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# Letters to the Editors

## Comments on 'Boiling of suspension of solid particles in water'

THE PAPER by Yu Min Yang and Jer Ru Maa [1] provides a useful addition to the knowledge of enhanced boiling heat transfer. The authors observe that the addition of a small amount of suspended solid particles increases the boiling heat flux due to the thermal boundary layer disturbance caused by the motion of solid suspended particles. The sedimentation of suspended particles is prevented by constant agitation. It would be interesting to know whether the authors have considered or intend to consider the contribution of agitation in the enhancement of the boiling heat transfer coefficient of water with suspended particles. The application of forced convection due to stirring increases the convective contribution and results in early removel of the bubbles adhering at the surface, which increases the bubble frequency.

With reference to Fig. 4 of ref. [1], the enhancement of nucleate boiling heat flux is stronger when solid content in the suspension is higher for solid particles of the same size. The slope of the nucleate boiling curve for water with suspended solids is higher compared to the pure water curve although it does not follow a set pattern. However, it implies an increase in critical heat flux for water systems containing suspended solids. It would be instructive to study the maximum limit of solid content in the suspension and boiling heat flux enhancement.

P. K. TEWARI
*Desalination Division*
*Bhabha Atomic Research Centre*
*Bombay 400085, India*

### REFERENCE

1. Yu Min Yang and Jer Ru Maa, Boiling of suspension of solid particles in water, *Int. J. Heat Mass Transfer* **27**, 145–147 (1984).

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## Comment on 'Measurement of high gas-stream temperature using dynamic thermocouples'

THE AUTHORS of ref. [1] recognized that the working equation usually employed in dynamic thermocouple temperature measurements [2–4]

$$T_g = T+\tau'\frac{dT}{dt} \qquad (1)$$

or

$$\frac{T-T_{in}}{T_g-T_{in}} = 1-\exp(-t/\tau') \qquad (2)$$

(the same symbols as in ref. [1] are used in this letter) is not always satisfactorily applicable. They included heat conduction and radiation terms in their modelling equation and obtained numerically correction factors due to these terms not being included in equation (1) or equation (2). Experimental results using a bunsen flame ($\sim 1700$ K) were introduced to support their model.

However, ref. [1], like many previous papers [2–4], assumed that $\tau' = \rho A C_p/(\alpha P)$ was a constant independent of thermocouple temperature. This assumption does not represent a practical dynamic thermocouple such as a chromel–alumel or a Pt–Pt+10%Rh thermocouple. This situation, as shown in refs. [5–7], is mainly caused by the variation of the specific heat of these thermocouple materials with temperature, although both $\alpha$ and $\rho A/P$ are also weak functions of temperature. For example, for a chromel–alumel thermocouple, the average specific heat can be expressed as [5, 8]

$$C_p = C_{p0}[1+2.83\times10^{-4}(T-273)] \qquad (3)$$

and for a Pt–Pt+10%Rh thermocouple a similar expression was expected [6, 7, 9]. The experimental data of the specific heat of platinum [9] can be expressed as

$$C_p = C_{p0}[1+2.11\times10^{-4}(T-273)]. \qquad (4)$$

For Pt+30%Rh–Pt+6%Rh, the following expression of the specific heat was suggested [7]

$$C_p = C_{p0}[1+2.41\times10^{-4}(T-273)]. \qquad (5)$$

If the temperature of the dynamic thermocouple increases in a measurement from 400 to 1273 K, the corresponding variations of the material specific heat and, thus, of $\tau'$ can be more than 18% from equations (3)–(5). It is obvious that such a great variation of $C_p$ or $\tau'$ should not be ignored. Now, assume $\tau'$ in equation (1) varies linearly with temperature, i.e. $\tau' = \tau'_0[1+a(T-273)]$. Then the solution of equation (1) for the temperature–time curve can be written as

$$\frac{t}{\tau'_0} = [1+a(T_g-273)]\ln\left(\frac{T_g-T_{in}}{T_g-T}\right)-a(T-T_{in}) \qquad (6)$$

as $a$ is assumed to be a constant. When the temperature–time data predicted by equation (6) are forced to fit a curve of the type given by equation (2) with $\tau' =$ const. to evaluate the correction factors, one obtains the calculated results, as shown in Fig. 1, for $a = 2 \times 10^{-10}$ and $3 \times 10^{-4}$ K$^{-1}$, respectively. Examination of this figure shows that the variation of $C_p$ or $\tau'$ with temperature is indeed an important source of systematic error.

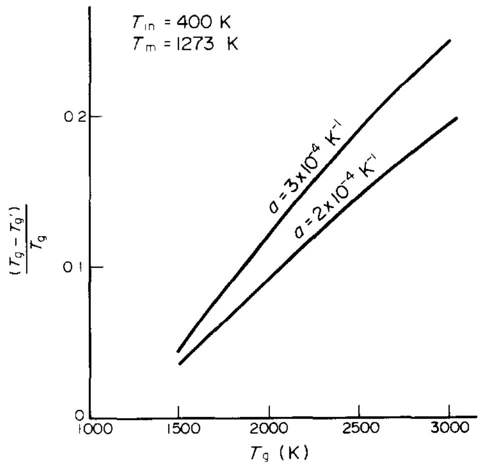


FIG. 1. The systematic error due to $\tau' = \tau'_0[1 + a(T - 273)]$. $T_g$ and $T'_g$ are actual and predicted gas temperatures, and $T_{in}$ and $T_m$ are initial and maximum thermocouple temperatures, respectively.

In addition, the effect of the conduction loss of the dynamic thermocouple may be somewhat overemphasized in ref. [1]. As $Fo = 0$, i.e. no conduction loss exists, Fig. 6 of ref [1] shows that the value of the correction factor is always equal to 1.0. However, equation (6) and the calculated results in Fig. 1 are obtained under the assumption that no conduction loss exists, and the correction factor is not 1.0. Numerical tests [5, 6] show that for a butt-welded dynamic thermocouple, the error due to conduction loss from the thermocouple junction to a porcelain tube can be negligible, provided the part of the dynamic thermocouple exposed to the hot gas-stream is long enough. In spite of the zero conduction error, errors due to radiation or non-constant $\tau'$ are still probably appreciable. In addition, experimental and theoretical studies [5, 6] show that for the case where the diameter of the thermocouple junction is considerably different from that of the wires, heat conduction between the wires and the junction would affect appreciably the temperature response curves due to the presence of the difference in their thermal inertia coefficients $\tau'$. This fact may be the reason why many authors [2–4] did not find a great systematic error due to non-constant $\tau'$ or radiation in their measurements. Unfortunately, ref. [1] did not give any information about the junction size and the wire diameter of the dynamic thermocouple used in their experiments; and this fact precludes any further comment to be made on their experimental results.

XI CHEN
*Engineering Thermophysics Division*
*Department of Engineering Mechanics*
*Tsinghua University*
*Beijing* 100084
*China*

## REFERENCES


1. N. Venkatramani, P. Satyamurthy, N. S. Dixit, J. P. Lancelot and V. K. Rohatgi, Measurement of high gas-stream temperature using dynamic thermocouples, *Int. J. Heat Mass Transfer* **26,** 663–669 (1983).
2. F. von Burger-Scheidlin und P. Stottmann, Eine dynamishe Temperaturmeßmethode mit Thermoelementen, *Z. Flugwiss.* **14,** 184–187 (1966).
3. A. I. Bannikov, On measurements of some parameters of low-temperature plasmas, in *Thermophysical Properties of Low-temperature plasmas* (in Russian), pp. 23–27. Science Press, Moscow (1970).
4. D. Gautrot, Sondes de température pour écoulement à haute enthalpie, *Mesures: Régulation/Automatisme* **37,** 95–99 (1972).
5. Research Group of Transient Gas-stream Temperature Measurements, On the transient thermocouple method for high gas-stream temperature measurements (in Chinese), *J. Tsinghua Univ.* No. 1, 97–116 (1978).
6. Xi Chen, Estimates of the methodic errors of the transient thermocouple for measuring high gas-stream temperature (in Chinese), *Instrum. Mater.* No. 6, 16–27 (1979); errata No. 2 (1980).
7. Bao-ding Chen, Corrections of transient error and radiation error for gas-stream temperature measurements using Pt + 30%Rh–Pt + 6%Rh thermocouple (in Chinese), Master's thesis, Department of Engineering Mechanics, Tsinghua University, December (1980).
8. A. K. Gangopadhyay and J. L. Margrave, Thermodynamic properties of inorganic substances—IV. The high temperature heat contents of Chromel-p and Alumel, *J. Chem. Engng Data* **8,** 204–205 (1963).
9. W. B. Kendall, R. L. Orr and R. Hultgren, Heat content of platinum, *J. Chem. Engng Data* **7,** 516–518 (1962).


# Reply to 'Comment on "Measurement of high gas-stream temperature using dynamic thermocouples"'

(1) As modelled in our paper the time constant $\tau$ of the dynamic thermocouple is given by

$$\tau = \frac{\rho A C_p}{\alpha P(1+R)}.$$

In general all the terms are functions of temperature. The authors of the letter have pointed out that $C_p$ is a function of temperature. So is $R$ and to a marked extent variation of $\alpha$ with temperature which is more complex and pronounced in chemically reactive flames. We do agree, in principle, with the author of the letter that variation of $C_p$ with temperature should be included. Since $\alpha$ also increases with temperature, the overall rise in $\tau$ with temperature is less compared to what authors have assumed. In view of this, the error plotted by the authors is an over-estimate of what actually happens. However, due to non-availability of precise data on temperature dependency of various parameters, it is difficult to estimate the error due to temperature dependency of the $\tau$.