II. THEORY

King's equation for the heat loss from a cylinder cooled by a stream of fluid was derived by solving Boussinesq's general differential equation for the conduction of heat in a moving fluid assuming the boundary condition of constant flux.

Except for very small wires and extremely low velocities

$$H = K\Theta + 2\sqrt{\pi K S \sigma A}\ V^{1/2}\ \Theta \tag{1}$$

where

H = heat loss per unit length of cylinders, $\frac{\text{cal}}{\text{sec.} \times \text{cm}}$

K = conductivity of the fluid, $\frac{\text{cal}}{\text{sec.} \times \text{deg. C.} \times \text{cm}}$ (assumed independent of temperature and, therefore, constant)

Θ = temperature difference between the cylinder and the stream, deg. C.

S = specific heat per unit mass of the fluid, $\frac{\text{cal}}{\text{g} \times \text{deg. C.}}$

σ = density of the fluid, $\frac{\text{g}}{\text{cm}^3}$

A = radius of cylinder, cm

V = velocity of stream, $\frac{\text{cm}}{\text{sec.}}$.

Since all quantities under the radical are assumed constant for a given fluid and cylinder, for a specific instrument equation (1) may be written more simply

$$H = \Theta\ (K + b\sqrt{V}) \tag{2}$$

The results of King's experimental work support the validity of this formula.

III. APPARATUS

For the present experimental work a grid made up of wire strung on an open frame was the instrument used to dissipate heat to the air stream. Preliminary attempts using commercial platinum and wires in parallel showed the advisability of constructing an anemometer which had one continuous strand of high purity platinum wire.

A sketch of the anemometer is shown in Figure 1. The frame (F) is made of 3/8 by 3/32 inch iron strip bent into a rectangle 7½ by 8 inches. A single piece of platinum wire (A) 153.3 cm long and 0.046 cm in diameter is strung nine times across the frame. Each end of the wire is connected by silver solder to a 0.15 cm round brass lead (L) insulated from the frame by a formica bushing (B). The other eight points of suspension are glass beads (G) which are attached to fine Monel wires (W) hard soldered to small threaded brass rods (R).

These rods pass through formica bushings threaded into the frame and are held on the outer side by knurled nuts (*N*) to provide adjustment for tension in the anemometer wire. The wire is stretched taut in the frame to prevent flapping or vibration in the air stream, which would cause mechanical and calibration difficulties.

Two wires are soldered to each of the brass terminals (*L*, *L*); one set being used for power input, the other being available for voltmeter connections.

IV. METHOD OF OPERATION

There are two principal methods of operation of hot-wire anemometers. In the first, the resistance of the platinum wire, and, therefore,

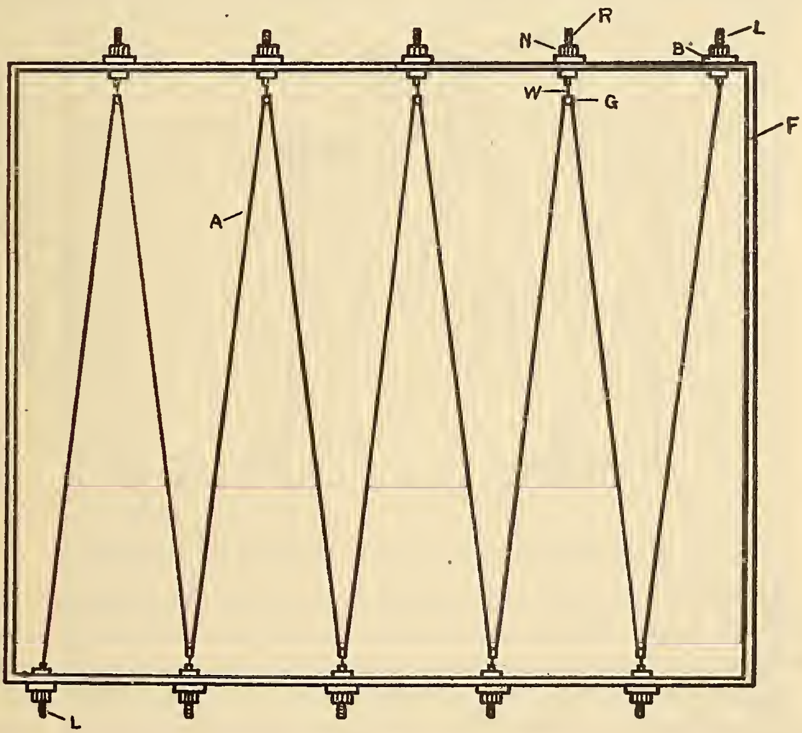

Fig. 1.—*Sketch of the anemometer*

its temperature, is kept constant by varying the current so that the energy input gives a measure of the rate of flow of air past the wire. In the second method a constant current is used, and the resistance of the wire is a measure of the rate of flow of air. The former method has been used in connection with the present instrument.

A diagram of electrical connections is given in Figure 2. The wire was maintained at a constant resistance of 1.2 ohms, corresponding to about 96° C. For convenience, the voltmeter scale was altered so that the voltmeter and ammeter readings would be identical when the wire resistance was 1.2 ohms. This was accomplished by contracting the voltmeter scale in the ratio 1.2 to 1. A 24-volt storage battery with a 2-ohm slide wire resistance was the source of the variable supply of power for heating the wire. In making a measurement the rheostat was adjusted until the readings of voltmeter and ammeter were identical, in which case the energy is the square of the current as given by the ammeter times 1.2, the constant resistance of the wire.

The heat dissipated from the anemometer wire is dependent on the temperature difference between the wire and the air. Since this temperature head is relatively small, accurate measurement of the air temperature is necessary. The instrument itself was used for this purpose, with a dry cell to furnish a small current, a milliameter

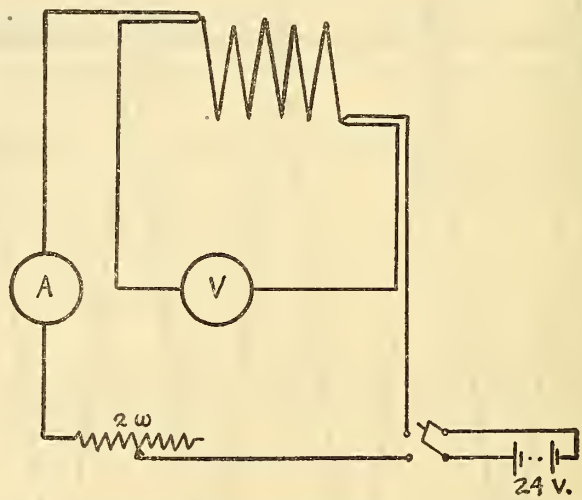

FIG. 2.—*Diagram of electrical connections for the anemometer*

to measure the current, and a portable potentiometer to measure the potential drop. The air temperature was computed from the resistance thus obtained and the known electrical constants of the platinum.

Later a portable resistance bridge was used to measure the resistance directly. Readings by a mercury thermometer were found to check temperatures computed from grid-resistance measurements, and for convenience this thermometer was used to obtain air temperatures.

V. CALIBRATION

The anemometer was calibrated in the 36-inch wind tunnel at the Bureau of Standards by comparison with a wall plate in the throat of the tunnel. The calibration of the wall plate had been well established in terms of average air speed through the central part of the tunnel.

The anemometer was mounted in the center of the throat of the tunnel slightly behind the wall plate. A series of runs were made with air speeds of 15, 30, 40, 50, 60, 70, 80, 90, and 100 miles per hour, the temperature of the wire being maintained constant. Runs were also made in which the temperature of the wire was varied.

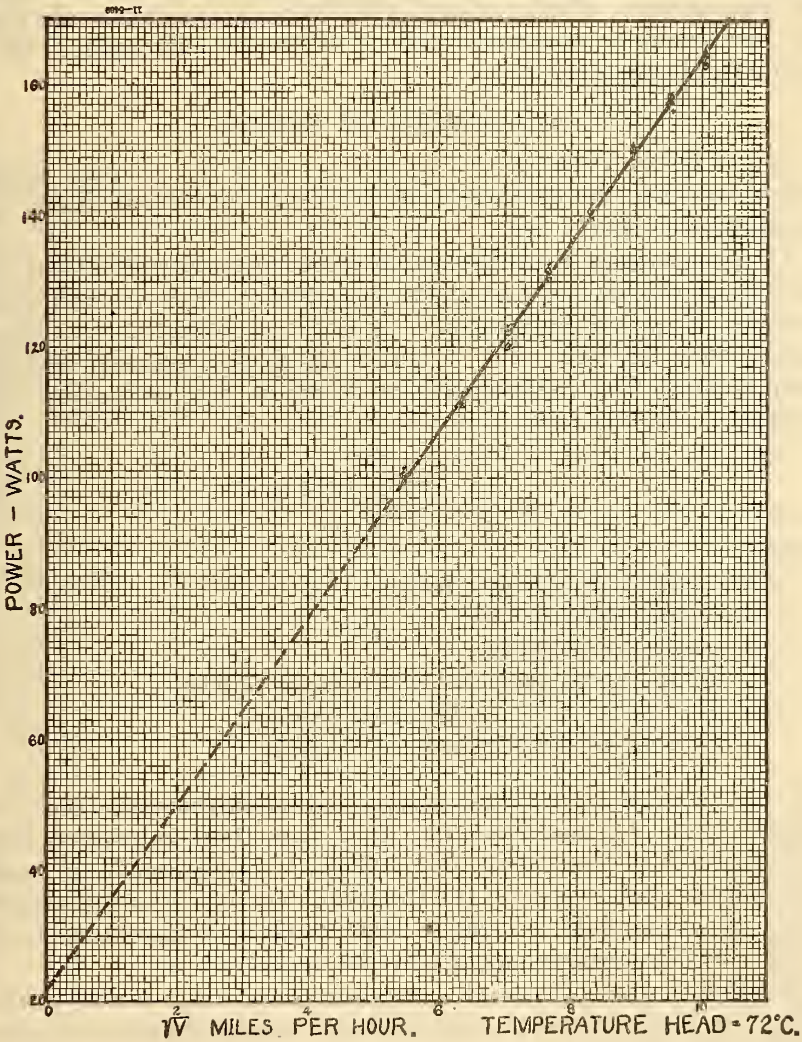

Fig. 3.—*Typical calibration curve*

The temperature of the air for any one run was maintained constant to within 1° C.

The results showed that the anemometer could not be used as an absolute instrument with King's equation as the fundamental relation between heat dissipation and air flow.

It could be used, however, by calibrating in a uniform stream of known velocity. A typical calibration given in Figure 3 shows a general linear relation between the heat dissipation and the square root of the air speed, in agreement with King's equation. It was found, also, that for changes in temperature head not exceeding 20°, the heat dissipated was directly proportional to the temperature head. This fact made it possible to correct readings taken at the existing air temperatures, which varied slightly from day to day, so that the air flow could be computed from a calibration determined for a particular temperature head.

VI. SOURCES OF ERROR

Errors in the instruments themselves or in the readings would affect the final results by giving incorrect temperature heads or wrong power values.

The percentage error in the measurement of temperature head can be computed from the well-known relations (1) between resistance, potential drop, and current, and (2) between resistance at a given temperature, resistance at 0° C., the temperature coefficient, and the temperature. Then, adding the errors due to each instrument, the result is

$$100\,\frac{\Delta\theta}{\theta}=\frac{\left(t_w+\frac{1}{\alpha}\right)(e+i)}{t_w-t_a} \qquad (3)$$

where

$\Delta\theta$ = error in temperature head
t_w = temperature of wire
t_a = temperature of air
α = temperature coefficient of resistance of wire
e = percentage error in voltmeter readings
i = percentage error in ammeter readings.

For the temperature range used with this anemometer, the percentage error was approximately five times the cumulative percentage errors in the instruments. Thus, it is apparent that small temperature heads as low as 10° C., which were unsuccessfully tried, would give too high an error. The smallest temperature head suitable for the accuracy required is 50° C.

In order to show the small error introduced from wrong power values the total derivative of the general simplified form of King's equation was computed.

$$H=\theta\ (K+b\sqrt{V}) \qquad (2)$$

The following substitutions were made in equation (2):

$$H = E\, I$$

$$\theta = t_w - t_a = \frac{R}{R_0 \alpha} - \frac{1}{\alpha} - t_a = \frac{E}{I}\left(\frac{1}{R_0 \alpha}\right) - \frac{1}{\alpha} - t_a$$

and the resulting derivative is

$$\frac{dV}{V} = \frac{2H}{b\theta\sqrt{V}}\left[\left(1 - \frac{t_w + \frac{1}{\alpha}}{\theta}\right)\frac{dE}{E} + \left(1 + \frac{t_w + \frac{1}{\alpha}}{\theta}\right)\frac{dI}{I}\right] \qquad (4)$$

Substituting values from Figure 3 in equation (4) it is found that the error is only 0.03 per cent for an air speed of 100 miles per hour when readings are correct to 0.01 volt and 0.01 ampere.

The wire, after use at low temperatures, had collected a thin film of dirt. It was thought that this condition might have changed the heat dissipation for a given air speed. The wire was cleaned and calibrated using five different temperature heads. The wire was then thinly coated with black shellac and calibration runs repeated. The results show that the heat dissipation was not appreciably changed by the presence of the shellac.

Strain in the platinum wire was next investigated. The anemometer while mounted in the wind tunnel was connected to a Wheatstone bridge. Resistance was determined after each run. After a series of runs the resistance at 0° C. was taken to detect any permanent change in the wire. There was a change of resistance with each succeeding calibration run with the anemometer. The force of the air blast and the adjustment of the tension on the wire stretched it slightly at each measurement, thus changing the resistance for a given wire temperature and consequently the temperature head.

For experimental purposes, however, it could be assumed that the resistance of the wire remained constant through five successive runs. The wire temperature corresponding to this resistance was taken as the average temperature computed from resistance measurements at 0° C. made before and after every five runs. The average change in resistance during five successive runs seldom exceeded the amount corresponding to a temperature change of 0.2° C., or 0.4 per cent of a 50° temperature head. When corrections were applied for resistance changes the anemometer could be relied upon to measure free air flow within 3 per cent.

VII. APPLICATION

As the grid was to be used to measure the mass of air flowing, calibrations were made in terms of mass flow of air in order to eliminate errors due to change in air density.

In measuring air flow through radiators, the final quantity to be determined is the air flow constant,[2] m; that is, the fractional part of the air approaching the radiator that passes through it.

$$m = \frac{M}{M_o} \qquad M_o = \rho V$$

where M = mass flow of air through radiator, $\frac{\text{lb.}}{\text{sec.} \times \text{ft.}^2}$

M_o = mass flow of air in tunnel, $\frac{\text{lb.}}{\text{sec.} \times \text{ft.}^2}$

ρ = density of air, $\frac{\text{lb.}}{\text{ft.}^3}$

V = air speed in the tunnel, $\frac{\text{ft.}}{\text{sec.}}$.

A number of measurements were made on radiators in a wind tunnel to study the behavior of the instrument in operation.

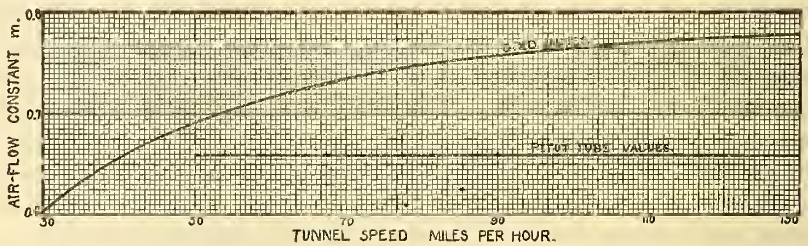

FIG. 4.—*Interference effect of radiator on grid in 36-inch tunnel*

The hot-wire anemometer, or grid, was clamped against the rear face of a radiator core which was mounted on a stream-line strut in a wind tunnel, 3 feet in diameter, in which a maximum speed of 150 miles an hour could be obtained. Air speed was measured by a calibrated static wall plate.

When the grid was attached to the back or downstream side of a radiator the value of m did not check satisfactorily with that obtained by reliable Pitot tube measurements, indicating that the grid was so affected by swirls or eddies, that the calibration in a uniform and nonturbulent stream did not apply. Figure 4 shows a comparison

[2] Radiators for Aircraft Engines, B. S. Tech. Paper No. 211.

of the values obtained at different speeds by the grid and by the Pitot tube.

In order to find a possible location where the calibration in a uniform stream would give true values of mass flow of air through a radiator core, a series of runs were taken in a closed tunnel; that is, with the radiator core completely filling the cross section of the tunnel. Of course, the eddies back of a radiator in a closed tunnel would differ from those occurring when the radiator is mounted in a large free-air stream, but even then some idea could be obtained as to the best possible position for using the grid. Measurements were made at six different mass flows ranging from 3.4 to 8.4 pounds per second per square foot, corresponding to air speeds in the open

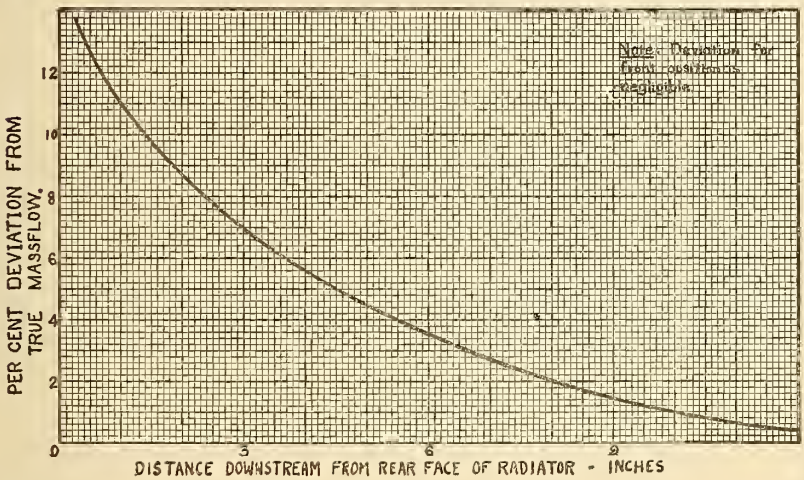

FIG. 5.—*Interference effect on grid in closed tunnel*

tunnel of 50 to 125 miles per hour. During the runs the grid was mounted against the front of the radiator, against the back, and at distances back of the radiator of 3, 6, 9, and 12 inches. When the grid is mounted against a radiator the wire is about 3/16 of an inch from it.

This survey showed that the grid gave true values of air flow within experimental error, when mounted against the front of the radiator core. When the grid was mounted behind the core, Figure 5 shows that too great flow was indicated at all distances up to 12 inches, where true air flow was again indicated.

Measurements were made on several radiator cores mounted in the 3-foot wind tunnel. The grid was clamped to the front of the core in each case and measurements of air flow taken using air speeds from 30 to 140 miles per hour. The air flow constant, m, thus obtained for each core, agreed within 5 per cent with values obtained by measuring the air flow through the cells of the core with a fine Pitot tube. The Pitot readings were corrected for the effects upon air flow in cells caused by the presence of the Pitot.[3]

VIII. CONCLUSION

The results indicate that a grid mounted against the front of a radiator can be used with reasonable accuracy to measure air flow through radiators in different positions on aircraft

WASHINGTON, September 30, 1924.

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[3] Pitot Tube Corrections in Aircraft Radiator Measurements. Not yet published.