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A transducer for the measurement of instantaneous local heat flux to surfaces immersed in high-temperature fluidized beds

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Abstract—An abrasion resistant, fast responding (settling time approximately 5 ms) heat flux transducer with associated analog signal conditioning equipment has been developed for the measurement of instantaneous local heat transfer rates to surfaces immersed in fluidized beds at combustion-level temperatures. Analog signal conditioning is used to provide a d.c. voltage which is linearly related to the instantaneous local heat flux. This voltage is suitable for direct oscillographic recording or digital data acquisition. Instantaneous local bed-to-wall heat flux data obtained in a small (102 × 102 mm) electrically heated fluidized bed at 282°C are presented.

INTRODUCTION

KNOWLEDGE of instantaneous local heat transfer rates (or equivalently, instantaneous local heat transfer coefficients) to surfaces immersed in low-temperature fluidized beds is relatively complete. Studies involving vertical or inclined surfaces include those of Mickley *et al.* [1], Tuot and Clift [2], Baskakov *et al.* [3,4], and Gloski *et al.* [5].

Similar measurements for horizontal tubes have been reported [6–8]. The instrumentation used in the three forementioned studies was described in detail by Fitzgerald *et al.* [9].

All of the above studies utilized electrically heated foils or thin metal films of low heat capacity as heat flux transducers. The instantaneous electrical power dissipated by the metal film, instantaneous surface temperature, knowledge of the geometry of the transducer and thermal properties of the materials of construction are adequate to calculate the instantaneous local heat flux. The operating principle of these devices and the signal conditioning methods used require that the transducer surface be at a higher temperature than the fluidized bed. For this reason, none of the heat flux transducers employed in the above studies are useful in high-temperature fluidized beds. Abrasion resistance is also limited for devices of this type.

Despite their limitations, the above studies conducted in low-temperature fluidized beds obtained data which served to partially validate certain detailed analytical models of the heat transfer process, e.g. the models proposed by Adams and Welty [10] and Decker and Glicksman [11]. The results obtained from the experimental studies could not be reliably extended to the prediction of heat transfer rates to immersed surfaces in fluidized beds at combustion-level temperatures.

The measurement of time-average local heat transfer coefficients does not require a rapid responding heat flux transducer and is therefore easier to perform that instantaneous measurements. Time-average local heat fluxes (or equivalently, time-average local heat transfer coefficients) for horizontal tubes immersed in high-temperature fluidized beds have been reported by a few investigators [12, 13]. While these data provide useful information concerning the local heat transfer coefficient around the periphery of an immersed tube, no information whatsoever is provided concerning the time-wise variation of the local heat transfer coefficient. The more detailed models of the heat transfer process involve the calculation of instantaneous bed-to-surface heat transfer rates from the instantaneous flow field and voidage distribution near the immersed surface. Time-average data are not adequate for validation or improvement of these sophisticated analytical models.

Previous attempts to accurately measure instantaneous local heat transfer rates to surfaces immersed in high-temperature fluidized beds failed due to lack of an adequate heat flux transducer. This paper describes a transducer which has been used to measure instantaneous local bed-to-wall heat transfer coefficients in a fluidized bed at 282°C. Operation at higher temperatures is certainly feasible.

HEAT FLUX TRANSDUCERS FOR FLUIDIZED BED APPLICATIONS

Background

As indicated above, the thin electrically heated films used for instantaneous local heat flux measurements in low-temperature fluidized beds are not suitable for use in high-temperature fluidized beds.

Thermopile type gages, which use arrays of thermocouple junctions or resistance temperature detectors

NOMENCLATURE

a	thermocouple sensitivity (V deg.$^{-1}$)
c	specific heat of transducer material
e	input voltage to signal conditioning circuit
j	$\sqrt{-1}$
k	thermal conductivity of transducer material
L	effective length of transducer
$q_w(t)$	instantaneous local heat flux at surface ($x = 0$)
$<q_w>$	time-average local heat flux at surface ($x = 0$)
$\delta q_w(t)$	instantaneous deviation of surface heat flux from the time-average value
s	Laplace transform parameter
T	temperature
T_w	surface temperature
$<T_w>$	time-average surface temperature
$\delta T_w(t)$	instantaneous deviation of surface temperature from the time-average value
T_L	constant temperature at position $x = L$
t	time
v	output voltage of signal conditioning circuit
v_2	voltage representing $\delta q_w(t)$
$<v_2>$	time average of v_2
x	position coordinate.
Greek symbols	
α	thermal diffusivity of transducer material
β	calibration constant defined in equation (8)
ρ	density of transducer material
ω	frequency.

to obtain the temperature difference across thin wafers of insulating material, are not abrasion resistant and must be covered with a protective film for fluidized bed use. One such implementation was described in ref. [12, 14] and later used by others [13]. The stainless steel shim stock which was used to cover the transducer increased the settling time (time interval required for 98% complete response to a step change in heat flux) from 80 ms for the transducer alone to approximately 960 ms for the transducer with protective cover. These values for the settling time are far too long to be useful for instantaneous local heat flux measurements in fluidized beds. Therefore, the two studies mentioned above reported only time-average local heat transfer coefficients.

The circular foil heat flux gage, also known as the Gardon gage [15, 16] was used in high-temperature fluidized beds as described in ref. [17] and later by the writer. Despite its success as a device for measuring radiant heat flux, it was ultimately shown to be not fully acceptable for use in fluidized beds. It was found that the Gardon gage did not accurately translate the heat flux to an output voltage unless the heat flux was applied uniformly to the gage surface. The complex interaction of particles and gas with the surface of interest did not provide a uniform heat flux over the surface of the gage and led to anomalous results. While the limitations of the Gardon gage as concerns uniform heat flux are well known [18], actual testing in a high-temperature fluidized bed was required before this relatively simple device was eliminated from further consideration.

Devices based on surface temperature measurement and application of the heat conduction solution for the semi-infinite wall are suitable for this application. These devices, if properly designed, have the advantage of providing negligible disturbance of the normal temperature distribution on the surface of interest and are highly abrasion resistant.

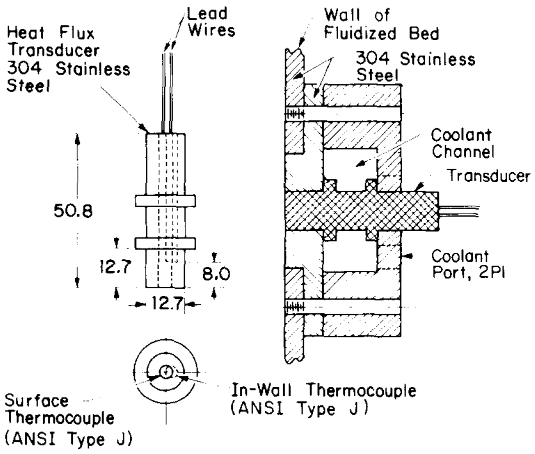

FIG. 1. Heat flux transducer and mounting fixture. Dimensions are in millimeters.

Design

Figure 1 shows the design of a heat flux transducer which has been used to measure instantaneous local bed-to-wall heat transfer rates in a high-temperature fluidized bed. The transducer body is made of type 304 stainless steel and incorporates two eroding type thermocouple junctions (fabricated by Nanmac Corporation, Framingham Center, Massachusetts, U.S.A.). The construction of these thermocouple junctions is shown in Fig. 2. The thermocouple junction is formed by small burrs at the surface which bridge over the thin mica sheets that separate the thermocouple metals and also contact the transducer body. Thus, a grounded thermocouple junction of extremely

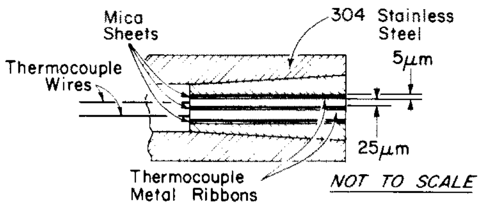

FIG. 2. Eroding type thermocouple junction.

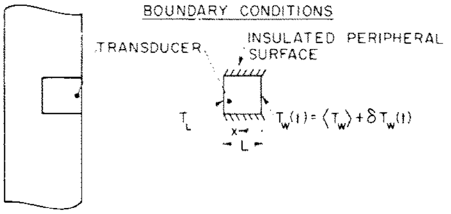

FIG. 3. Boundary conditions for conduction problem.

low thermal mass is formed at the surface. As the fluidized bed slowly erodes the transducer surface, new burrs are formed while the junction remains in contact with the stainless steel.

This system of surface temperature measurement is inherently insensitive to abrasion and does not need to be covered by any form of protective film for fluidized bed use. During a 200 h duration test in which the transducer was exposed to a low-temperature bubbling fluidized bed of approximately 500 μm diameter sand, the combined electrical resistance of the surface thermocouple junction and lead wires remained within the range $20 \pm 0.5\ \Omega$ throughout the test. Therefore, the small burrs which form the junction do renew themselves as the surface is slowly eroded by the fluidized bed.

Later testing in a small electrically heated fluidized bed, with various sizes of glass beads used as particles, covered approximately 100 h of operation at bed temperatures up to 370°C. When identical operating conditions were maintained, no significant change in transducer output was found between tests conducted near the end of the test sequence and those conducted near the beginning of the test sequence. The transducer appears to have adequate abrasion resistance for most research uses.

The in-wall thermocouple is not subject to abrasion and functions in a conventional manner.

Principle of operation

Consider a heat flux transducer embedded in the surface of interest as shown in Fig. 3. One-dimensional unsteady heat transfer is assumed to occur within the transducer between the surface and in-wall thermocouples. Boundary conditions are also shown in Fig. 3. By design, the fluctuations in the surface temperature, $\delta T_w(t)$, are rapid enough that they are damped out before reaching the position $x = L$. Thus, the transducer is semi-infinite as far as the surface temperature fluctuations are concerned and a constant value of T_L is assumed.

Thermal properties of the transducer are taken as constants. This assumption is adequate for the moderate changes in temperature which occur within the transducer.

Measured values of the temperatures $T_w(t)$ and T_L are used as boundary conditions to solve the unsteady conduction problem for the region. From this solution, the surface heat flux $q_w(t)$ can be computed by either digital or analog methods. An apparent problem with the formulation is that it is not possible to establish the initial temperature distribution in the transducer body from measurements of T_L and $T_w(t)$ alone. However, the solution for large values of time is independent of the initial temperature distribution within the transducer and is given by

$$q_w(t) = \frac{k}{L}[\langle T_w \rangle - T_L] + \left(\frac{k\rho c}{\pi}\right)^{1/2} \int_{\eta=0}^{t} \frac{1}{(t-\eta)^{1/2}} \left(\frac{\mathrm{d}T_w}{\mathrm{d}\eta}\right) \mathrm{d}\eta. \quad (1)$$

The first term in the above solution represents the constant time-average heat flux which will be denoted $<q_w>$. The second term has been obtained by using the semi-infinite medium solution for a step change in surface temperature [19] and applying Duhamel's superposition integral. This second term is a function of time which represents the fluctuations in the heat flux due to $\delta T_w(t)$ and will be denoted $\delta q_w(t)$.

For use in a high-temperature bubbling fluidized bed, it has been estimated that the minimum frequency present in the surface temperature history is 0.5 Hz or greater. This estimate follows from inspection of instantaneous local heat transfer coefficient data for a single horizontal tube in a low-temperature fluidized bed [6]. In a bubbling fluidized bed combustor, the minimum frequency present in the local surface temperature history will likely be significantly higher than 0.5 Hz. With the transducer body constructed of type 304 stainless steel, it follows from the steady periodic solution for one-dimensional heat transfer in a semi-infinite medium [20] and the complete solution of the problem with a uniform initial temperature [21] that slightly over 5 s are required for the influence of the unknown initial condition to become negligible (error in computed heat flux less than 1.5% of the time-average value) and a minimum length (L) of 6.4 mm is required for the in-wall temperature (T_L) to remain essentially constant (fluctuates less than 2% of the magnitude of the surface temperature fluctuation). Since, at minimum, several minutes will be required to establish a stable time-average surface temperature for a particular set of operating conditions, lack of knowledge of the initial condition is not significant in this application.

Uncertainty will exist concerning the minimum frequency given above until actual measurements of the local surface temperature history and associated frequency spectrum are obtained for a range of fluidized bed sizes, operating conditions and heat transfer surface configurations. However, the transducer described here could be adapted to whatever minimum frequency future measurements indicate by changing the length (L) or material of construction.

Several investigators have used numerical (digital computer) methods to evaluate the integral in equation (1) [22, 23]. Finite-difference formulations of the semi-infinite wall conduction problem have also been used as a means of computing the instantaneous local heat flux [24].

Despite the success of numerical techniques, it is very convenient to utilize analog signal conditioning to produce a d.c. voltage which is linearly related to the instantaneous local heat flux. This allows direct oscillographic recording of the heat flux history or, if digital data acquisition is used, allows simple digital calculation of the instantaneous local heat flux without complex numerical procedures. The advantages of an analog rather than a purely numerical solution of the integral in equation (1) become very significant when data are to be obtained simultaneously from several heat flux transducers.

Analog signal conditioning and data acquisition

The analog solution of this problem provides a d.c. voltage which is linearly related to the heat flux fluctuations $\delta q_w(t)$. The time-average component of the local heat flux can be computed easily by digital methods. Therefore, no special analog signal conditioning is needed to efficiently compute $\langle q_w \rangle$.

By the use of the Laplace transformation and the heat conduction formulation for the semi-infinite medium, the following transfer function can be obtained

$$\frac{\overline{\delta q}(s)}{\overline{\delta T_w}(s)} = \sqrt{(k\rho c)}\sqrt{s} \tag{2}$$

where s is the Laplace transform parameter. Let

$$\left.\begin{aligned} \bar{v}(s) &= \beta_1 \overline{\delta q}(s) \\ \bar{e}(s) &= a_1 \overline{\delta T_w}(s) \end{aligned}\right\} \tag{3}$$

where β_1 and a_1 are constants. Therefore, the transfer function for the signal conditioning circuit is

$$\frac{\bar{v}(s)}{\bar{e}(s)} = \frac{\beta_1 \sqrt{(k\rho c)}}{a_1}\sqrt{s}. \tag{4}$$

It follows that the frequency response of the signal conditioning circuit must be

$$\frac{v(j\omega)}{e(j\omega)} = \frac{\beta_1 \sqrt{(k\rho c)}}{a_1}\sqrt{\omega} \measuredangle 45^\circ. \tag{5}$$

In words, the circuit must provide an amplitude ratio proportional to the square root of frequency and a constant phase angle of 45°. An equivalent form of this relationship was first given by Skinner [25].

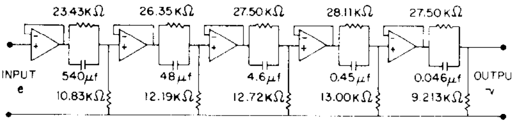

FIG. 4. Analog signal conditioning circuit.

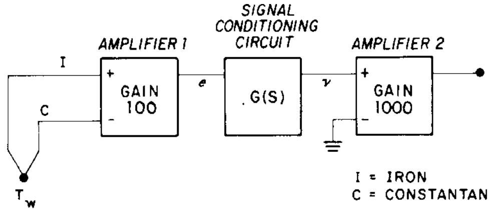

FIG. 5. Signal amplification system.

The transfer function given by equation (5) can be approximated over a finite frequency range by several different circuits. After some experimentation, the circuit shown in Fig. 4 was developed specifically for the present application. The circuit shown approximates the transfer function

$$G(s) = (1.194 \times 10^{-2})\sqrt{s} \tag{6}$$

within 5% in amplitude and 2° in phase angle for the frequency range 0.2–260 Hz. The constant 1.194×10^{-2} has units of $(\text{seconds})^{0.5}$. For the frequency range 0.1–300 Hz the amplitude is within 7% and the phase angle within 3° of that given by equation (6). This frequency range is fully adequate for the present application.

A circuit which incorporates the analog signal conditioning circuit discussed above is shown in Fig. 5. To improve signal-to-noise ratio, both of the instrumentation amplifiers shown incorporate two-stage low pass filters with a cutoff frequency (−3 db) of 1000 Hz. The voltage v_2 can be recorded on an oscillographic recorder or in digital form via analog-to-digital converters. The temperatures $\langle T_w \rangle$ and T_L are obtained using digital thermometers for ANSI type J thermocouples. The instantaneous local heat flux is computed from

$$q_w(t) = \frac{k}{L}[\langle T_w \rangle - T_L] + \frac{1}{\beta}[v_2(t) - \langle v_2 \rangle] \tag{7}$$

where β is the calibration constant discussed below.

A useful check on the input–output relationship for the analog signal conditioning circuit is to subject the transducer to a step change in surface heat flux and verify that a near step change in output voltage (v_2) is produced. A propane torch and shutter were used to produce a step change in heat flux at the transducer surface. The settling time, as measured on a storage oscilloscope, was found to be approximately 5 ms which is fully adequate for fluidized bed application. Due to a small amount of electrical noise present on the signal, the peak overshoot could not be accurately resolved on the oscilloscope trace but appeared to be less than 2%. The fact that the above test produced a near step change in the output voltage provides indirect evidence that the surface thermocouple responds accurately to the surface temperature fluctuations for the frequency range considered. For comparison, the heat flux measuring system described in ref. [9] and utilized for an extensive study in low-temperature fluidized beds [6–8] provided a settling time of approximately 20 ms.

Calibration

Little uncertainty is associated with the transducer itself. Its input–output characteristics are accurately provided by the thermal properties, geometry and thermocouple e.m.f. vs temperature relationship.

The calibration constant is defined as

$$\beta = \frac{dv_2}{dq_w}. \tag{8}$$

By considering the input–output relationship of each of the circuit elements, it can be shown that

$$\beta = \frac{10^5 a}{83.8\sqrt{(k\rho c)}} \tag{9}$$

where the constant a is the thermocouple sensitivity at the surface temperature of interest and the constant 83.8 has units of $(\text{seconds})^{-0.5}$. At a surface temperature of 100°C

$$\beta = 7.50\,\mu\text{V}\,\text{m}^2\,\text{W}^{-1}. \tag{10}$$

Direct calibration by comparison with a known heat flux is difficult for the heat flux levels encountered in high-temperature fluidized beds.

The major source of uncertainty in determining the calibration constant analytically is that the material properties $k\rho c$ must be specified. However, since only the expression $\sqrt{(k\rho c)}$ appears in equation (9), a 12% uncertainty in the product $k\rho c$ yields only a 6% uncertainty in $\sqrt{(k\rho c)}$. It is estimated that the calibration constant can be computed with an uncertainty of less than 6%.

The time-average local heat flux, $<q_w>$, depends on the ratio k/L. It is estimated that k/L can be established analytically with an uncertainty of less than 5%.

For operating conditions which include significant radiant heat transfer between the fluidized bed and transducer surface, errors in surface temperature measurement due to the difference in radiative properties of the surface thermocouple junction and insulating material (mica) relative to the transducer body may occur. This source of error would influence both the measured time-average local heat flux and the instantaneous local heat flux. Since alternative methods of measuring the time-average local heat flux are available [12, 13], a direct *in situ* test of the significance of this error source is possible but not part of the work reported here.

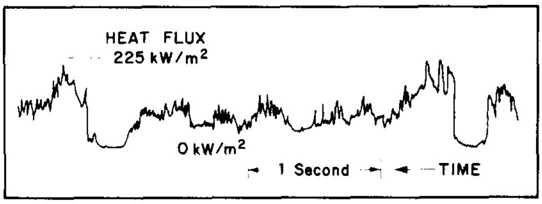

FIG. 6. Instantaneous local bed-to-wall heat flux for 150 μm glass beads. Bed temperature 282°C, superficial gas velocity 0.33 m s^{-1}, time-average surface temperature 107°C.

Data

A sample of data for the instantaneous local bed-to-wall heat flux as a function of time is shown in Fig. 6. An oscillographic recorder was used to record the instantaneous local heat flux. Therefore, the time scale advances from right to left.

A small (102 × 102 mm) electrically heated fluidized bed was used. The transducer was mounted approximately 140 mm above the distributor plate. Glass beads of approximately 150 μm mean diameter were used as particles. Other conditions of operation were: bed temperature 282°C, superficial gas velocity 0.33 m s^{-1}, time-average surface temperature 107°C.

The measured time-average local heat flux was 147 kW m^{-2} which corresponds to a time-average local heat transfer coefficient of 841 W m^{-2}°C^{-1}. The fluidized bed was bubbling intensely but not slugging.

Since small particles were used, the dominant mode of heat transfer was unsteady conduction between the particles and the wall. Therefore, the heat flux was near zero during those times that gas bubbles covered the transducer surface. The maximum value of the instantaneous local heat flux generally occurs immediately after the passage of a bubble which brings fresh hot particles in contact with the wall. This behavior is, of course, consistent with the theory of bed-to-surface heat transfer based on unsteady conduction described about 25 years ago by Mickley *et al.* [1].

While the data shown in Fig. 6 are for one set of operating conditions only, the viability of the measurement technique described above is demonstrated. A second generation transducer will utilize two surface temperature thermocouples rather than one and should provide more accurate results during time intervals when particles contact the surface. An analog summation circuit will be utilized to sum the voltage outputs of the surface thermocouples. The resulting voltage will be applied to the same analog signal conditioning circuit as described above. Provided the gain of the final stage amplifier is reduced from 1000 to 500, the calibration constant (β) would not be affected. With a center-to-center spacing of approximately 6 mm between surface thermocouple junctions, the resulting surface temperature measurements should more accurately represent the spatial-average temperature over the central portion of the transducer.

The present transducer provides good results when gas bubbles contact the surface but a somewhat noisy output during periods of particle contact with the surface.

Conclusions

The transducer and associated signal conditioning circuit described above provide a means of measuring the instantaneous local heat flux to surfaces immersed in high-temperature fluidized beds. The measurement system provides a settling time of approximately 5 ms. This value of the settling time is significantly shorter than that provided by some systems previously used for similar measurements in low-temperature fluidized beds. Abrasion resistance appears to be adequate to allow for long-term use of the transducer (at least several hundred hours).

Due to limitations imposed by the small (102 × 102 mm) electrically heated fluidized bed used, the maximum bed temperature for which data were reported above was 282°C. However, operation of the transducer, or one of similar design, at combustion-level temperatures (approximately 800°C) is certainly feasible. While not part of the present work, possible errors in the measured heat flux due to the influence of radiant heat transfer on the measured surface temperature could be quantified by *in situ* testing since alternate methods of measuring the time-average local heat flux are available.

The transducer could be improved by incorporating two or more surface temperature thermocouples rather than only one as currently used. This modification would probably provide more accurate heat flux measurements during the time intervals when particles contact the surface of the transducer.

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TRANSDUCTEUR POUR LA MESURE DU FLUX THERMIQUE LOCAL INSTANTANE SUR UNE SURFACE IMMERGEE DANS UN LIT FLUIDISE

Résumé—Une sonde à réponse rapide (temps de stabilisation de 5 ms environ) pour flux de chaleur, associée à un équipement de traitement de signal analogique, est développée pour la mesure des flux de chaleur instantanés locaux transférés à des surfaces immergées dans des lits fluidisés à des niveaux de température correspondants à la combustion. L'équipement analogique fournit une tension continue qui est linéairement reliée au flux de chaleur local instantané. Cette tension est compatible avec une visualisation oscillographique ou une acquisition digitale. On présente les flux thermiques instantanés entre le lit et la paroi obtenus expérimentalement dans un petit lit fluidisé (102 × 102 mm) chauffé électriquement.

EIN MESSWERTAUFNEHMER FÜR DIE MOMENTANE ÖRTLICHE WÄRMESTROMDICHTE AN OBERFLÄCHEN IN HOCHTEMPERATUR-FLIESSBETTEN

Zusammenfassung—Ein verschleißfester, schnell ansprechender (Einschwingzeit ca. 5 ms) Wärmestromdichte-Aufnehmer mit angeschlossener Analogsignalverarbeitung ist für die Messung des momentanen örtlichen Wärmestroms an Oberflächen entwickelt worden, die sich bei Verbrennungstemperaturen in einem Fließbett befinden. Die Analogsignalverarbeitung liefert eine Gleichspannung, die in linearer Beziehung zur momentanen örtlichen Wärmestromdichte steht. Diese Spannung ist für die direkte oszillographische Registrierung oder für die digitale Datengewinnung geeignet. Momentanwerte der örtlichen Wärmestromdichte vom Bett zur Wand werden dargestellt, die in einem kleinen (102 × 102 mm) elektrisch beheizten Fließbett bei 282°C gewonnen wurden.

ДАТЧИК ДЛЯ ИЗМЕРЕНИЯ МГНОВЕННОГО ЛОКАЛЬНОГО ТЕПЛОВОГО ПОТОКА К ПОВЕРХНОСТЯМ, ПОГРУЖЕННЫМ В ВЫСОКОТЕМПЕРАТУРНЫЕ ПСЕВДООЖИЖЕННЫЕ СЛОИ

Аннотация—Для измерения интенсивности мгновенного локального теплового потока к поверхностям, погруженным в псевдоожиженные слои при температурах горения, разработан устойчивый к абразивному износу быстродействующий датчик (время срабатывания ~5 мс) с соответствующей аппаратурой обработки сигнала в аналоговой форме. Аналоговый сигнал постоянного тока линейно зависит от мгновенного локального теплового потока. Полученного напряжения достаточно для прямой осциллографической регистрации или получения цифровой информации. Представлены данные по мгновенному локальному тепловому потоку от слоя к стенке в небольшом (102 × 102 мм) нагреваемом электрическим током псевдоожиженном слое при 282°C.