The Response of Thermocouples to Rapid Gas-Temperature Changes[1]

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This paper presents practical data which were taken from the main results of a research program dealing with the response of thermocouples to changing gas temperatures. Experimental and theoretical data for the response time of thermocouples ranging in wire size from 0.01 to 0.0005 in. are presented. The experiments were performed over a range of temperatures from 70 F to 950 F, and for air velocities ranging from 0 to 125 fps. All of the experiments were carried out in such a way that the hot junction of the thermocouple was always cooled. An equation is presented for computing the response time for thermocouples fabricated from fine wires and subjected to sudden air-temperature changes. Heat transfer by conduction and radiation were negligible in the experiments performed.

INTRODUCTION

A thermocouple placed in a gas stream, the temperature of which suddenly changes, will usually indicate a temperature different from that of the true value at any given time before the equilibrium condition has been attained. Due to the fact that the measurement of instantaneous gas-temperature changes is becoming increasingly important in the fields of heat transfer and thermodynamics, this particular part of our main investigation was undertaken to obtain and correlate data on the response time of thermocouples fabricated from fine wires.

One of the purposes of this investigation was to study the response of a thermocouple made from fine wires, by suddenly subjecting it to a low-temperature air stream. The research program consisted of the design and construction of suitable apparatus, development of a satisfactory welding technique, and the collection and analysis of experimental data. Thermocouples composed of platinum and platinum 10 per cent rhodium with wire sizes of 0.01, 0.002, 0.001, and 0.0005 in. were used in the experiments. All of the work was carried out at approximately atmospheric pressure. The temperature range was 70 F to 950 F.

Before undertaking the experimental part of the program, a survey of the literature available to the authors was undertaken. Many of the contributions and suggestions made by previous investigators, as reported in the technical literature, were incorporated in the program. Space limitation does not permit the inclusion of the many references studied, hence only a short Bibliography[5] is included. However, the authors are cognizant of the value of the work of previous investigators.

DESCRIPTION OF THE APPARATUS

Welding Apparatus. Before the actual experimental investigation could he undertaken, it was first necessary to develop suitable apparatus and a technique for welding the fine wires. Many different methods were tried before a satisfactory technique was developed. Finally a satisfactory method was obtained whereby the wires were electrically welded between graphite electrodes. The wires were joined by first crossing the ends and placing the intersection of the wires on the surface of a horizontal graphite rod. A second graphite rod was placed at right angles to the first and then rolled over the intersection of the two wires. A satisfactory weld was obtained when the rods were connected to a 3-volt d-c source. After welding, the excess material was removed carefully from the junction of the thermocouple.

Recently Hammel (1)[5] described a butt-welding technique based on the use of a special jig. By means of this apparatus successfully butt-welded thermocouples have been constructed from wires as small as 0.003 in. diam. If the same apparatus may be used for fabricating thermocouples of even smaller diameter, this procedure may prove to be more effective than the method used by the authors.

Recording Apparatus. Since the object of this phase of the work was to study the response of thermocouples during very rapid temperature changes, it was not possible to use standard laboratory equipment. As a result a large amount of time was spent in constructing suitable recording apparatus.

The thermocouple voltage change was. finally recorded by means of an apparatus consisting of an interrupter, alternating. voltage amplifier, Oscilloscope, and a rotating-drum camera equipped with a modulator tube for placing timing marks on the .photographic paper. Due to unstable operation of the direct- current amplifiers, it was finally decided to use a voltage interrupter in the circuit and a stable alternating-voltage amplifier. The rotating-drum camera was found to be very satisfactory for recording the trace on the oscilloscope. The apparatus was designed on the basis of the idea previously advanced by Champion and Brokaw (2).

Test Apparatus. Two devices were used to subject the thermocouples to a sudden decrease in temperature. The first apparatus consisted of a T-shaped section of aluminum mounted in such a way that it could be moved instantly a short distance in a horizontal direction. In the normal operating position a jet of high-temperature air passed through a slot in the aluminum section and flowed over the test thermocouple. Horizontal displacement of the section shut off the high-temperature air stream, and a second slot allowed a cold-air stream to pass over the thermocouple. Whenever the T-section was moved, the hot-air stream was suddenly replaced by a cold-air jet which subjected the thermocouple to an instantaneous air-temperature change.

The second method consisted of placing a thermocouple in a low-temperature air stream and raising the temperature of the wire by

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[5] Numbers in parentheses refer to the Bibliography at the end of the paper

a current through it. After a desired temperature had been reached, the current was cut off, and the couple allowed to cool rapidly in the air stream.

In all tests the thermocouples were placed in a horizontal position, the wires extending in opposite directions from the junction. The horizontal thermocouple was mounted at right angles to the air stream. In this way the thermocouple resembled a very thin cylinder placed at right angles to the air flow.

EXPERIMENTAL PROCEDURES

Before undertaking the main part of the experimental program, calibration tests and preliminary calculations and experiments time elapsed after temperature change occurs were conducted.

Experiments were conducted to ascertain as to whether or not conduction of heat along the lead wires of the thermocouples was of large enough magnitude to merit consideration. The results obtained indicated that the heat lose by conduction was negligible.

Calculations indicated that for the experimental range of the apparatus, the transfer of heat by radiation from the junction of the thermocouple to the surroundings was very small in comparison with the convective heat transfer; hence it could also be neglected.

Several experiments were carried out in an effort to determine the maximum air velocity which the couples could withstand without breaking. The results obtained indicated that the couples could be used for velocities up to 400 fps.

Considering only convective heat transfer to or from the couple, a heat balance was written and the final result written in a form similar to that used by Rhodes (3), Harper (4), Mock (5), and Bailey (6) which follows

$$(t_i - t) = (t_i - t_a)\ (1 - e^{-\tau/\beta}) \qquad [1]$$

$$\beta = \frac{\rho D c}{4h} \qquad [2]$$

where

t_i = initial temperature as indicated by thermocouple before temperature change occurs
t = temperature indicated by thermocouple τ millisec after change occurs
t_a = temperature of air stream after temperature change occurs
ρ = density of thermocouple material
c = specific heat of thermocouple material
h = coefficient of heat transfer
D = diameter of thermocouple wire
τ = time elapsed after temperature change occurs

If the time elapsed τ is selected equal to β, then Equation [1] reduces the following

$$(t_i - t) = 0.632\ (t_i - t_a) \qquad [3]$$

when $\tau = \beta$. This means that if τ is equal to β, then the temperature change $(t_i - t)$ is 63.2 per cent of the total change $(t_i - t_a)$

Therefore it was decided to measure on the records obtained the time elapsed temperature change had reached a value of 63.2 per cent of the total. The average experimental values obtained for τ are recorded in Table 1. The averages are based on 103 individual experiments.

In order to check experimental values, a mean coefficient of heat transfer was considered during 63.2 per cent of the change and was computed by means of the following correlation given by McAdams(7)

$$\frac{hD}{k_f} = 0.32 + 0.43\left(\frac{DV\rho}{\mu_f}\right)^{0.52} \qquad [4]$$

In order to determine the values for the thermal conductivity, viscosity and density of the air for use in Equation [4], a mean temperature was used as found by use of the following equation

TABLE 1, EXPERIMENTAL AND COMPUTED DATA

Thermocouple number	Diam of wire. in. 0.0005	Initial temp of thermocouple t_i, deg F,	Air Temp t_a, deg F	Average air Velocity,	Average for 63.2 percent response time obtained from photographic records ,millisec	Calculated Reynolds	Calculated time for 63.2 percent response
701	0.0005	776	84	24.5	3.6	3.18	3.4
701		794	83	47.1	2.8	6.05	2.6
711		665	87	22.5	4.5	3.17	3.5
711		677	86	49.4	3.5	6.92	2.6
711		667	83	106.8	2.4	15.15	1.9
700	0.001	834	99	49.4	8.0	12.04	7.7
700		840	103	28.8	11.0	6.93	9.7
701		867	104	28.9	12.7	6.83	9.6
701		852	102	48.4	10.8	11.72	7.7
703		814	91	29.2	11.5	7.29	9.6
703		821	90	50.7	9.7	12.62	7.6
703		795	88	118.0	6.5	30.19	5.2
704		580	74	27.3	9.2	8.43	9.9
704		580	70	48.9	7.9	15.22	7.7
500	0.002	908	104	18.2	34.3	8.32	34.8
500		916	100	27.9	31.1	12.77	29.1
500		915	96	50.4	24.9	23.24	22.4
500		910	93	73.8	22.3	34.32	18.7
500		913	91	98.3	20.1	45.70	16.3
500		902	90	124.8	18.2	58.90	14.6
501		853	99	11.1	34.9	5.32	42.5
501		860	93	23.6	31.5	11.40	31.4
501		870	90	49.0	24.8	23.55	22.5
501		886	89	98.8	18.9	47.00	16.3
502		803	104	11.9	35.0	5.93	41.4
502		807	98	26.2	27.2	13.02	29.9
502		818	97	48.9	21.5	24.23	22.6
502		843	92	102.0	16.0	49.95	16.1
542		429	64	25.4	26.4	18.20	30.2
542		372	64	48.9	21.1	37.00	22.3
501		531	80	25.5	28.8	16.07	30.8
501		520	80	48.9	22.3	31.50	20.5
543		417	62	23.7	27.5	17.24	30.9
543		574	84	24.1	26.1	14.73	30.8
542		815	81	21.6	31.4	10.97	32:4
542		830	80	48.9	24.0	24.53	22.6
705	0.01	570	66	54.5	237.0	171.8	246.0
705		574	63	107.4	180.0	340.1	178.0

$$t_f = \frac{\dfrac{(t_i + t)}{2} + t_a}{2} \qquad [5]$$

The symbols have the same significance as previously mentioned.

In the development of Equation [4], the Prandtl number was considered constant, which is a satisfactory assumption for the temperature range used in this investigation.

Using the value for h, together with the density, specific heat, and diameter, the theoretical values for τ were determined for 63.2 per cent of the total time by means of Expression [2] since τ is equal to β under the condition specified.

RESULTS AND CONCLUSIONS

The values for the theoretical response for various sizes of couples for the range of temperatures and velocities covered in the experiments are shown by the solid lines in Figs. 1 and 2. The points represent the experimental values obtained. From the results it may be concluded that the relations developed may be used to predict the time required for a thermocouple to cool to a value of 63.2 per cent of the total impressed temperature difference for the temperature and air-velocity ranges covered during the investigation. The air velocity was varied from approximately 0 fps to 125 fps. The temperature range was 70 F to 950 F.

Although the experimental data have not been evaluated for other response times, it is felt that other values for the response interval may be calculated by using different relationships for τ and β, such as the following:

Relation between τ and β	Value for ratio $\frac{t_i - t}{t_i - t_a}$
$\tau = \beta$	0.632
$\tau = 2\beta$	0.865
$\tau = 3\beta$	0.95

or by evaluating β by use of Equations [2] and [4] and solving for τ in Equation [1].

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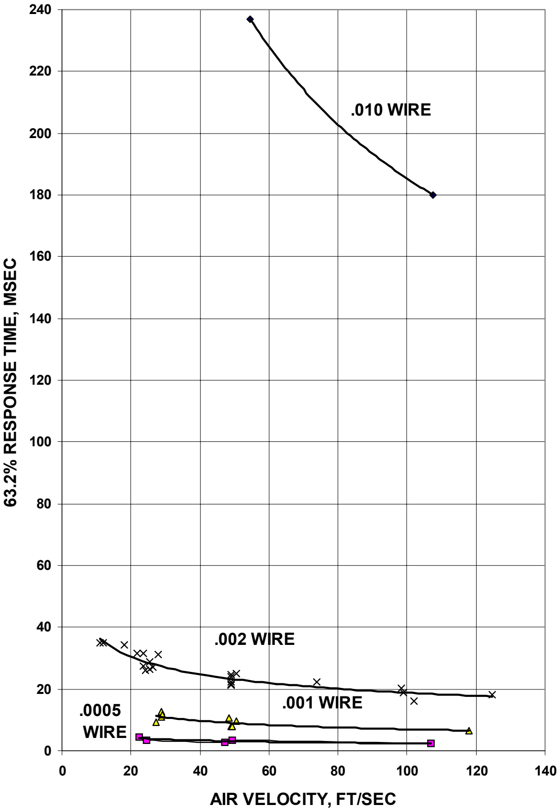

Fig. 1 Response Time Versus Air Velocity

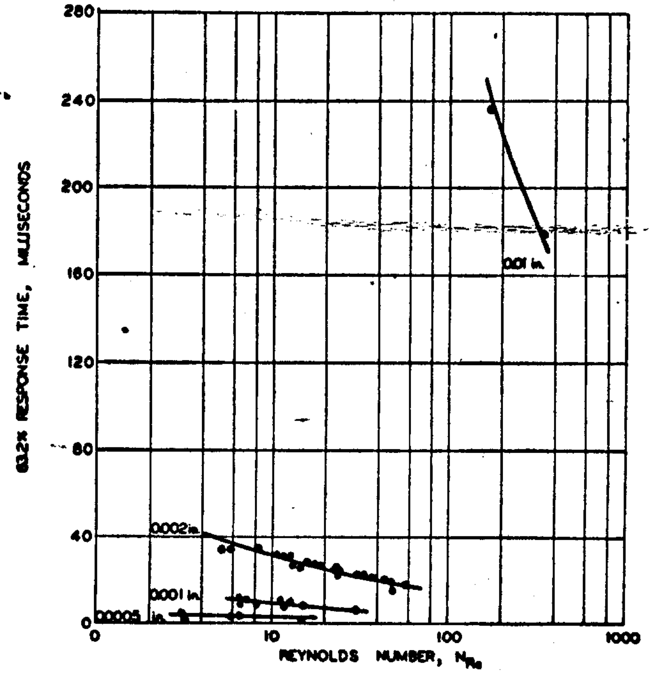

Fig. 2 Response Time Versus Reynolds Number