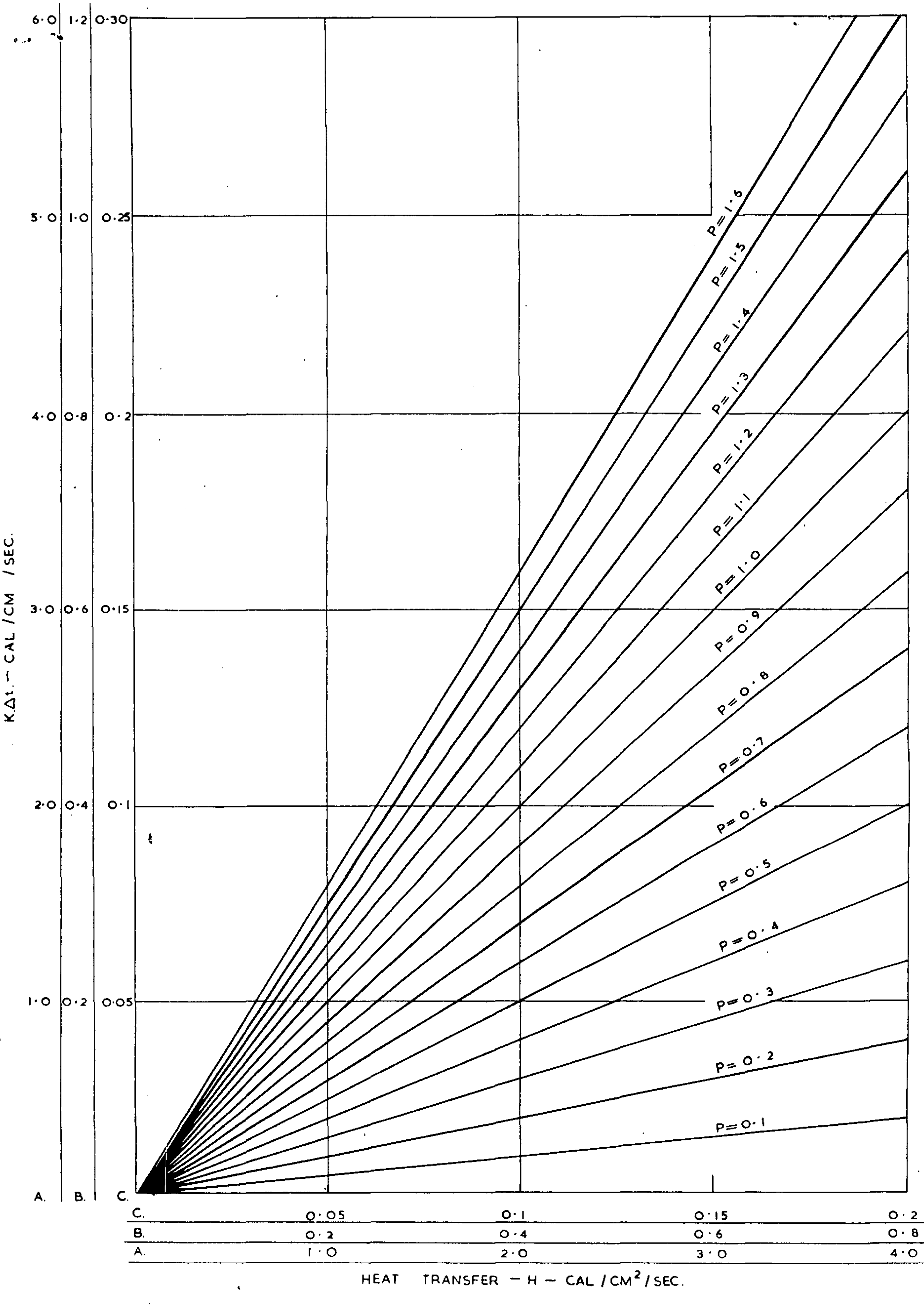


FIG. 3. PRODUCT K.Δt. FOR VARIOUS RATES OF HEAT CONDUCTION AND EQUIVALENT THICKNESS OF PIPE.

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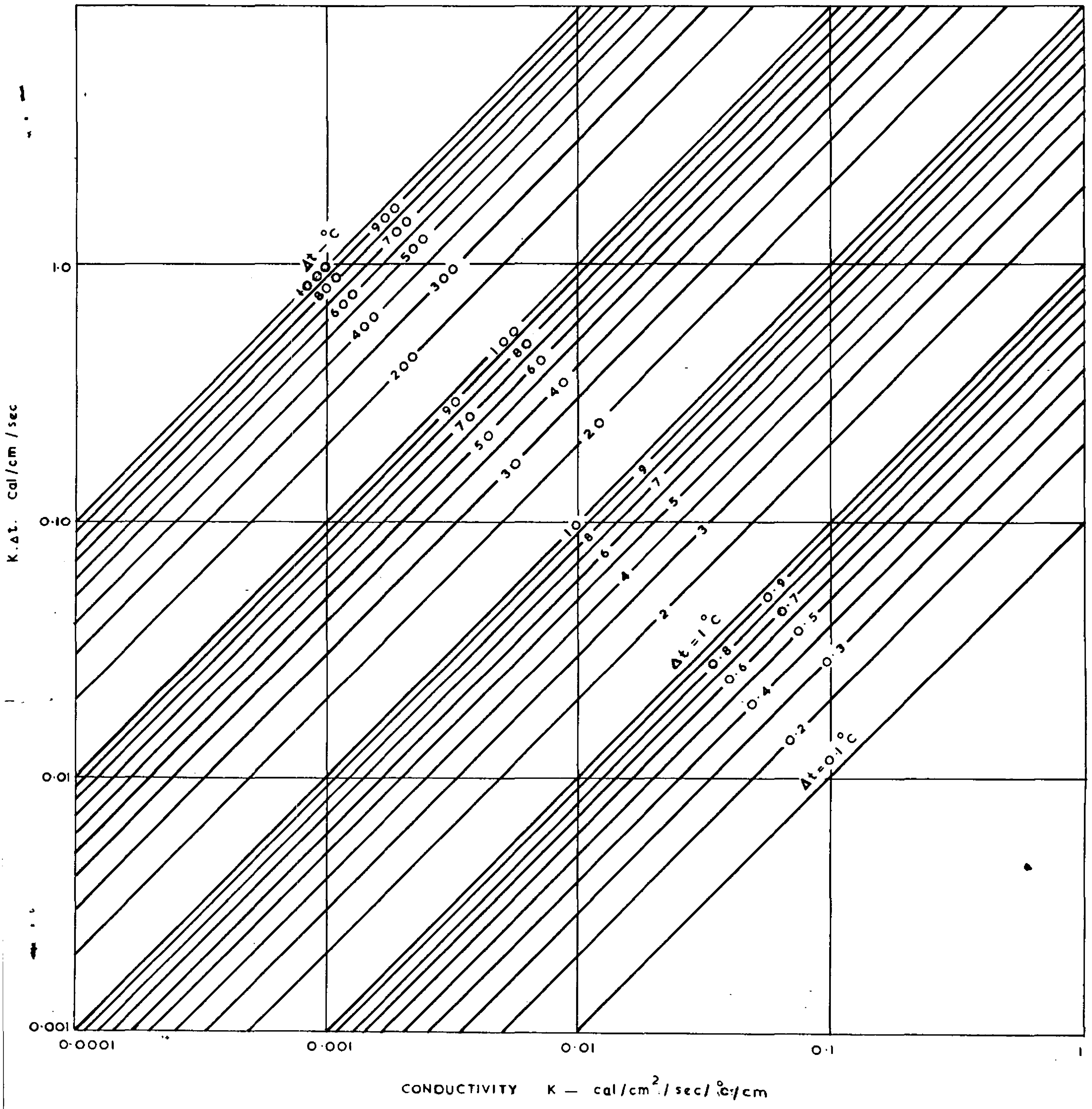

FIG. 4. CURVES SHOWING THE VALUE OF Δt HAVING THE VALUES OF PRODUCT K AND CONDUCTIVITY K.