



## LXXXIII. The thermometric anemometer

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LXXXIII. *The Thermometric Anemometer.* By J. S. G. THOMAS, D.Sc., A.R. C.Sc., A.I.C., Senior Physicist, South Metropolitan Gas Company, London\*.

*Introduction.*

THE thermometric type of anemometer due to C. C. Thomas †, which has found application in industrial practice, more especially in the measurement of large volumes of gases flowing in mains etc., is based upon the principle that if heat is imparted from a source to a stream of gas so as to raise the temperature of the stream by a constant amount, then the heat energy imparted to the gas to produce such rise of temperature is proportional to the rate of flow of the gas. Assuming constancy of the specific heat of the gas, the supply of energy to the stream to effect a given rise of temperature is independent of the initial temperature of the stream. Such a type of anemometer possesses the desirable characteristic that it measures the mass-flow of gas, and hence its indications may be made to read directly in terms of standard pressure and temperature conditions. An elaborate series of calibrations of this type of anemometer against others of the Pitot and Venturi types has been made by C. C. Thomas ‡, and over the range of velocities employed, the indications of the three types of instruments were found to be in very close agreement. The calibrations referred to were carried out in a pipe of 24 in. diameter and the lowest velocity corresponded with an hourly flow of 7,000 lb. of air, *i. e.* a mean velocity of about 230 cm. per sec. The straight lines obtained by plotting the rate of revolution of the fan producing the flow, as abscissæ against the flow determined from the indications of the Pitot, Venturi, and Electric meters respectively, were extrapolated for low values of the flow and passed through the origin of co-ordinates. Such extrapolation is justifiable in the case of the Pitot and Venturi meters. In the case of the electric meter, however, such extrapolation is clearly unjustifiable, as under no circumstances is the whole of the heat supplied to the heating coil imparted to the gas. There are necessarily heat losses due to radiation, conduction, and convection, and such losses

\* Communicated by the Author.

† Journ. Amer. Soc. Mech. Eng., xxxi. pp. 1325-1340 (1909). Journ. Franklin Inst., vol. 172, pp. 411-460 (1911). Proc. Amer. Gas Inst., vii. pp. 340-381 (1912).

‡ See *e.g.* Journ. Franklin Inst., *loc. cit.* p. 433.

become relatively more important the less the velocity of the stream. It is clear that if the thermometers be symmetrically disposed with regard to the heating coil employed, no value of the heat supply to the latter would be such as to maintain the desired difference of temperature between the two thermometers in the absence of flow. If, however, the second thermometer be disposed closer to the heater than the first thermometer, in the absence of flow, the value of such heat supply is perfectly definite and determined principally by radiation and convection losses from the channel in which the heater is placed. The effect of the predominance of such heat losses for low velocities appears to have been overlooked in the papers already referred to\*. It will be found that the curves obtained by plotting the rate of flow of gas as abscissæ against the rise of temperature due to a constant supply of energy to the heating coil as ordinates, is not asymptotic to the ordinate axis. Owing to the heat losses referred to, there exists a finite maximum temperature rise through which the stream is heated by a constant supply of energy. The value of the velocity of flow at which such maximum rise of temperature occurs is conditioned by a variety of factors, the size of pipe, heat insulation of pipe, etc. For velocities of flow less than this critical value, decreasing velocity is accompanied by a decreasing rise of temperature. Attention has been directed to the phenomenon in a previous paper†. Its consideration is of some consequence in technical practice, *e.g.*, in the design of heat interchangers or regenerator furnace-settings for the attainment of a maximum temperature in the gases to be heated.

In the technical form of thermometric meter, the ratio of maximum flow to minimum flow for correct registration is about 15 : 1, and by employing a second pair of temperature-difference resistances this ratio can be increased to about 60 : 1. Velocities quite commonly occurring in technical practice are of the order of a few cms. per sec., and upwards, and it is important to determine the forms of the calibration curves of a low capacity anemometer of the thermometric type for such velocities, and more especially the variation in such calibration curves accompanying a variation of the heat losses due to conduction and radiation. The present paper details some of the results obtained in the course of such an investigation.

\* See *e.g.* Journ. Franklin Inst., *loc. cit.* p. 447.

† Phil. Mag. vol. xli. p. 258 (1921).

*Experimental.*

The flow tube consisted of a brass tube of 2.011 cm. diameter wound with one layer of asbestos cord (diameter of cord about 3 mm.), inserted in the flow system as detailed in previous papers\*. The supply of air was derived from a gas-holder of 5 cubic feet capacity connected with the laboratory high-pressure air service, and a steady and calculable flow of dry air in the system was established as already detailed†. The heating element employed is shown in fig. 1 (*a* and *b*). *A* is a portion of brass tube 6 mm. in length, exactly similar to the main flow tube. It fitted tightly within the ebonite ring *B*. A number of thin copper pins, bent at right angles

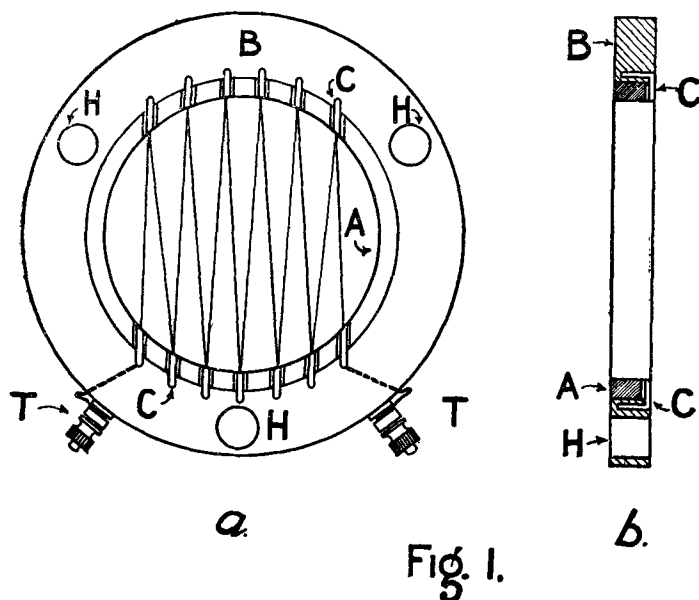


Fig. 1.

as shown at *C* in fig. 1 *b*, were driven securely into holes drilled in the ebonite ring, and slots were cut of an appropriate width and depth in the brass ring *A* so that these pins were insulated from the latter. A length of fine platinum wire was soldered in zigzag fashion to these pins as shown, the minimum amount of solder being employed for this purpose. The ends of the wire were connected by short copper leads with the terminals *T*. Holes *H* were drilled at angular

\* See *e.g.* Phil. Mag. vol. xli. p. 242 (1921).

† Phil. Mag. vol. xxxix. p. 509 (1920).

intervals of  $120^{\circ}\text{C.}$  in the ebonite ring B. These served for the insertion of the heating element in the flow system. This was effected by means of brass rods passing through the holes H and through similar holes drilled in ebonite rings attached to the main flow tube. The whole was securely fixed by means of nuts on the ends of the brass rods \*. The heating element was inserted in a vertical plane in the horizontal flow system with the several wires about equally inclined to the vertical as shown in fig. 1, so that the free convection currents tended to equalize the temperature distribution across the section of the flow tube. The construction of the two platinum thermometers employed resembled that of the heating element: there was in this case, however, no necessity to employ an inner brass ring, and the pins for the support of the platinum wires were made considerably smaller than in the case of the heating element. The thermometers were inserted in the flow system in a similar manner to that employed for the insertion of the heater. The distances between the respective thermometers and the latter could be adjusted to any desired values by the use of suitable lengths of tube provided with ebonite ends affixed to the tube and suitably bored. For very small distances between heater and thermometer, thin separating disks of ebonite bored to the appropriate diameter were similarly employed. The thermometers were calibrated by the determination of their respective resistances at  $0^{\circ}\text{C.}$  and at a temperature of  $50^{\circ} \pm 0.02^{\circ}\text{C.}$  on gas scale, corresponding to  $49.62 \pm 0.02^{\circ}\text{C.}$  on Pt scale ( $\delta = 1.5$ ), this temperature being maintained thermostatically in a water bath, and determined by a mercury thermometer standardized at the N. P. Laboratory. The thermometers were adjusted as nearly as possible to equality of resistance at  $0^{\circ}\text{C.}$ , and they were, in use, connected differentially with a Callendar and Griffiths' bridge, the scale of which was provided with a vernier, enabling the balance to be determined to  $0.01\text{ cm.}$  The supply of energy to the heating element was determined from a knowledge of the current supplied and the drop of potential occurring across the heater. The current was read from a Siemens & Halske ammeter reading to  $0.001\text{ amp.}$  The voltage drop across the heater was determined by means of a Rayleigh potentiometer composed of two P. O. Boxes adjusted so that their total resistance was  $10,000\text{ ohms}$  throughout. The potentiometer readings were calibrated by means of a Weston cell standardized at the N. P. Laboratory.

\* See Phil. Mag. vol. xliii. p. 279 (1922).

The mode of experiment was as follows :—A steady flow of dry air was established in the system for about an hour, and the balance of the Callendar & Griffiths' bridge ascertained in the absence of any current in the heating element. The point of contact on the bridge wire was then moved to the point corresponding to  $2^{\circ}\text{C.}$  difference between the two thermometers, and the value of the current in the heater adjusted until the bridge balance was restored at the point so determined. The necessary displacement at  $15^{\circ}\text{C.}$  was  $2.65\text{ cm.}$  of bridge wire. The bridge current was throughout adjusted to  $0.010\text{ amp.}$  On account of the relatively large thermal capacity of the flow system, a considerable time—of the order of 2 to 3 hours when the thermometers were widely separated—elapsed before the system attained a steady condition. Owing to slight inequality of the two thermometer resistances at  $0^{\circ}\text{C.}$ , a slight alteration of balance accompanied a change of atmospheric temperature. Such alteration was taken account of throughout the observations. The potential drop across the heater was determined as already explained. The velocity of flow in the system was determined as detailed in previous papers.

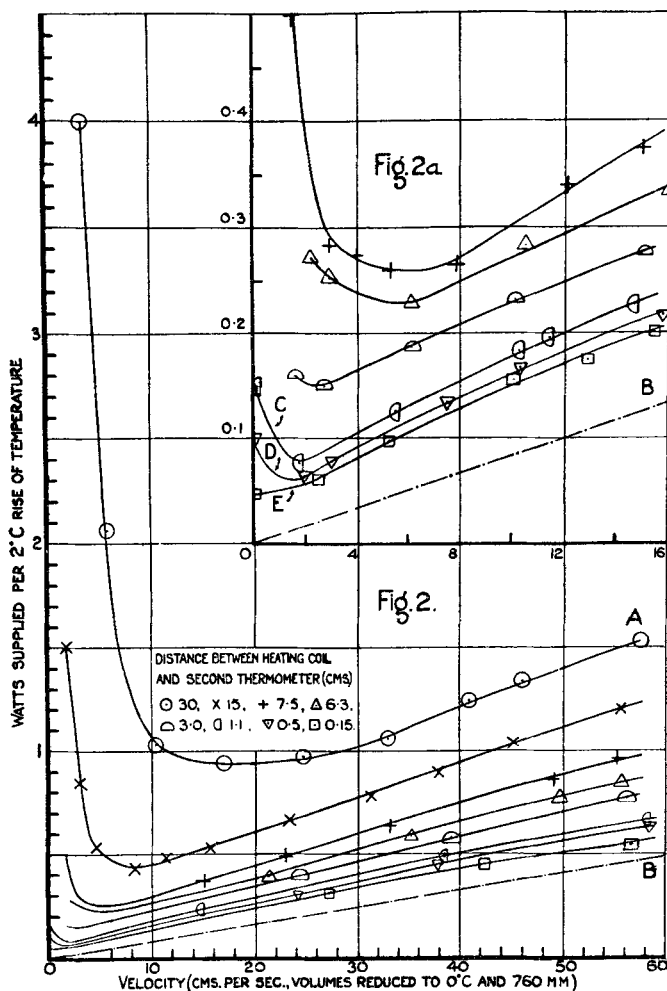
The results were plotted in the form of curves in which the abscissæ represent velocities of flow, and ordinates the respective supplies of energy to the heater to maintain the second thermometer at a temperature  $2^{\circ}\text{C.}$  above that of the first.

#### *Results and Discussion.*

Internal diameter of flow tube .....	2.01 cm.
External diameter of flow tube .....	2.22 cm.
$R_0$ of 1st Thermometer (cms. of bridge wire) ..	363.40
Temperature coefficient of 1st Thermometer .....	0.003556
$R_0$ of 2nd Thermometer (cms. of bridge wire) .....	368.75
Temperature coefficient of 2nd Thermometer .....	0.003552
Shift of balance for $1^{\circ}\text{C.}$ change of atmospheric temperature (cm. of bridge wire) .....	0.017

In fig. 2 are given the forms of the calibration curves obtained when the first thermometer was throughout placed at a distance of 30 cm. from the heating element while the

distance between the latter and the second thermometer assumed the values 30, 15, 7.5, 6.3, 3.0, 1.1, 0.5, and 0.15 cm., as indicated by the respective curves. The initial portions of some of the curves are plotted on an enlarged



scale in fig. 2a. The variation of distance between the heating element and the second thermometer affords a convenient method of studying the effect of a variation of the heat losses due to radiation etc. upon the form of the calibration curves. The broken line B in the figure gives the theoretical form—a straight line passing through the

origin—of the calibration curve in the absence of any such losses, the whole of the energy supply being utilized to heat the air stream through 2° C. on the gas scale. In all cases within the range of velocities studied, the necessary energy supply to the heating element in order that a difference of 2° C. may be indicated by the thermometers is considerably greater than that theoretically necessary. Owing to the absence of a device for stirring the gas so as to render the temperature of the gas stream uniform over a cross section, an indication of 2° C. difference of temperature in the thermometers does not necessarily correspond exactly with a 2° C. rise of temperature of the stream. The use of any efficient stirring device was precluded by the experimental conditions in the present case and is impossible in many of the technical applications of anemometry, more especially where gas streams carrying dust etc. in suspension are to be measured.

The various calibration curves show considerable departure from the straight line B which would be obtained in the absence of any heat losses and if the temperature indicated by the second thermometer accurately represented the mean temperature of the stream. The greatest departure from the linear relation between the energy supply and the velocity is seen in the case of curve A, corresponding to the greatest distance between heating element and second thermometer, as is to be anticipated owing to the heat losses being greatest in this case.

The approximate form of the curve A can be best discussed by reference to the relation given by Callendar\* and employed in the determination of the specific heat of gases and vapours by the continuous-flow method. Where the velocities of flow are larger than those concerned in the present series of experiments, and where the heat losses are small, Callendar has shown that  $W = SQd\theta + hd\theta + \frac{k}{Q}d\theta$ , where  $W$  is the energy supply to the heating element,  $S$  the specific heat of the gas,  $Q$  the mass flow,  $d\theta$  the rise in temperature,  $hd\theta$  the portion of heat loss independent of the flow, and  $kd\theta/Q$  the residual portion of the heat loss varying inversely as the flow. Applying the appropriate value of  $S$ , and employing  $v$  the velocity of flow in place of  $Q$ , the relation becomes in the case of a flow of air in the present flow system:— $W = 0.004147 v d\theta + h d\theta + \frac{243.6 k d\theta}{v}$ , representing a series of hyperbolæ,  $h$  and  $k$  being variable

\* See *c. g. Phil. Trans.*, A. 535. p. 390 (1915).

parameters. The asymptotes are given by  $v=0$  and  $W=0.004147 v d \theta + h d \theta$ . The value  $v$  corresponding to the minimum value of  $W$  is  $v=242 \sqrt{k}$ . It is seen therefore that if the experimental conditions are such that the relation between the energy supply  $W$  and the velocity  $v$  is of the hyperbolic type discussed, corresponding to very large values of the velocity, the energy supply to maintain a difference of temperature  $d\theta$  will be in excess of that represented by the curve  $B$  by an amount  $h d \theta$ , and practically independent of  $k$ . Moreover the thermometric type of anemometer would, under the same conditions, permit the velocity to be uniquely determined from the energy supply, only if such velocity were, in the case of the flow tube used in the present experiments, known to be either less than or greater than  $242 \sqrt{k}$ . Similarly in the general case, when the energy supply is given in the form  $W = S Q d \theta + h d \theta + \frac{k}{Q} d \theta$  the minimum value of  $Q$  that can be uniquely determined from the value of the energy supply is equal to  $\sqrt{\frac{k}{S}}$ . The close approach to parallelism of the curve  $B$  and the various calibration curves, more particularly those for small values of the distance apart of the heating element and the second thermometer, for large values of the impressed velocity of the stream, indicates that the actual increase of temperature of the stream was very approximately  $2^{\circ} \text{C}$ . Owing to the increased facility for mixing occurring with slow flows, the same was probably true in the case of low velocities of flow also.

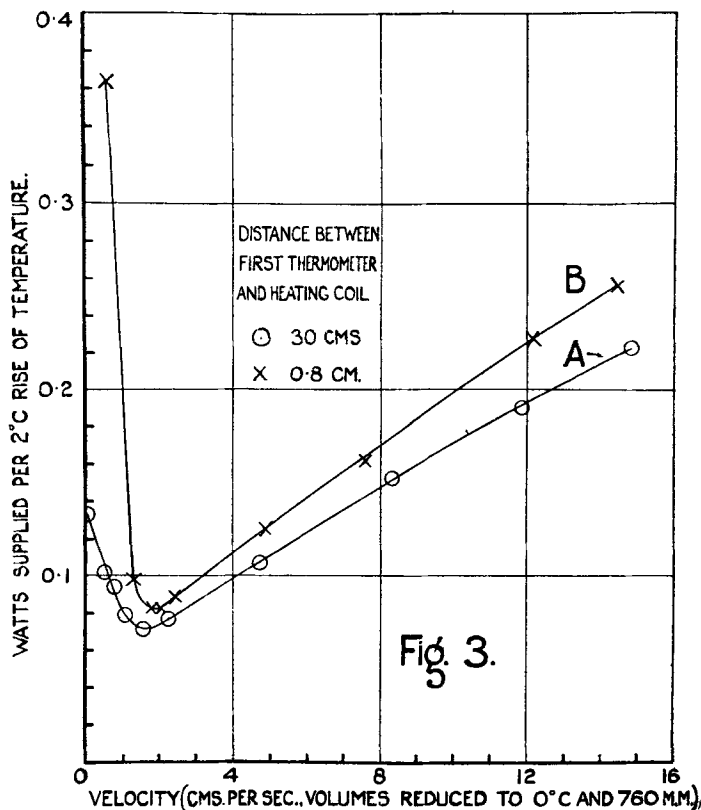
The calibration curve  $A$  is approximately hyperbolic. It will be noted however that for velocities of from 30 to 60 cms. per sec., the curve is slightly concave to the axis of velocities. This same feature of slight concavity is seen to be present in all the other curves of the series. This characteristic is probably attributable to the asymmetrical disposition of the resultant convection current from the heating element with regard to the two thermometers. Consider the case of curve  $A$  for which the two thermometers are disposed at equal distances of 30 cm. from the heating element. With zero flow, the two thermometers would indicate equal temperatures, and the highest temperature in the flow system would be found at the point immediately above the heating element. When a slow flow is imposed, the region of maximum temperature in the flow system is moved towards the second thermometer. The energy requisite to

maintain an indicated difference of  $2^{\circ}\text{C.}$  in the two thermometers is diminished on this account below the value it would have were the region of maximum temperature not so displaced. This effect increases with increasing velocity of the stream, as with such increase of velocity, the region of maximum temperature in the flow system advances towards the second thermometer. Such increase of effect must, however, attain a limiting value as it is clear that for large values of the impressed velocity only a small proportion of the energy supplied is utilized to raise the temperature of the flow system. The form of the calibration curve A may therefore be regarded as derived from the theoretical hyperbolic form by drawing it through a series of points the ordinates of which are slightly less than those of points on the hyperbola, the proportional difference of ordinates initially increasing with increase of velocity from zero until a limiting velocity is reached, and thereafter decreasing.

The remaining calibration curves in figs. 2 and 2*a* were obtained with the second thermometer placed closer than the first to the heating element. These curves are not asymptotic to the axis of energy supply. Clearly, with such dispositions of the respective thermometers, a finite energy supply would establish a difference in the temperatures indicated by the two thermometers. This effect is clearly seen in the curves C, D, E in fig. 2*a*. The curve E obtained with the second thermometer placed at a distance of only 1.5 mm. from the heating element is characterized by the fact that the minimum value—if any such occur—of the energy supply necessary to maintain the indicated difference of  $2^{\circ}\text{C.}$  must correspond with a very small velocity of the stream. The lower limit of velocities of gas streams for which the thermometric anemometer may be employed is clearly reduced by reducing the distance between the heating element and the second thermometer. For low values of the velocity, the time lag of response of the thermometric anemometer to a change of velocity is conditioned principally by the distances between the heating element and the thermometers. For small time lag, these distances should be as small as possible.

The disposition of the second thermometer has been discussed above. There is also a most suitable position at which the first thermometer should be placed. Such position is clearly not at too great a distance from the heating element, nor near thereto. In the latter case the temperature indicated by it would be conditioned largely by that of the heating element and its surroundings. An indicated difference of

2° C. between the two thermometers would under these circumstances correspond to a greater rise of temperature than 2° C. in the stream. This effect is shown in fig. 3.



Both curves were obtained with the second thermometer at a distance of 0.8 cm. from the heating element. The respective distances of the first thermometer therefrom were 30 cm. (curve A) and 0.8 cm. (curve B).

#### Summary.

An experimental investigation of the application of the thermometric anemometer to the determination of slow rates of flow of gases is detailed. It is shown that values of such low velocities cannot, in general, be uniquely determined by such type of anemometer. This arises owing to the existence of a minimum value of the energy supply required to heat

the stream through a definite range of temperature. The dependence of the limiting velocity upon the disposition of the thermometers with regard to the heating element is shown by means of calibration curves obtained for various distances between the respective thermometers and heating element.

The author desires to express to Dr. Charles Carpenter, C.B.E., his thanks for the provision of the facilities necessary for carrying out the work detailed in this paper.

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Dec. 29, 1921.

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LXXXIV. *On a Possible Physical Interpretation of Lewis and Adams' Relationship between h, c, and e.* By GERALD A. NEWGASS, B.A. (Cantab.)\*.

CONSIDER the hypothetical case of two spheres carrying equal but opposite charges  $e$ , of no mass other than electromagnetic, of equal radii. Imagine that the two spheres are touching, but that they are prevented from discharging. If the system is set rotating about its centre of mass and an axis at right angles to the line joining the centres of the spheres, there will be a certain angular velocity, angular momentum, and rotational energy at which the centripetal force would balance the electrostatic attraction. These values were roughly calculated, making use of the simplifying assumptions that the electromagnetic masses as given by the equation  $m = e^2 / (6\pi rc^2)$  were concentrated at the centres of the spheres, and that any possible effects of relativity etc. due to the high velocities cancelled out, and it was found that while the angular velocity and the rotational energy of the system varied with the radii of the spheres, the *angular momentum was independent of the size of the system* and was given by

$$\frac{1}{2} \sqrt{6\pi} \frac{e^2}{c}.$$

If the electricity is assumed to be distributed uniformly throughout the spheres instead of on the surface, or if, instead of both spheres being equal, one is considerably larger than the other, the only effect is to alter the coefficient. Accordingly, it is suggested that if the values of the moment of inertia and angular momentum were

\* Communicated by the Author.