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AN EXPERIMENTAL INVESTIGATION OF THERMOCOUPLE RESPONSE TIMES IN STATIC GAS ENVIRONMENTS

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Abstract—The output EMF of a fine-wire thermocouple element (chromel–alumel, 0·025 mm dia) has been recorded in detail after rapid electrical heating to 25 K above ambient in various gaseous environments. The EMF always decayed exponentially, thus confirming that thermocouple response in such environments may be characterized by a 'time constant' (τ). Time constants have been obtained for a variety of *Pt*/*Pt*–13%Rh elements in static gas environments. The time constant fell with increasing initial temperature differential (> 40 K) at near atmospheric pressure and variation of τ with support wire alignment indicates that this was due to convective heat transfer. For low initial differential (< 40 K), τ rose with falling gas thermal conductivity but was independent of pressure above a few mmHg. Values of τ obtained from a predictive equation due to Melvin did not agree well with experimental results for this pressure range. Below approximately 20 mm Hg the time constant of a 0·019 mm dia (0·0125 mm wire diameter) element rose with falling pressure; it is shown that the rise can be attributed to increasing heat-transfer resistance due to accommodation effects.

NOMENCLATURE

A,	area;
M,	molecular weight;
R,	gas constant;
$T_{1,2,3}$,	temperature, at wire surface, accommodation layer surface and vessel wall;
V,	volume;
a,	thermocouple element radius;
b,	radius of vessel in which element is enclosed;
c,	specific heat;
h_1, h_2,	heat-transfer coefficient of accommodation layer and overall heat-transfer coefficient for transfer from element to wall when $h_1 = 0$;
p,	pressure;
q,	heat transfer rate;
t,	time.

Greek symbols

α,	accommodation coefficient;
λ,	thermal conductivity;
ρ,	density;
$\tau; \tau_{T,2}$,	time constant; time constants at low and high pressure.

Subscripts

g,	gas;
s,	solid.

INTRODUCTION

FINE wire thermocouples have been used to observe changes in the temperature of static gases during recent investigations of ignition phenomena [1, 2]. To be able to determine whether the more rapid of the temperature changes observed are full representations of the changes which actually occurred, and to apply suitable compensation for response lag if necessary the response characteristics of the thermocouple must be known.

Only limited investigations of thermocouple response in static gases have been previously reported. Melvin [3] has heated thermocouple elements by laser irradiation and observed the EMF decay after heating ceased; Gray *et al.* [4] have made similar observations, but heated the elements by passing a current through the support wires. In both investigations the EMF (hence temperature excess) was found to decay exponentially.

Typical values of the 'time constant, τ', which could therefore be derived were 90–150 ms for elements constructed from 0·025 mm dia *Pt* and *Pt*–13%Rh wires. It was found that τ was constant for fixed composition of the surrounding gas and at pressures above a few mm Hg when the initial temperature differential was low. Below this pressure range, Gray *et al.* [4, 5] found that the time constant rose rapidly with falling pressure. They also found that the time constant fell significantly when the initial temperature differential was increased from 60 to 600 K.

There is a clear need for measurement of the time constants of typical thermocouples over a wide range of experimental conditions. There is evidence that these measurements should be made using as small initial temperature differential as possible—the previously observed decrease in the time constant with increasing initial temperature differential strongly suggests that convective heat transfer occurred.

EXPERIMENTAL METHOD AND RESULTS

Two groups of experimental results have been obtained. In one, a chromel–alumel element constructed

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by electrically butt-welding 0·025 mm dia wires was used. The element diameter was very close to that of the wires, and the support wires were located axially in a 6 cm dia cylindrical pyrex vessel. Gases were admitted to the vessel to the required pressure via a standard all-glass gas handling system. The thermocouple was heated by direct current from dry cells via variable resistances and a rotary wafer switch. The switch was rotated rapidly from a null position, through the position where heating current was applied to the element, to a position where the thermocouple output EMF was applied to a digital transient recorder (Datalab DL 905). The heating time was *ca* 10 ms. Initial temperature differentials were approximately 25 K.

Logarithmic plots of the thermocouple output EMF vs time were always linear. It was thus established that the temperature of the element decayed exponentially after the heating current was switched off. Time constants for various environments were 90–150 ms.

The second set of experimental results was obtained for several *Pt*/*Pt*–13%Rh elements typical of those used in the investigation of ignition phenomena. (The diameters of the elements were significantly larger than those of the support wires.) The elements were at the centre of a 10 cm dia spherical Pyrex vessel. Time constants were derived from stored oscilloscope traces; a dividers- and scale method was used to determine the time which elapsed after a chosen initial time before the EMF fell to 37 per cent (1/e) of that at the initial time. Checks that the decay was exponential were made; two values of the time constant were measured from traces chosen at random, using two different initial times. No significant tendency for the time constant to increase or decrease with delay after heating ceased before the measured period was noted.

It was found that when the pressure of the surrounding gas was more than approximately 0·5 atm, the time constant was dependent on the initial temperature differential, although the dependence was small for initial temperature differentials less than 40 K. The following typical results were obtained for temperature differentials less than 40 K and in air at atmospheric pressure: for two elements of diameter 0·0190 mm made from 0·0125 mm dia wire time constants were 29 and 30 ms; for elements 0·15 mm dia constructed from 0·1 mm dia wire time constants were 612 and 505 ms. Two elements 0·05 mm dia made from 0·025 mm dia wire had time constants 102 and 104 ms, but an element 0·08 mm dia made from the same diameter wire with opposed support wires had a time constant 122 ms when the support wires were horizontal and 151 ms when they were vertical.

The time constant of a thermocouple with support wires aligned in a 'V' (element diameter 0·05 mm, wire dia 0·025 mm) was also markedly altered by the direction of the 'V' with respect to the horizontal. The time constant was significantly larger when the 'V' was inverted than when it was aligned in any other direction.

Time constants for low initial temperature differential were independent of pressure from 760 mm Hg to below 100 mm Hg; since convective effects were absent below *ca* 400 mm Hg, time constants obtained for comparison of the values for one element in various gases were obtained at 230 mm Hg. Some values for species with vapour pressures less than this were also obtained (the vapour pressures of each species were sufficiently high that it could be assumed that the increase in the time constant which occurs at low pressures was not significant). The results for a *Pt*/*Pt*–13%Rh element 0·05 mm dia, made from 0·025 mm dia wire, are shown in Fig. 1 as a function of the thermal conductivity of the gas.

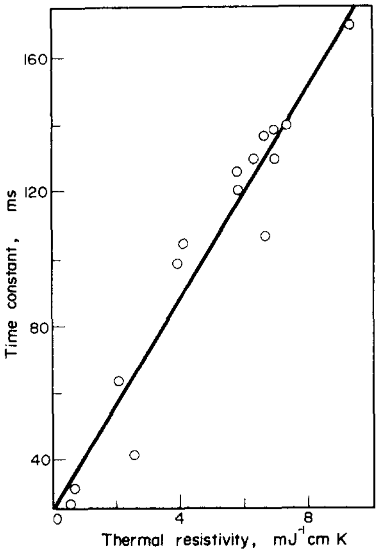

FIG. 1. Variation of the time constant of a 0·025 mm dia wire *Pt*/*Pt*–13%Rh thermocouple (element diameter twice wire diameter) with thermal conductivity of the surrounding gas (pressure 230 mm Hg) or vapour (for species with vapour pressure less than 230 mm Hg at 288 K); ambient temperature 288 K.

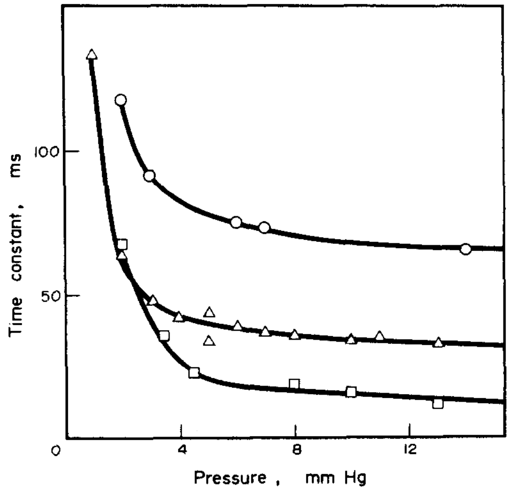

FIG. 2. The variation of the time constants of a 0·0125 mm dia wire thermocouple (element diameter $1\frac{1}{2}\times$ wire diameter) with pressure in air, krypton and helium.

Below 20 mm Hg the time constant of the thermocouples rose rapidly with falling pressure. Figure 2 shows the variation of the time constant of a 0·019 mm dia element (0·0125 mm dia wire) as a function of pressure of helium, krypton and air.

DISCUSSION

The variation of the time constant at high pressures with support wire alignment is good evidence that the variation of the time constant with initial temperature differential is due to convective effects. The alignment of the support wires which gave the highest time constant was in each case that in which hot air flowing upwards over heated support wires would shield the elements most effectively. In the other positions cold air flows over the elements when convection occurs.

The 'high pressure' time constants have been compared with those predicted by the equation proposed by Melvin [3]. The equation is an approximate solution to the problem of heat loss from a composite sphere considered by Bell [6]. The approximation assumes that the inequality

$$\frac{3\rho_g c_g}{\rho_s c_s}\frac{b(b-a)}{a^2} \ll 1$$

is fulfilled; a is the radius of the inner sphere (the element) and b is the radius of the outer sphere (the vessel in which the element is mounted); $\rho_g c_g/\rho_s c_s$ is the ratio of volumetric heat capacities of the gas and the element (4×10^{-4} for a typical gas at atmospheric pressure and a typical metal).

$$T_t = T_0 \exp - \frac{3\lambda_g t}{\rho_s c_s a^2}$$

where λ_g is the thermal conductivity of the gas, and T_0, T_t are temperature differentials at times 0 and t. The time constant is thus $\rho_s c_s a^2/3\lambda_g$. (Melvin also includes a small correction for heat losses down the support wires.) Unfortunately a typical element in a typical vessel does not satisfy the required inequality; for a 0·025 mm dia element in a 10 cm dia vessel $b/a = 400$, so $b(b-a)/a^2 \doteqdot 1{\cdot}6 \times 10^5$, and on combining this with the representative value $\rho_g c_g/\rho_s c_s = 4 \times 10^{-4}$ it may be seen that the inequality is far from fulfilled.

Nevertheless, Melvin's proposed predictive equation requires assessment, if only as a potential useful empirical equation. However, the agreement between our observed time constants and those predicted is poor. The predicted values of τ for the six elements with small element/wire diameter ratio in air were 3·35, 24 and 215 ms for wire diameters 0·0125, 0·025 and 0·1 mm respectively; not only are the values much lower than those observed experimentally, but the rate of change of time constant with wire diameter is approximately three times greater than observed. It is concluded that better values of the time constant can in general be obtained by assuming the value to be that previously obtained for a similar element in a similar environment. From Fig. 1 it would appear that a reasonable estimate for the time constant of an element immersed in a gas of known conductivity might be obtained by interpolation in a calibration chart for a similar element, although there is some experimental scatter in the present results.

The increase in time constant with decreasing pressure below 20 mm Hg cannot be attributed to 'molecular heat-transfer' effects within the main volume of the gas, since the mean free path over the relevant pressure range is much smaller than the wire diameter. The following analysis provides a test of the proposal that the rise in τ is due to increasingly significant accommodation effects at the surface of the wire.

The heat-transfer coefficient of the layer of gas at the surface of a solid, in which the molecules of gas collide with the surface and only partially adjust to its temperature (the 'accommodation layer' in the following discussion) is given by [7]

$$h = \alpha p(C_v + R/2)/(2\pi M R T_1)^{\frac{1}{2}}$$

where α is the accommodation coefficient, p is the gas pressure, C_v and M are the heat capacity at constant volume and molecular weight of the gas respectively, R is the gas constant and T_1 is the temperature of the surface of the solid. Let the heat-transfer coefficient for transfer from the wire to the surroundings in the absence of accommodation effects be $h_2 = \rho_s c_s V/A\tau_2$, where V, A are the volume and area of the element, and τ_2 is the experimentally determined time constant at high pressure $[\tau_2 \neq f(p)]$. Let the temperature at the (arbitrarily defined) shell where the accommodation layer and the main volume of the gas meet be T_2, and the ambient temperature be T_3; the rates of heat transfer through the inner and outer surfaces of the accommodation layer, q_1 and q_2, are assumed equal, since the layer is thin and its heat capacity is vanishingly small. The expressions for q_1 and q_2 in terms of heat-transfer coefficients and temperature differentials are $q_1 = h_1 A(T_1 - T_2)$ and $q_2 = h_2 A(T_2 - T_3)$. We equate the RHS of these expressions to obtain an expression for T_2 (which cannot be determined directly). The rate of change of the temperature of the element is given by $\mathrm{d}T_1/\mathrm{d}t = q_1/V\rho_s c_s$; substituting the expression for T_2 in the original equation for q_1, and substituting the equation for $\mathrm{d}T_1/\mathrm{d}t$, we obtain

$$\frac{\mathrm{d}T_1}{\mathrm{d}t} = \frac{Ah_2(T_1 - T_3)}{1 + h_2/h_1}\frac{1}{V\rho_s c_s}.$$

The time constant when accommodation effects are significant, τ_T is thus

$$\tau_T = \tau_2 + \rho_s c_s \frac{V}{A}\frac{(2\pi M R T_1)^{\frac{1}{2}}}{\alpha p(C_v + R/2)}$$

$$\left(\text{since } h_2 = \rho_s c_s \frac{V}{A}\frac{1}{\tau_2}\right).$$

No shape of solid has been specified in deriving this equation; we need to specify the shape in order to obtain V/A if we are to compare the results obtained with experimentally observed values. The extreme assumptions about the shape of the body involved in heat loss from the present thermocouples are that heat losses are mainly controlled by a significant length of support wire on either side of the element, hence V/A is that for a cylinder of radius a, i.e. $V/A = a/2$, or that the element loses heat in the same way as would an isolated sphere of the same radius, hence, since in the case examined here the element diameter was $3/2a$, $V/A = (3/2a)/3$. The true situation is thought to lie between these extremes, but it is of interest to note that, fortuitously, the value of V/A is $a/2$ in either extreme case, in the present instance.

The expression for τ_T has been compared with the results obtained experimentally by noting that when $\tau_T = 2\tau_2$,

$$p = \rho_s c_s a(2\pi MRT)^{\frac{1}{2}}/2\tau_2 \alpha p(C_V + R/2).$$

The observed and predicted pressures at which the time constant is double that at 'high' pressure are compared. The experimental pressures are 4·1 mm Hg for helium, 1·8 mm Hg for krypton, and 2·05 mm Hg for air. The predicted values are 5·3 mm Hg for helium and krypton ($\alpha = 0{\cdot}4$ for helium is adopted from [8] and α for krypton is assumed to be the same), and 2·05 mm Hg for air ($\alpha = 0{\cdot}5$ is adopted as equal to the value for air on tungsten given in [8]). The agreement between the observed and predicted experimental results is considered good evidence that the rise in the time constant with falling pressure is due to accommodation effects. It follows from this, that since the contribution to the time constant due to accommodation effects is dependent on a/p, the use of very small elements to carry out observations in stagnant gases at only moderately low pressures must be approached with caution.

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ETUDE EXPERIMENTALE DES TEMPS DE REPONSE DE THERMOCOUPLES DANS UN MILIEU GAZEUX AU REPOS

Résumé—La fem de sortie d'un élément de thermocouple de fil fin (chromel–alumel, 0,025 mm de diamètre) a été enregistrée de façon détaillée après un chauffage électrique rapide à 25 K au-dessus de la température ambiante dans divers milieux gazeux. La fem décroit toujours exponentiellement et cela confirme le fait que la réponse du thermocouple dans un tel milieu peut être caractérisée par une constante de temps (τ). Des constantes de temps ont été obtenues pour un certain nombre d'éléments *Pt*/*Pt*–13%Rh dans des milieux gazeux au repos. La constante de temps diminue lorsque la différence initiale de température (> 40 K) augmente, sous une pression voisine de la pression atmosphérique et la variation de τ avec la direction du support du fil fait apparaitre que cet effet est dû à la convection thermique. Pour de faibles différences initiales de température (< 40 K), τ augmente lorsque la conductivité thermique du gaz diminue, mais reste indépendante de la pression au dessus de quelques mm Hg. Les valeurs de τ obtenues à partir d'une équation prévisionnelle dûe à Melvin ne sont pas en bon accord avec les résultats expérimentaux dans ce domaine de pressions. Au dessous de 20 mm Hg environ, la constante de temps d'un élément de 0,019 mm de diamètre (diamètre du fil 0,0125 mm) augmente lorsque la pression diminue; on montre que l'augmentation peut être attribuée à un accroissement de la résistance thermique dûe aux effets d'accommodation.

EINE EXPERIMENTELLE UNTERSUCHUNG DER ANSPRECHZEIT VON THERMOELEMENTEN IN RUHENDEN GASEN

Zusammenfassung—In verschiedenen Gasen wurde das elektrische Signal eines Chromel-Alumel Thermoelements von 0,025 mm Durchmesser genau aufgezeichnet, nachdem die Gase durch schnelle elektrische Aufheizung auf Übertemperaturen von 25 K gebracht waren. Die EMK nahm stets exponentiell ab; damit läßt sich in Gasen das thermoelektrische Signal durch eine Zeitkonstante (τ) charakterisieren. Zeitkonstanten wurden bestimmt für eine Vielzahl von *Pt*/*Pt*–13%Rh Thermoelemente in ruhenden Gasen. Die Zeitkonstante nahm ab mit zunehmendem Anfangstemperaturanstieg (> 40 K) bei atmosphärischen Drücken; die Änderung von τ mit der Drahtanordnung zeigt, daß dies auf konvektiven Wärmeübergang zurückzuführen ist. Für einen kleinen Anfangstemperaturanstieg (< 40 K) nahm τ mit kleiner werdender Wärmeleitfähigkeit zu, erwies sich aber als druckunabhängig bei einigen mm Hg.

Die nach einer Gleichung von Melvin ermittelten Werte von τ stimmten mit experimentellen Werten in diesem Druckbereich nicht überein. Unterhalb etwa 20 mm Hg stieg die Zeitkonstante eines 0,019 mm (0,0125) Thermoelements mit abnehmendem Druck; es wird gezeigt, daß dieser Anstieg einem zunehmenden Wärmeübergangswiderstand infolge von Akkommodations-Effekten zuzuschreiben ist.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ИНЕРЦИОННОСТИ ТЕРМОПАР В СТАТИЧЕСКИХ ГАЗОВЫХ СРЕДАХ

Аннотация — Проводилась тщательная регистрация выходной э. д. с. проволочной термопары (хромель-алюмель, диаметр 0,025 мм) после её быстрого нагрева электрическим током в различных газах до температуры, на 25°К выше температуры окружающей среды. Величина э. д. с. падала всегда экспоненциально, подтверждая тем самым тот факт, что в этих средах чувствительность термопары может характеризоваться «постоянной времени» (τ). Значения постоянной времени получены для различных элементов Pt/Pt — 13% Rh в статистических газовых средах. При увеличении разности температур (>40*К), при давлении, равном почти атмосферному, величина постоянной времени падала и изменение τ при наличини поддерживающей проволоки указывает на то, что это снижение вызывается конвективным теплообменом. Для небольшой разности температур (<40°К) значение увеличивалось при снижении теплопроводности газа, но не зависело от давления выше нескольких мм рт. ст. Значения τ, полученные из расчетного уравнения Мельвина не очень хорошо согласуются с экспериментальными данными для этого диапазона давлений. Примерно ниже 20 мм рт. ст. значение постоянной времени для чувствительного элемента термопары диаметром 0,019 мм (диаметр проволоки 0,0125 мм) увеличивалось с падением давления. Показано, что этот рост можно объяснить увеличением сопротивления переносу тепла, вызванным эффектами аккомодации.