Int. J. Heat Mass Transfer. Vol. 26, No. 5, pp. 663–669, 1983
Printed in Great Britain

0017–9310/83/050663–07 $03.00/0
Pergamon Press Ltd.

MEASUREMENT OF HIGH GAS-STREAM TEMPERATURE USING DYNAMIC THERMOCOUPLES

N. VENKATRAMANI, P. SATYAMURTHY, N. S. DIXIT, J. P. LANCELOT and V. K. ROHATGI
Plasma Physics Section, Bhabha Atomic Research Centre, Trombay, Bombay 400 085, India

(*Received* 20 *July* 1981 *and in final form* 3 *February* 1982)

Abstract—The dynamic probe technique using the transient response of a thermocouple is one of the methods of measuring high temperature flowing gases. In this paper, the complete dynamic response of a thermocouple has been solved consisting of convective, conductive, and radiative terms. The solution has been used to arrive at correction factors for actual experimental data. The use of dynamic thermocouples in the measurement of temperature profiles has also been illustrated by experiment. The model is verified at lower temperatures using a bunsen flame.

NOMENCLATURE

- A, cross-sectional area of the thermocouple wire [m^2];
- c_p, specific heat of the thermocouple wire [J kg^{-1} K^{-1}];
- Fo, Fourier number;
- l, length of the wire exposed to gas [m];
- P, perimeter of the wire [m];
- R, radiation term, equation (4);
- t, time [s];
- T, temperature [K];
- T_g, gas temperature [K];
- T_i, initial temperature of the thermocouple [K];
- T_w, wall temperature [K];
- x, distance from the junction of the thermocouple along the wire [m].

Greek symbols

- α, convective heat transfer coefficient between gas and thermocouple wire [W m^{-2} K^{-1}];
- κ, thermal diffusivity [m^2 s^{-1}];
- ρ, density of the wire [kg m^{-3}];
- σ, Stefan's constant [W m^{-2} K^{-4}];
- λ, thermal conductivity of the wire material [W m^{-1} K^{-1}];
- ε, emissivity of the wire material;
- τ, time constant [s];
- $\bar{\theta}$, nondimensionalized temperature;
- $\bar{\theta}_g$, nondimensionalized gas temperature before correction.

A bar on a parameter denotes a nondimensionalized quantity.

1. INTRODUCTION

THE CONVENTIONAL technique of the measurement of the temperature of a body consists of inserting a thermocouple, allowing it to come to thermal equilibrium, and measuring the electrical e.m.f. generated. It is relatively easy to bring the sensor to equilibrium at low to moderate temperatures ($<1500°C$) and also to isolate the sensor from the ambient so that corrections for the conduction along the thermocouple leads and other errors can be minimized. On the other hand at high temperatures, especially at temperatures higher than the maximum operating temperatures of the thermocouples, viz. combustion plasmas in MHD generators, the conventional approach will not be useful. In these cases, it may be necessary to infer the temperature indirectly by: (a) a cooled probe technique using steady state data, or (b) a dynamic probe technique using transient response.

The use of the cooled probe technique involves the accurate measurement of the heat flux through the probe and a complex cooling arrangement. The analytical and design details have been given [1–3].

The dynamic probe technique has been investigated [4–6]. In the investigations by Sukewer, no corrections have been made for the conduction and radiation effects, thereby resulting in much lower gas temperatures [6]. On the other hand, Giedt *et al.* used radiation shields and dual probes with hollow and solid thermocouples to eliminate radiation effects [4, 5]. The use of hollow thermocouples and radiation shields with the same time constant as thermocouples are experimentally complicated.

In this paper, the complete dynamic response of a thermocouple has been solved involving convective, conductive and radiative terms. The solution has been used to arrive at correction factors for actual experimental data. The use of dynamic thermocouples in the measurement of temperature profiles has also been illustrated by experiment.

2. MODELLING OF DYNAMIC THERMOCOUPLE

If a certain length of a thermocouple element is exposed to a hot stream of gas, the temperature–time response of the thermocouple will be a function of the gas temperature (and velocity), the physical and geometric properties of the thermocouple wire and the rates of convective, radiative and conductive heat transfer between the thermocouple element and its surroundings. Figure 1 shows a schematic diagram of a thermocouple. A part of the thermocouple (length $2l$) with the junction at the centre is exposed to the hot gas

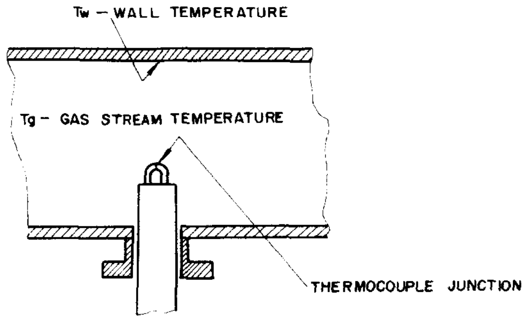

FIG. 1. Schematic diagram of the thermocouple element in the high temperature gas-stream.

and the rest of the wire is enclosed in an alumina tube. The thermocouple is inserted in a hot stream with local gas temperature T_g at the point of insertion and enclosed in a duct whose walls are at a temperature T_w.

Figure 2 shows the modelling of the thermocouple element. For the sake of simplicity both the elements of the thermocouple are assumed to have the same constant physical properties (density, specific heat, thermal conductivity etc.) with the junction at the centre whose temperature is recorded. As the radius of the wire is much smaller than the length of the wire, the temperature at any cross-section is assumed to be uniform with the characteristic time of equilibration being a few milliseconds. The x axis is chosen from the junction. In the region $0 \leqslant x \leqslant l$ there is convective, radiative and conductive heat transfer, whereas for $x > l$ the element being enclosed in an alumina tube, there is only conductive heat transfer. If the temperature at any point x is T, the instantaneous heat-rate balance yields

$$\rho A c_p \frac{\partial T}{\partial t} = \alpha P(T_g - T) + \sigma \varepsilon P(T_w^4 - T^4) + \lambda A \frac{\partial^2 T}{\partial x^2}, \quad 0 \leqslant x \leqslant l, \quad (1a)$$

$$\rho A c_p \frac{\partial T}{\partial t} = \lambda A \frac{\partial^2 T}{\partial x^2}, \quad x > l, \quad (1b)$$

with the following boundary conditions:

$$T = T_{in} \quad \text{at } t = 0 \text{ for all } x,$$

$$T = T_{in} \quad \text{at } x \to \infty \text{ for all } t,$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{at } x = 0 \text{ for all } t,$$

$$T, \frac{\partial T}{\partial x} \text{ continuous} \quad \text{at } x = l \text{ for all } t.$$

In equation (1a), the first term on the RHS represents the convective heat transfer from plasma, the second term radiative heat transfer from wall to the element, and the last term conduction through the wire. The radiative heat flux from plasma has been neglected in comparison with the convective term. This equation is non-linear and no analytical solution is possible.

If the radiative and conduction terms are neglected, equation (1a) has a simple analytical solution of the type

$$\frac{T - T_{in}}{T_g - T_{in}} = 1 - \exp -\left[\frac{t}{\left(\frac{\rho A c_p}{\alpha P}\right)}\right], \quad 0 \leqslant x \leqslant l. \quad (2)$$

We shall subsequently solve numerically equation (1a) and (1b) and obtain the temperature of junction as a function of time. This numerical temperature–time data will be forced to fit a curve of the type given by equation (2) to evaluate the corrections. These corrections will be applied to estimate the actual gas temperature from experimental data. The equations (1a) and (1b) are nondimensionalized, and are given by

$$\frac{\partial \bar{\theta}}{\partial \bar{t}} = (1 - \bar{\theta}) + Fo \frac{\partial^2 \bar{\theta}}{\partial \bar{x}^2}, \quad 0 \leqslant \bar{x} \leqslant 1, \quad (3a)$$

$$\frac{\partial \bar{\theta}}{\partial \bar{t}} = Fo \frac{\partial^2 \bar{\theta}}{\partial \bar{x}^2}, \quad \bar{x} > 1 \quad (3b)$$

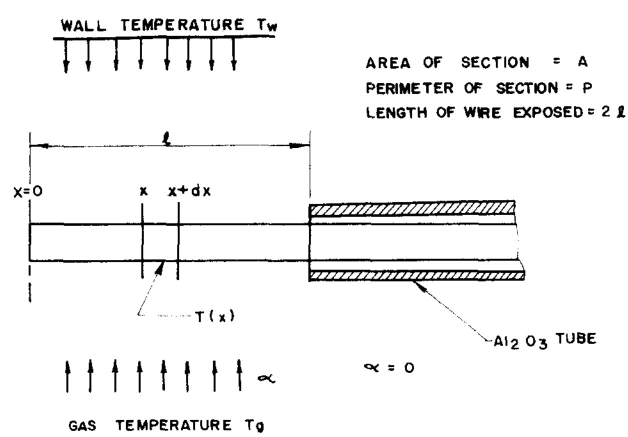

FIG. 2. Model of the thermocouple element.

where

$$\bar{\theta} = \frac{T - T_{in}}{T_g - T_{in}},$$

$$\bar{t} = \frac{t}{\tau} = \frac{t}{\left[\dfrac{\rho A c_p}{\alpha P(1+R)}\right]},$$

$$\bar{x} = \frac{x}{l}, \qquad Fo = \left(\frac{\lambda}{\rho c_p}\right)\left(\frac{\tau}{l^2}\right).$$

Radiation term R

The radiation term R can be written as a product of two parts

$$R = R_1 R_2$$

where

$$R_1 = \frac{\sigma \varepsilon T_g^3}{\alpha}$$

and

$$R_2 = \frac{\left(\dfrac{T_w}{T_g}\right)^4 - \left(\dfrac{T}{T_g}\right)^4}{1 - \left(\dfrac{T}{T_g}\right)}.$$

The first part R_1 is essentially independent of T, provided α and ε remain constant. In practice α and ε will be weakly dependent. Also for most of the combustion plasma experiments R_1 is less than 1. The second part R_2 is an explicit function of T. Figure 3 shows the variation of R_2 as a function of T/T_g with T_w/T_g as a parameter. It can be seen that for $T_w/T_g > 0.6$, the radiative heat transfer will be considerable as compared to convective transfer from gas. For $0.2 < T_w/T_g < 0.6$. R_2 remains fairly constant till T/T_g is of the order of T_w/T_g. For $T_w/T_g < 0.2$, the value of R_2 is quite small, compared to 1. In view of this for the subsequent analysis, the radiation term $R(= R_1 R_2)$ will be treated as constant. This should be verified for individual experimental data.

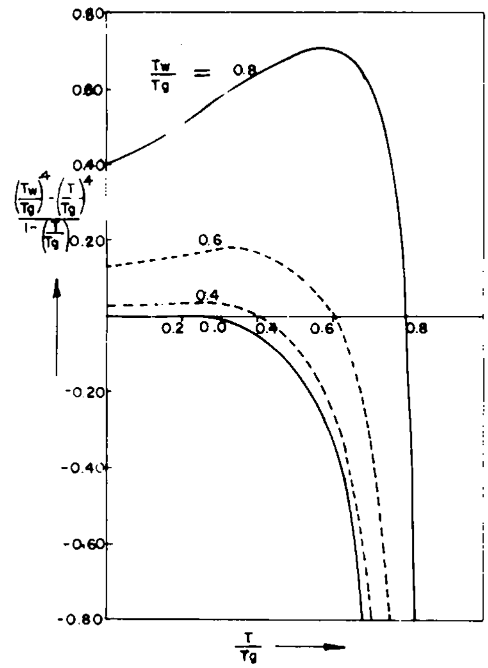

FIG. 3. The variation of the temperature dependent part of the radiation term (R_2) as a function of temperature.

3. NUMERICAL ANALYSIS

Equation (3) is solved numerically by an explicit finite-difference marching technique for various values of Fo [7]. The temperature of the junction $\bar{\theta}$ (at $\bar{x} = 0$) is determined for all values of $\bar{t}$ (Fig. 4). Nominally the points are chosen at time intervals of $\Delta\bar{t} = 0.05$. This data is now expressed, similar to equation (2), by an equation of the type

$$\bar{\theta} = \bar{\theta}'_g\left[1 - \exp\left(-\frac{\bar{t}}{\tau'}\right)\right].$$

This is done by fitting a linear curve between $\Delta\bar{\theta}/\Delta\bar{t}$ and $\bar{\theta}$ where the slope gives $-\tau'$ and the intercept $\bar{\theta}'_g$ (Fig. 4). In other words, the numerical experiment $\bar{\theta}$ as a function of $\bar{t}$, which is analysed to yield a gas

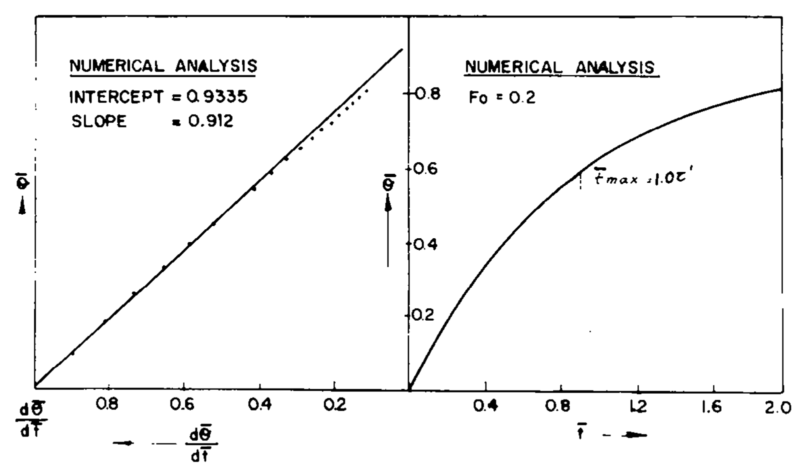

FIG. 4. Plot of $\bar{\theta}$ vs time and $d\bar{\theta}/d\bar{t}$ against $\bar{\theta}$ based on the results obtained from numerical analysis.

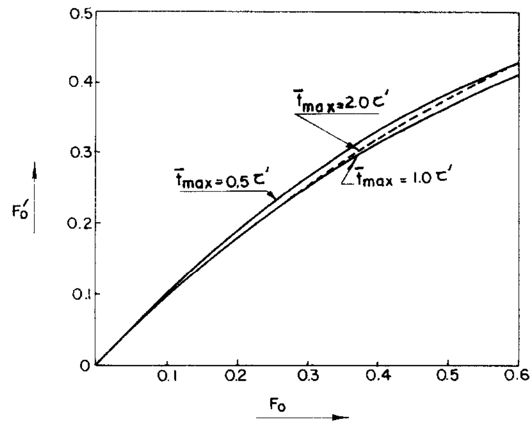

FIG. 5. Plot of Fo' as a function of Fo.

temperature $\bar{\theta}'_g$ and time constant τ'. Thus for a given Fo, if the value of intercept is $\bar{\theta}'_g$, the actual gas temperature is 1. Also, since the slope in general is not equal to 1, the value of Fo obtained using τ' as characteristic time will be the initial Fo multiplied by τ',

$$Fo' = Fo\,\tau'.$$

Figure 5 gives a plot of Fo' as a function of Fo. Since equation (4) is a curve forced to fit the points, the number of points included in terms of $t_{max} = 0.5\,\tau'$ or $1\,\tau'$ will have an influence in the determination of $\bar{\theta}'_g$ and τ'. Thus Fig. 5 indicates the curves for different t_{max} expressed in terms of τ'. (Note that τ' is chosen for convenience as it can be obtained as an experimental value.) Figure 6 shows the variation of the intercept as a function of Fo'. This is the important correction curve obtained from the present analysis.

Consider the response of a dynamic thermocouple obtained experimentally in real time. The temperature time data is now fitted in the form of equation (6) by plotting the temperature against time derivative of temperature. The slope of the line gives the time constant which with the given geometric dimensions ($2l$) and physical properties (κ) can be used to calculate Fo' [$Fo = \kappa\tau'/(l^2)$]. Then Fig. 5 is used to estimate the correction factor and the intercept is divided by the correction factor and added to initial temperatures to give the actual gas temperature. Knowing the true gas temperature, T_w, and the Fourier number, Fo, R and α can be estimated and the constancy of $1+R$ can be verified.

If the conduction is negligible ($Fo = 0$), the correction is 1, as expected. As the conduction becomes dominant (Fo increases), the correction also increases.

4. EXPERIMENT

In order to substantiate the analysis, experiments were carried out in an LPG–O_2 combustion plasma rig. The rig has a test section 45 × 45 mm square lined with refractory materials. Ports have been provided on the walls of the test section for the introduction of probes or for other measurements (Fig. 7). The probe consists of a platinum–platinum (10% rhodium) thermocouple enclosed in a twin bore alumina tube which can be inserted into the gas stream for controlled time durations through a pneumatic drive. The thermocouple response is recorded on a u.v. recorder and translated into temperature.

A typical run corresponding to a flame core is presented in Fig. 8. This is analysed and the intercepts and the slopes are calculated. In order to calculate the

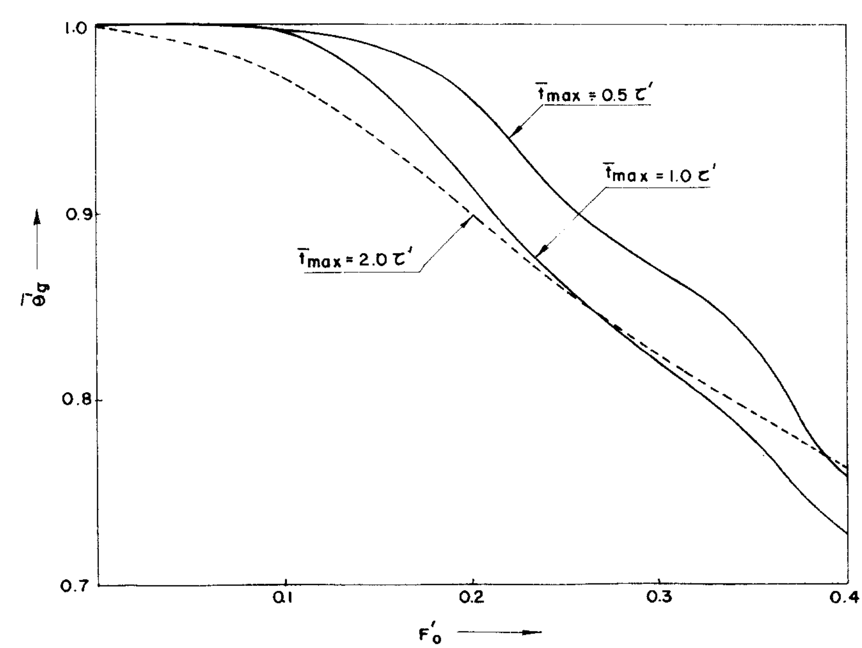

FIG. 6. Variation of intercept as a function of Fo' (the correction function).

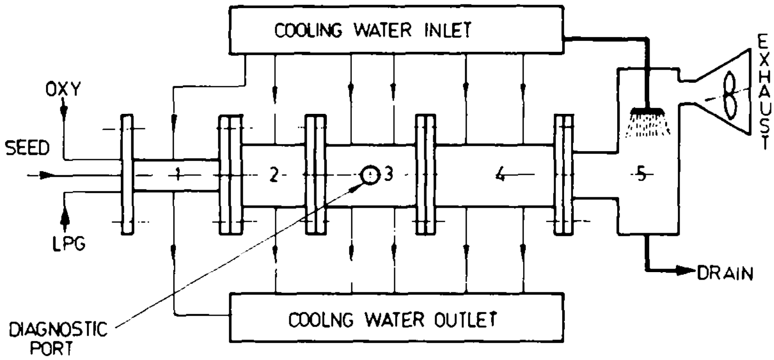

FIG. 7. Schematic of experimental facility. (1) Burner. (2) Mixing chamber. (3) Test section. (4) Spacer. (5) Spray chamber.

Fo value, data from standard reference books are used. The thermal diffusivity data for platinum is extensively tabulated and varies between 0.244×10^{-4} and $0.259 \times 10^{-4}\ m^2\ s^{-1}$ in the temperature range 0–1200°C [8]. However, there is no data available for a platinum–10% rhodium alloy. For the present work, for both the wires a mean thermal diffusivity of $0.19 \times 10^{-4}\ m^2\ s^{-1}$ is assumed for further calculations. The total length of wire exposed to hot gas is 9.8 mm.

The values of the intercepts and slopes are averaged over several runs. For instance, corresponding to the point for which the data has been presented in Fig. 8, the average values of the intercept and slope are 2038 K and 0.395 s, respectively. Using 0.395 s and the given thermal diffusivity, the value of Fo is calculated to be 0.301. The correction as found from Fig. 6, corresponding to $t_{max} = 1.0\,\tau$ is 0.82 which yields the flame temperature of 2790 K after adding an initial temperature of 303 K. The complete temperature profile across the cross-section is also given in Fig. 9.

The wall temperature as measured by pyrometer and obtained from other data is about 1500 K. This gives the value of (T_w/T_g) about 0.55 and max (T/T_g) about 0.60. Using these values, Fig. 3 shows that R_2 remains substantially constant. Also, the value of Fo as calculated from Fo' using Fig. 5 is 0.38. Since Fo is given by

$$Fo = \left(\frac{\lambda}{\rho c_p}\right)\left[\frac{\rho A c_p}{\alpha P(1+R)}\right]\left(\frac{1}{l^2}\right)$$

the value of $\alpha(1+R)$ is found to be about 850. The value of R and α is found to be 0.05 and 810 W m^{-2} K^{-1}, respectively.

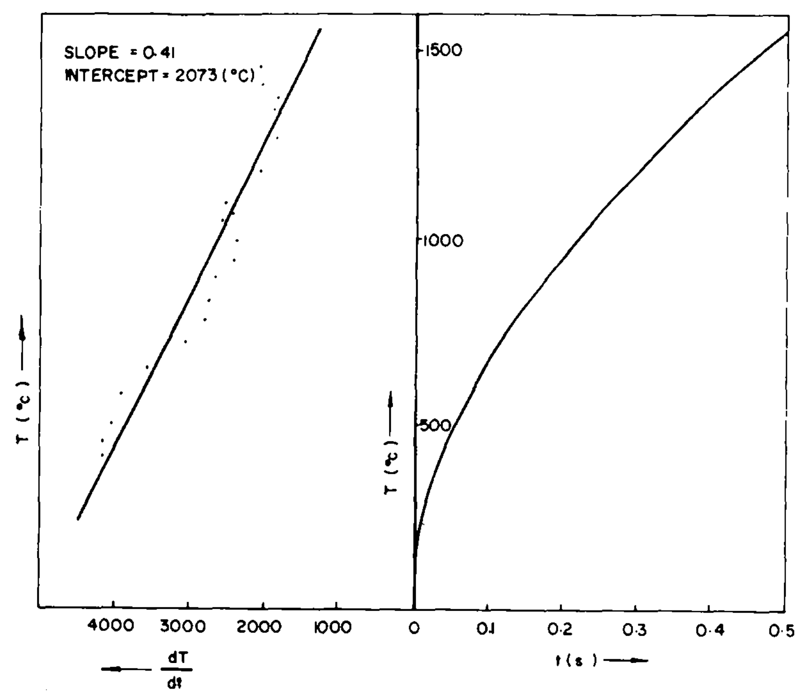

FIG. 8. Experimental plot of $\partial T/\partial t$ vs T and t vs T.

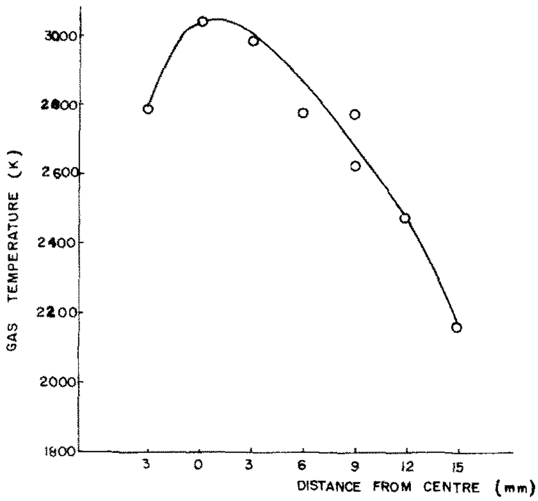

FIG. 9. Temperature profile across the flame in the experimental rig.

Validity of the model

The estimation of accuracy of this technique is complex as it is a forced curve fitting type. The use of a u.v. recorder ensures accuracy in time of 0.1% and in temperature of about 2%. However, this data is averaged by fitting a curve. The coefficient of linear regression is in the range 0.9–1.0. As the same analysis is applied to the numerical experiment and real experiment, the accuracy of the technique can only be limited by the model. The other sources of error are the assumption of constant properties of the material, the constancy of heat transfer coefficient, radiation term R and the catalytic action of the thermocouple surface. As the reproducibility of data is good, the temperature can be normalized to yield accurate profiles across the cross-section.

To verify the model experiments were conducted at lower temperatures using a bunsen flame. The temperature of the flame estimated using the above model was 1705 K. The reproducibility was within ± 15 K. The flame temperature is also obtained from steady state thermocouple temperature measurements after correcting for radiation losses. This measured temperature was 1730 K. Hence the agreement is within 25 K.

To analyze the catalytic effect of the thermocouple, a thin alumina paste was added as a coating and experiments were conducted. The results were slightly on the lower side (for the bunsen flame the temperature obtained was 1570 K) due to finite thickness of the coating. Also the coating tends to peel off leading to slow increase in measured temperature.

5. CONCLUSIONS

This paper develops a model for the determination of the temperature of a high temperature gas stream, similar to MHD generator conditions, using a dynamic thermocouple. The conduction and radiation effects are accounted for in the analysis. The model has been verified by experimental data. This technique is very useful in the determination of temperature profiles.

REFERENCES

1. J. Grey, Thermodynamic methods of high temperature measurements, *Rep. ISA*, Vol. 1, Number 2 (1965).
2. A. Kanzawa, Estimation of temperature of plasma flow using a thermocouple, *Kagaku Kogaku* **37**, 533–535 (1973).
3. L. N. Krause, G. E. Glawe and R. C. Johnson, Heat transfer devices for determining the temperature of flowing gases, in *Temperatures—Its measurement and Control in Science and Industry*, Vol. 3, Part 2. Reinhold, New York (1962).
4. W. H. Giedt, Determination of high gas-stream temperature from short exposure probe response, *ISA trans.* **8**, 43–51 (1969).
5. W. H. Giedt and J. T. Chambers, A dual-element transducer for measuring high gas-stream temperatures, ASME Publication 64-Wa/HT-45 (1964).
6. S. Sukewer, Ya. Litski, B. Mizera and P. Zhelvazni, Study of various methods of determining the temperature of a plasma in a MHD duct, Proceedings of symposium on MHD electrical power generation, Warsaw, pp. 2179–2194 (1968).
7. W. F. Ames, *Numerical Methods for Partial Differential Equations*. Nelson, London (1969).
8. Y. S. Tonlonkian, R. W. Powell, C. Y. Ho and M. C. Nicolaov, *Thermophysical Properties of Matter*, Vol. 10. IFI/Plenum, New York (1973).
9. Manual on the use of thermocouples in temperature measurement, ASTM Special Technical Publication 470A (1974).

MESURE DE TEMPERATURE ELEVEE D'UN COURANT GAZEUX AVEC DES THERMOCOUPLES DYNAMIQUES

Résumé—La technique dynamique utilisant la réponse transitoire d'un thermocouple est l'une des méthodes de mesure de la température élevée d'un gaz en mouvement. La réponse dynamique complète d'un thermocouple a été résolue en tenant compte de la convection, de la conduction et du rayonnement. La solution a été utilisée pour obtenir des facteurs de correction pour les données expérimentales brutes. L'utilisation des thermocouples dynamiques à la mesure des profils de température est illustrée par l'expérience. Le modèle est vérifié à plus basse température sur une flamme Bunsen.

INSTATIONÄRE MESSUNG HOHER TEMPERATUREN IN STRÖMENDEN GASEN MIT TRÄGHEITSARMEN THERMOELEMENTEN

Zusammenfassung—Eine Methode zur instationären Messung hoher Temperaturen in strömenden Gasen ist die Verwendung von Thermoelementen unter Berücksichtigung ihrer Übergangsfunktion. In der vorliegenden Arbeit wird die vollständige Bestimmung der Übergangsfunktion eines Thermoelements durchgeführt, die aus entsprechenden Termen für Konvektion, Leitung und Strahlung besteht. Die Lösung wird verwendet, um Korrekturfaktoren für Versuchsergebnisse zu erhalten. Die Verwendung von trägheitsarmen Thermoelementen bei der Messung von Temperaturprofilen wurde auch durch ein Experiment verdeutlicht. Das Modell wurde bei niedrigeren Temperaturen in der Flamme eines Bunsen-Brenners verifiziert.

ИЗМЕРЕНИЕ ВЫСОКОТЕМПЕРАТУРНОГО ПОТОКА ГАЗА ТЕРМОПАРАМИ С УЧЕТОМ ИХ ДИНАМИЧЕСКИХ СВОЙСТВ

Аннотация—Метод динамического зондирования, основанный на переходной характеристике термопары, является одним из способов измерений в высокотемпературных потоках газов. В данной работе разработана модель полной динамической характеристики термопары с учетом конвекции, теплопроводности и излучения. С помощью этой модели получены поправочные коэффициенты для обработки экспериментальных данных. На примере показано использование термопар с учетом их динамических характеристик для измерения профилей температур. Модель проверена для случая низких температур при измерениях в пламени газовой горелки.