Characteristics of a Thermocouple Anemometer

By

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1. Introduction

In the previous paper¹⁾ one of us (S. K.) has considered thermocouple anemometers chiefly from the point of compensation for the temperature effect of ambient air on the basis of King's theory²⁾ about hot-wire anemometers. In that case, if we use a hot wire the electric resistance of which is practically independent of its temperature, and a thermocouple the electromotive force of which is proportional to the difference of temperature between the two junctions, then for a hot wire put perpendicularly to a stream of gas of velocity v and heated by current i, we will have approximately the relation in some region of velocity

$$i^2 = kE(A+B\sqrt{v}), \tag{1}$$

where E is an electromotive force produced in the thermocouple by the difference of temperature between the hot junction attached to the heated wire and the surrounding gas stream, and k is a constant of the instrument independent of the velocity and temperature of the stream. In this equation

$$\mathrm{A} = \kappa,$$

and

$$B = \sqrt{2\pi D\rho c_p\kappa}, \tag{2}$$

where κ is the thermal conductivity of gas, ρ its density, c_p its specific heat at constant pressure and D the diameter of the wire assumed to be a circular cylinder in King's original formula for a single hot wire considering only heat losses due to conduction by gas. But as heat losses due to radiation and conduction through supporters of the wire and thermocouple wires also ought to be taken into account, A may be understood to be equal to $\kappa+a$.

Now we have constructed some thermocouple anemometers, performed wind tunnel experiments and studied characteristics of the anemometers in reference to formula (1).

2. Construction of Thermocouple Anemometers

As shown in Fig. 1, a nichrome wire of 0.1 mm was put between two supporters made of annealed piano wires fixed to an ebonite rod, and one junction of a thermocouple of chromel and alumel wires of 0.1 mm thick was attached to the middle point of the nichrome wire with a silver solder or by an electric arc. In cases where the linear relation is not required between the thermoelectromotive force and the difference of temperature between the two junctions, thermocouples of chromel and constantan of larger electromotive force were used.

3. Method of Calibration

To obtain air streams of various speeds two apparatuses were used. Fig. 2·1 shows an apparatus for streams with speed of less than 90 cm/sec. Currents of air are sucked into this apparatus by a vacuum pump and the rate of revolution of a wet gas-meter is read with a stop-watch, and the quantity of the flow is adjusted by a stopcock. Then, by assuming the distribution of velocity of the stream immediately after it has passed through the nozzle to be uniform, the speed is calculated from the rate of the flow divided by the area of the exit of the nozzle at the immediate back of which an anemometer is situated. Fig. 2·2 is an apparatus for higher speed. Currents of air are sucked in with a propeller. In the wind tunnel an anemometer and next to it a static tube are put behind the nozzle. The speed of the air stream is found by the static tube and a Chattock

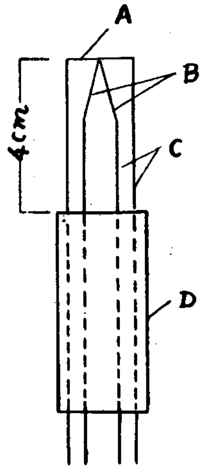

Fig. 1. Diagram of the thermocouple anemometer.
A: Hot wire. B: thermocouple
C: Stem. D: Ebonite

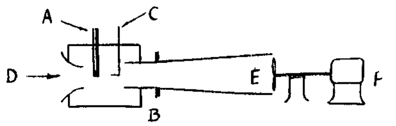

Fig. 2. 2. Schematic diagram of the test apparatus for wind of higher speed.
A: Anemometer. B: Wind tunnel.
C: Static tube. D: Nozzle. E: Propeller. F: Motor.

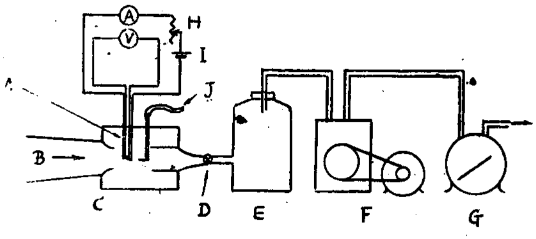

Fig 2. 1. Schematic diagram of the test apparatus for wind of lower speed.
A: Anemometer. B: Nozzle. C: Wind tunnel.
D: Stopcock. E: Glass bottle. F: Vaccuum pump. G: Wet gas-meter. H: Rheostat.
I: Battery. J: Static tube.

manometer. The apparatus is used for the streams having speed of 1 m/sec to 8 m/sec. Directions of those streams are always horizontal in the both apparatuses.

There are two methods in using the anemometers. One is the method of comparing E and v by passing a current through the hot wire, and the other is that of making i correspond to v by adjusting E to a prescribed value. The former is called the method of the constant current and the latter the method of the constant electromotive force. The most simple circuit shown in Fig. 2·1 was used.

4. Experimental Results

(i) A hot wire was placed perpendicularly to an air stream (flowing horizontally as stated before) and vertically. Fig. 3·1 shows the relation between i and v at constant E of 3, 4 and 5 mV for streams of lower speed, and Fig. 3·2 shows the relation between i and v at constant E of 4 mV for streams of higher speed. In Fig. 4 the data used in Fig. 3·1 are again represented but this time as the relation between i^2 and $\sqrt{v}$. It will be seen that i^2 and $\sqrt{v}$ hold a linear relation for speed between 5~6 cm/sec and 90 cm/sec, and slopes of the lines of 3, 4 and 5 mV against $\sqrt{v}$ axis have ratios of 3.0 : 4.0 : 5.1 which may be assumed to be 3 : 4 : 5, thereby proving the correctness of formula (1). But downwards from 5~6 cm/sec the lines alter their directions to become parallel with $\sqrt{v}$ axis. The fact seems to be due to natural convection currents and will be discussed in (iii). Fig. 5 shows correlation of i^2 and $\sqrt{v}$ with constant E of 4 mV for streams, investigated with the two apparatuses for higher and lower speed. It will be found

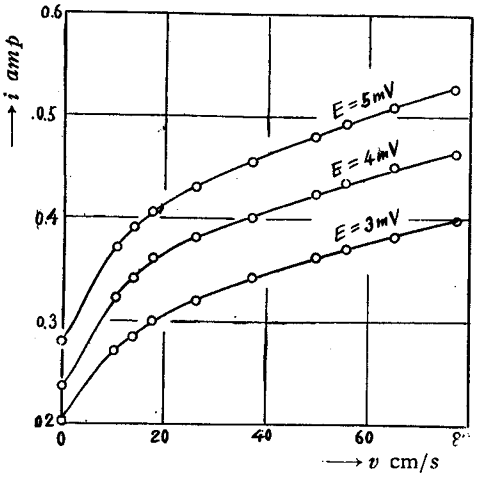

Fig. 3·1. Correlation plots of i versus v for wind of lower speed. (Constant E method.)

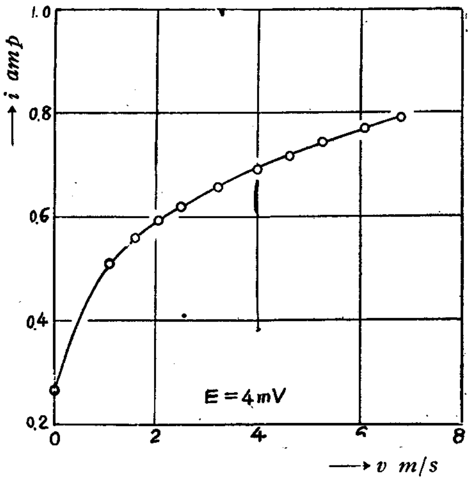

Fig. 3·2. Correlation plots of i versus v for wind of higher speed. (Constant E method.)

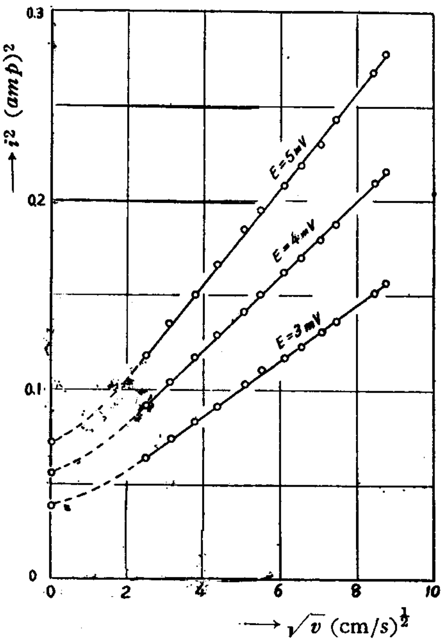

Fig. 4. Correlation plots of i^2 versus $\sqrt{v}$ for wind of lower speed. (Constant E method.)

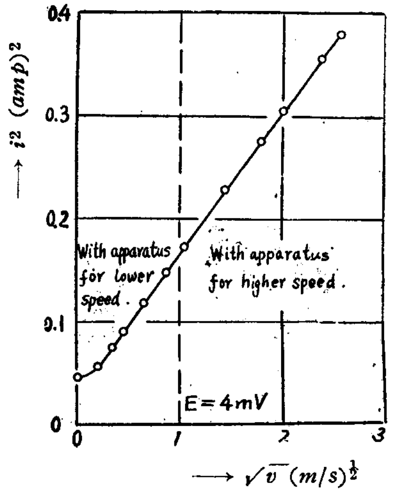

Fig. 5. Correlation plots of i^2 versus $\sqrt{v}$ for wind of higher and lower speed. (Constant E method.)

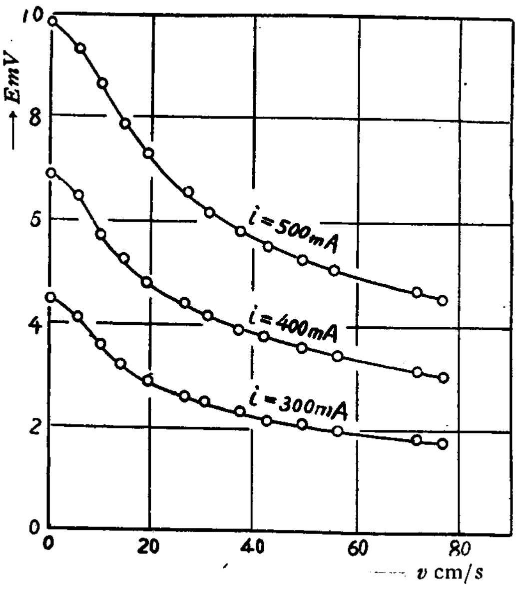

Fig. 6-1. Correlation plots of E versus v for wind of lower speed. (Constant i method.)

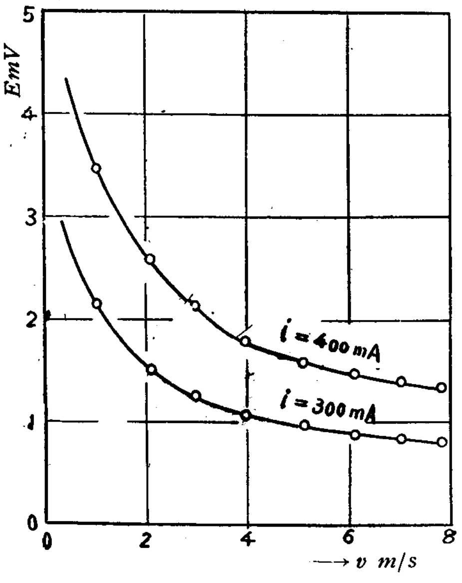

Fig. 6-2. Correlation plots of E versus v for wind of higher speed. (Constant i method.)

that points of both sets of data lie on one straight line. There is a possibility that the line changes its direction somewhat at a point where Reynolds number takes 30~40[3] or v takes 6~8 m/sec in the present case, but we could not make this clear.

(ii) The position of the hot wire being the same as before, the relation between E and v was studied with constant heating currents of 300, 400 and 500 mA. Fig. 6·1 and Fig. 6·2 were obtained by using the apparatuses for lower and higher speed, respectively. As expected from formula (1), by the constant i method variation of E with v is very large and the instrument is highly sensitive in the region of very low speed, but its sensitivity soon becomes very poor when speed gets higher. The error may be estimated at about 10% for wind of 5 m/sec and will become much larger for wind of higher speed. Contrary to this, by the constant E method the high sensitivity of the instrument continues in the region of fairly high speed. The error seems to be less than 3% for speed of 7 m/sec. From formula (1) a linear relation will be presumed approximately between $1/E$ and $\sqrt{v}$ by the constant i method, but it should be remembered that A is a function of temperature, so, strictly speeking, it is a function of v in this method, and it is possible that the correlation line changes its direction gradually. As a matter of fact, Fig. 7 shows a linear relation between $1/E$ and $\sqrt{v}$ in experimental errors for speed higher than about 10 cm/sec, but for lower speed the curve deviates markedly from the straight line and tend to parallel $\sqrt{v}$ axis.

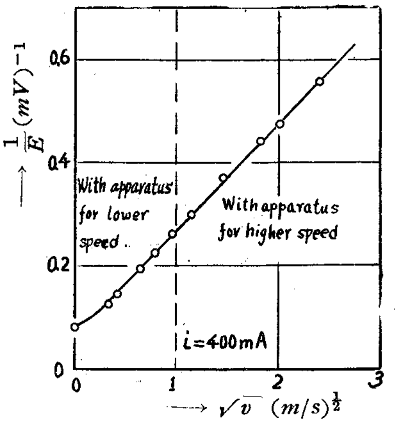

Fig. 7. Correlation plots of $\frac{1}{E}$ versus $\sqrt{v}$ for wind of higher and lower speed. (Constant i method.)

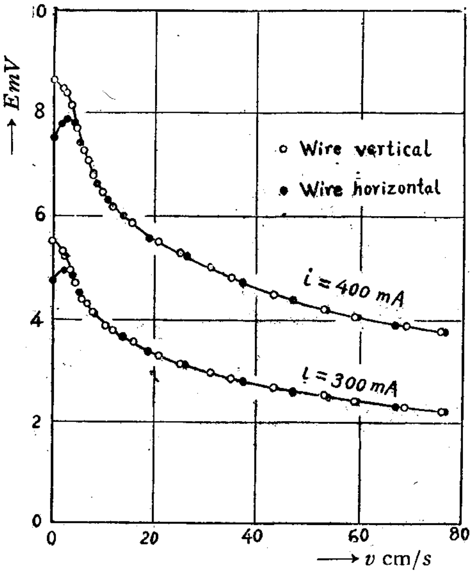

Fig. 8. Correlation plots of E versus v with constant i for two different orientations of the hot wire.

(iii) Fig. 8 shows correlation plots of E and v with constant i when the hot wire is placed vertically (○), or horizontally (●), in streams of air of lower speed. From the figure it is found that points of ○ and ● seem to lie on a single curve for speed higher than 5~6 cm/sec, but markedly deviate for lower speed. And attention should be paid to the fact that in a vertical position, E becomes larger monotonously as v decreases, and one value of v corresponds to one value of E, but in a horizontal position, there is the maximum value of E, and two values of v correspond to one value of E. Similar facts are recognized by Hukill[4)] and Simmons[5)] who have performed experiments with thermocouple anemometers of considerably different construction from ours. With Hukill's anemometer one of the junctions of a thermocouple is wrapped with about 60 turns of nichrome wire, so the orientation of the hot wire may be complicated from the point of verticality. Simmon's anemometer consists of a hot wire and a thermocouple sealed parallel with each other in a two-bore silica tube. Moreover, our anemometers seemed to be unsteady with a hot wire in a horizontal position. Thus it becomes necessary to hold a hot wire in a vertical position for streams of low speed. The deviation of correlation plots of i^2 and $\sqrt{v}$, and $1/E$ and $\sqrt{v}$ from straight lines in the region of very low speed as stated in (i) and (ii) and the above facts will be assumed to be chiefly due to the natural convection currents of air. 5~6 cm/sec will be the speed of the natural convection currents caused by the difference of temperature between the wire and the stream of air in the present experiments, and if we consider the resulting cooling effect of the horizontal forced stream and vertical natural convection currents upon the hot wire, a rather abrupt change in inclination of the curve of i^2 versus $\sqrt{v}$ etc. may be roughly understood. As to the existence of the maximum point in the curve E versus v similar to that for a horizontal hot wire, Hukill has given an explanation by a chimney effect.

(iv) By the reason above mentioned a hot wire was held perpendicularly to streams in standard measurement. But now to see results in different orientations experiments were performed in a horizontal stream of air of 3.6 m/sec with a hot wire heated by a constant current rotating around horizontal axis perpendicular to the stream, and the correlation between E and θ, the angle of inclination to the vertical line, was plotted as shown in Fig. 9. From the figure it will be found that the cooling effect becomes smaller with alteration of θ from 0° (perdendicular to stream) to 90° (parallel to stream) and the rate of the change of the cooling effect to inclination is minimum in a perpendicular position.

(v) Effect of the temperature of the stream. By changing the temperature of the stream of air change in A, B and the naural convection will be caused, but in practice change in A alone may come into question. To see the effect, sucked-in air heated by electrically heated latticed wires to make several layers, and made a laminar flow by a rectifier was introduced into the wind tunnel for lower speed but with streams of higher speed, and the temperature was measured with a thermocouple thermometer in the neighbourhood of an anemometer. The thermometer was moved from time to time to different positions to ascertain the uniformity of temperature. If the effect of temperature on the anemometer be caused practically by A alone plots of i^2 versus $\sqrt{v}$ with constant E will give a set of straight lines parallel to each other corresponding to various temperatures. Really, results shown in Fig. 10 examined at three different temperatures of about 20°C, 40°C and 60°C seem to justify the expectation. From calculation by the figure, at 20°C and 60°C difference of speed corresponding to the same heating current will amount to about 12.5% at 1 m/sec, 6% at 4 m/sec and 4% at 9 m/sec.

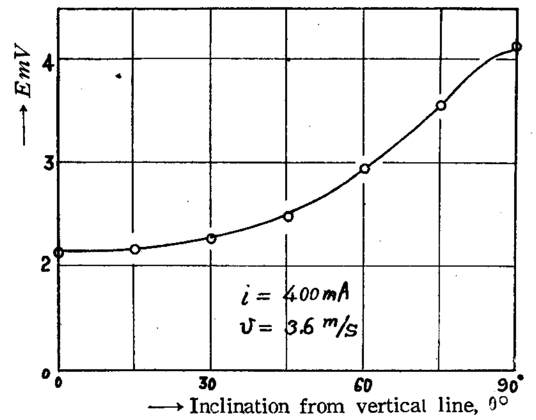

Fig. 9. Diagram showing directional feature of the anemometer.

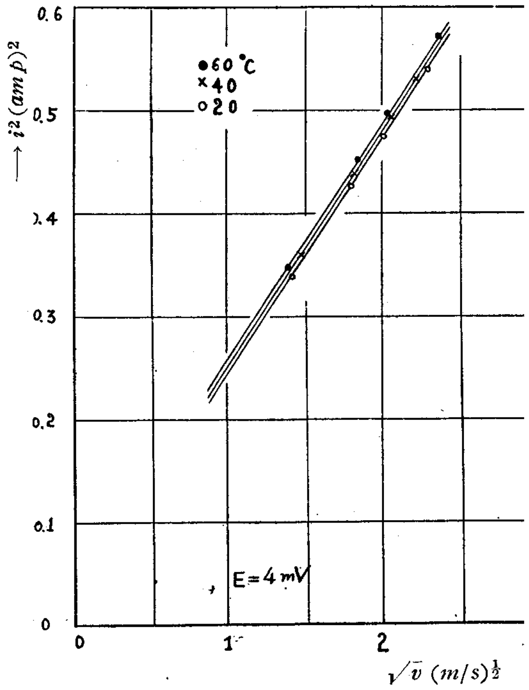

Fig. 10. Correlation plots of i^2 versus $\sqrt{v}$ for wind of three different temperatures.

7. Practical Use

Advantage of the two methods—the constant E method and the constant i method—was described partly in (ii). The constant E method will be of standard type for theoretical investigation and superior in that good sensitivity is obtained for the region of fairly higher speed. By the constant i method the anemometer is highly sensitive in the region of very low speed, but the sensitivity soon becomes very poor for higher speed. Now with streams of very low speed the disturbing effect of free convection currents will be made more marked by the constant i method. Furthermore, this method causes the temperature of a hot wire to get higher for lower speed, thus detracting somewhat from its advantage. Another and more excellent character of the method is that as a hot wire is selected of an electric resistance of very small temperature coefficient, heating current i remains constant for different speeds when it is once adjusted to an assigned value, and wind of even rapidly varying speed may be measured by only observing electromotive force of a thermocouple with a millivoltmeter. In contrast to this case, by the constant E method efforts should be made to bring variant E to an assigned value by adjusting the standing i, so it is impossible to apply the method to varying speed. Summarizing, the constant E method may be recommended for purposes such as calibration of the steady wind while the constant i method will be preferred in general practical use. Of course it will be recommended to adopt either method as occasion calls for by using both an ammeter and a millivoltmeter in the circuit.

The anemometer may naturally be used as a gas-meter. But in that case its characteristics ought to be studied previously for the gas in question as κ, ρ and c_p will be variable according to kinds of gases, and special care should be taken when the composition of gas may be changeable at times.

8. Aging

Aging of a hot wire owing to use for a long period ought to be considered. So, three anemometers were examined at times after heating the wires up to about 200°C and during 200 hours in total, but any of them has shown no appreciable change in characteristics. The success might have been accidental, but it is possible that the anemometer endures for a fairly long time in ordinary clean air. Further, for the sake of safety, an anemometer was constructed after Simmon's method by inserting one junction of a thermocouple into a fine glass tube, putting a hot wire along the tube and covering them with another glass tube of 0.8 mm thick, and its characteristics were examined by the constant i method. Fig. 11 shows the results in contrast to an ordinary bare wire anemometer. The sensitivity seems to have been reduced by sealing.

A thermocouple anemometer has inertia somewhat larger than a single wire anemometer and is inferior to the latter in point of quick response, but serious inconveniences will not occur for ordinary purposes, and it may be even preferred in some cases where rather an average velocity of wind is required. It is robust, easy to handle and recommended as a convenient instrumet for practical use.

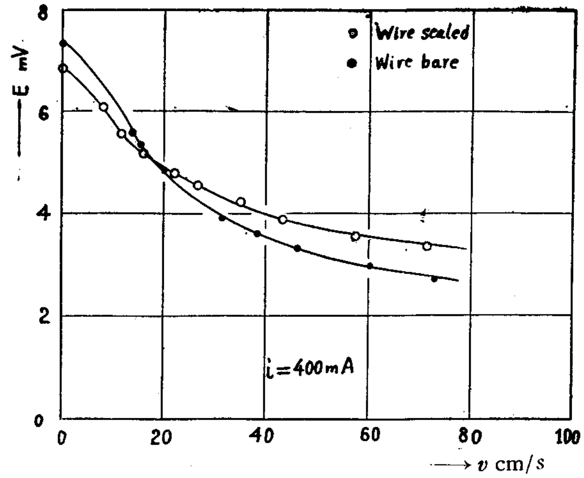

Fig. 11. Comparison of characteristics of a sealing-in-glass anemometer and an ordinary anemometer.

Lastly we wish to express our cordial thanks to Prof. B. Hudimoto for his valuable advices about the measurement of wind velocity and the loan of a wind tunnel, a static tube and a Chattock manometer, and to Mr. T. Koshida for his earnest assistance in the experiments. Thanks are also due to the Ministry of Education for the financial support given us for the present research.

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