of design parameters on the aerodynamics of cyclone chambers," Teploenergetika, No. 2. 67-70 (1967).
2. G. F. Knorre (editor), in: Problems of Aerodynamics and Heat Transfer in Boiler-Heating Processes, GÉI, Moscow (1958), pp. 23-73.
3. P. S. Kuts, É. G. Tutova, and G. S. Kabaldin, "Investigation of the aerodynamics of an eddy spray dryer," Inzh.-Fiz. Zh., 24, No. 4, 708-714 (1973).
4. R. M. Masagutov, M. M. Khannanov, R. Kh. Mukhutdinov, and Yu. T. Portnov, Inventor's Certificate No. 552482, Byull. Izobret., No. 12, 104 (1977).
5. M. M. Khannanov, Yu. T. Portnov, and R. M. Masagutov, in: Petrochemical Synthesis and Technical Progress, Ufa (1976), pp. 90-93.
6. A. I. Petunin, in: Methods and Technique of Measuring the Parameters of a Gas Stream [in Russian], Mashinostroenie, Moscow (1972), pp. 88-99.
7. B. P. Ustimenko, in: Processes of Turbulent Transfer in Rotating Flows [in Russian], Nauka, Kazan SSR, Alma-Ata (1977), pp. 174-192.

PIEZOELECTRIC MEASUREMENT OF THE LOCAL CHARACTERISTICS OF THE MOTION OF SOLID PARTICLES IN A TWO-PHASE FLOW

L. I. Krupnik, V. N. Oleinik, and V. G. Ainshtein

UDC 53.082.73:532.529.5

We develop the design of a piezosensor and a method for measuring the hydrodynamic characteristics of the motion of solid particles in a two-phase flow.

The mechanism and intensity of various transfer processes in the flow of a gas suspension are determined to a large extent by the structure of the suspension, in particular by the transverse distribution of concentrations, velocities, and flow rates of the solid material. These characteristics, in spite of the considerable number of studies [1-8] on the hydrodynamics of two-phase flows, have not been adequately investigated; this fact is due to the multiplicity of forms and the complexity of the systems themselves, as well as to inadequate development of the methods of measurement. The instrumentation used today is, as a rule, limited either to flows with a low flow-rate concentration ($\mu_f < 2$ kg/h/kg/h) of the solid phase (high-speed cinematography [3, 4] and other optical methods [5, 6]) or to small ($d < 200$ μm) particles (isokinetic sampling [7, 8], laser diagnostics [9]) or else by the information on the values averaged over the cross section (the cutoff method [10, 11], photoelectric methods [12, 13]).

According to available estimates [14], the experimental conditions impose no practical limitation on a method using the piezoelectric effect for measuring the local characteristics of the motion of solid particles. The present paper is devoted to a discussion of the possibilities of piezosensors. The special features of two-phase flow as an object of investigation place a number of specific requirements on the design of the sensor. Above all, it is necessary to maintain high sensitivity when the solid particles exert a destructive effect (impact and abrasion).

The sensor was designed in accordance with current recommendations [15]. The total thickness of the impact-absorbing sensitive zone, made of steel, and the piezoplate did not exceed 1 mm. As the inertial mass, we used a zinc rod whose significant dimensions ensured three-dimensional scattering of acoustic deformation waves.

An analysis of the oscillograms of the first series of experiments (Fig. 1a) enabled us to establish the duration of the contact between small glass spheres ($d \sim 1$ mm) moving at a velocity of 1-15 m/sec with the steel end-face zone of the sensor, $\tau = (3.0\text{-}3.2)\cdot 10^{-6}$ sec; this corresponds to a response of $n \sim 3\cdot 10^5$ impacts/sec. Obviously the response of the sensor must exceed the possible frequency of particle collisions with its sensitive zone:

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 40, No. 1, pp. 101-108, January, 1981. Original article submitted November 20, 1979.

 0022-0841/81/4001-0072$07.50

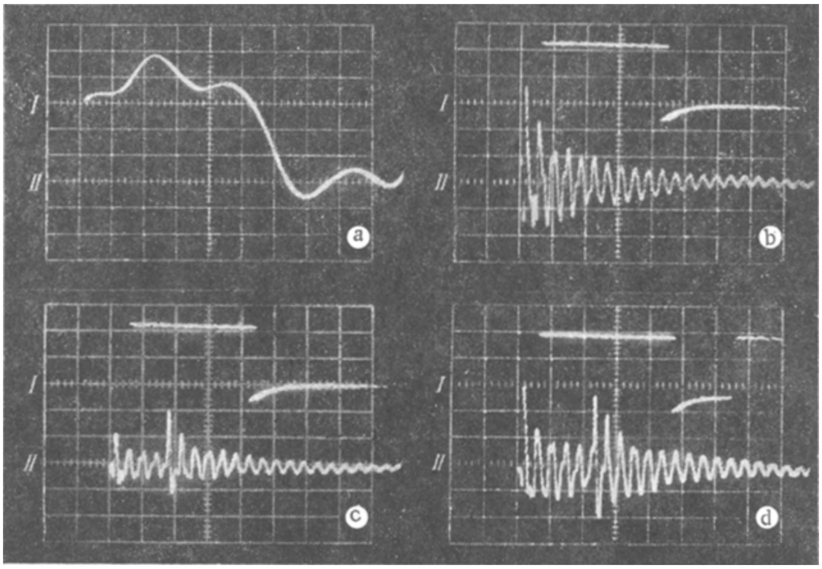

Fig. 1. Oscillogram of impacts: a) interaction of glass sphere (d = 1 mm) with metal surface (one cell along the abscissa axis corresponds to 0.5 μsec; v = 1-15 m/sec); b) sensor reaction to a single impact; c, d) two successive impacts: c) miss in counting; d) both impacts recorded; I, II) lines on the oscillograph screen from the generator and piezosensor signals, respectively (for b, c, d one cell along the abscissa axis corresponds to 50 μsec).

$$n > \frac{6\mu_f \rho \overline{w} f_0}{\pi d^3 \rho_s} \tag{1}$$

and there must be no substantial disturbance of the flow structure.

For a concentration of μ_f = 45 kg/h/kg/h [1], which is critical for the flow of the gas suspension, a velocity of $\overline{w}$ = 20 m/sec in the carrying medium, d = 1 mm, and f_0 = 1 mm², in accordance with (1), we obtain n > 1000 impacts/sec. Thus, condition (1) can be satisfied in the flow of a gas suspension when we make the measurements with a sensor whose response is lower by two orders of magnitude than the resolving power of the piezoelectric measurement method. A consequence of this was the development of the design for a piezosensor (Fig. 2A) which satisfies sufficiently completely the rigid requirements of the measurement process. The sensitive element which transforms the elastic stresses arising as a result of the particle impacts was made from a barium titanate plate 0.3 mm thick. The relatively small diameter of the steel receiving waveguide, the inertial mass, and their contact with the sensitive element guarantee a sensor response of n ≃ 4000 impacts/sec. The rubber insulation prevents destruction of the sensor and penetration of acoustic noise into the measuring circuit.

The measuring circuit (Fig. 2B) was developed in accordance with the individual electrical parameters of the piezosensors and the possible conditions of the experiment. The reaction of the sensor 8 to a single impact is a damped harmonic signal, whose oscillogram is shown in Fig. 1b. This signal then passes through a cathode follower 10 with an input resistance of $7 \cdot 10^7$ Ω, which eliminates any effect of the measuring circuit on the operation of the sensor, a phase inverter 11, which ensures normal operation of the circuit under conditions with an unknown direction of polarization of the electric field in the piezoplate, and a wide-band amplifier 12. The first (maximal) semisinusoidal pulse of the signal starts up the generator 15, and the front edges of the square pulses of the generator start the frequency-meter-chronometer 16 in an impact-counting regime or in a time-interval-counting regime. The adjustment of the measuring-circuit parameters and the monitoring of the reliability of the measured quantities is carried out by the two-line memory oscillograph 14. For this purpose, the first channel of the oscillograph is connected to the square-pulse

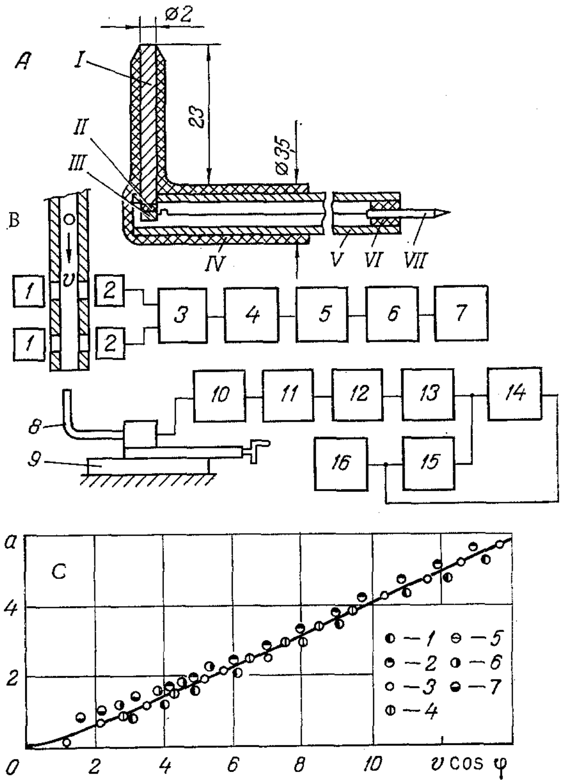

Fig. 2. Schematic of the piezosensor (A), measuring circuit (B), and amplitude characteristic of the sensor (C) (a in volts, v in m/sec, φ in deg, ϕ in mm): A) I, receiving waveguide; II, sensitive element; III, inertial mass; IV, acoustic insulation; V, holder; VI, insulating sleeve; VII, electrode; B) 1, illuminator; 2, FD-3 photodiode; 3, transfer device; 4, U7-2 amplifier; 5, trigger; 6, emitter follower; 7, Ch3-35A frequency meter; 8, piezosensor; 9, coordinator; 10, 13, cathode followers; 11, phase inverter; 12, U3-29 wide-band amplifier; 14, C8-2 memory oscillograph; 15, square-pulse generator; 16, F5080 frequency meter; C) 1, d = 1.0 mm; 2, 1.2; 3-7, 1.15; 1-3, φ = 0°; 4, 20°; 5, 60°; 6) 70°; 7, 80°.

generator output, and the signal is shown on line I.* The second channel is connected to the output of the amplifier 12, and the signal from the piezosensor is shown on line II. From line II on the screen of the oscillograph, we can determine the minimum and maximum amplitudes, a_{min} and a_{max}, of the first pulse of the piezosensor signal. On the basis of the value of a_{min}, we select the amplification factor of the wide-band amplifier 12 to be high enough to start the generator 15. This eliminates possible misses in the count as a result of "weak" pulses. On the basis of a_{max}, we determine the duration of the square pulse of the generator 15. Thus, we preclude any startup of the generator resulting from the damped part of the piezosensor signal.

Nevertheless, the measuring circuit may miss some counts as a result of the finite response of the piezosensor.

*Because the recording speed of the oscillograph is limited, the front and rear edges of the square pulse from the generator are not reproduced on the screen.

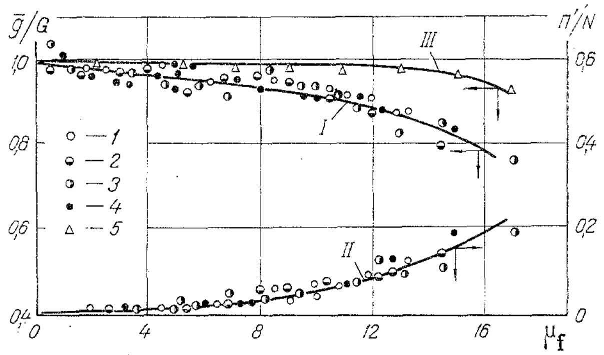

Fig. 3. Error in measurement ($\bar{g}$, G, kg/h; μ_f, kg/h/kg/h): I) imbalance of the measured and specified flow rates of solid particles; II) fraction of unrecorded particles; III) corrected imbalance of $\bar{g}$ and G; 1) $\bar{w} = 13.0$ m/sec; 2) 16.5; 3) 19.3; 4) 21.0.

In Figs. 1b, c, and d we show the characteristic oscillograms of the impacts. The sensor was set up along the axis of the pipe in a stream with $\mu_f = 14$ kg/h/kg/h and $\bar{w} = 16.5$ m/sec. The signal from a single impact, on the basis of which we showed the duration of the square generator pulse, is shown in Fig. 1b. In the situations represented by oscillograms c and d, the time interval between two successive impacts was less than the duration of the square pulse. If beyond its limits the amplitude of the damped oscillation, a_d, is lower than the generator startup level a_{min} (Fig. 1c), then the frequency meter misses the count; for $a_d > a_{min}$ (Fig. 1d) it records both impacts.

The local density (with respect to the radial coordinate r) of the stream of solid particles, g(r), was determined from the data of measurements of the number of their collisions N(r) with the effective zone of the sensor f_0 in time τ:

$$g(r) = \frac{N(r)\bar{m}}{f_0 \tau}. \tag{2}$$

The averaging time, $\tau = 100$ sec, was found to be sufficient for reliable reproducibility of N(r). The maximum deviation of the frequency-meter readings from the average value was no more than ±0.5%.

The value of f_0 is obtained by taking account of all the particles interacting with the end face (diameter d_0) of the receiving waveguide of the sensor:

$$f_0 = \frac{\pi}{4}(d_0 + \bar{d})^2, \tag{3}$$

where $\bar{d}$ is the average particle diameter.

The validity of formula (3) was confirmed experimentally by shifting the point of contact of a particle from the center of the end face of the receiving waveguide to the periphery. A necessary condition for measurement is (see above) the choice of a signal amplification factor for the oscillograph such that the amplitude of a weak peripheral signal is higher than the level required to trigger the square-pulse generator. It should be noted that observations during a prolonged experiment showed that the diameter of the end face of the receiving waveguide remains unchanged under conditions of impact and abrasion by a stream of solid particles acting upon it.

The reliability of the results obtained by measuring the number of impacts N(r) was evaluated by comparing the total (integral) flux of solid particles

$$\bar{g} = 2\pi \int_0^R g(r)\, r dr \tag{4}$$

with their flow rate G, which was known for each experiment.

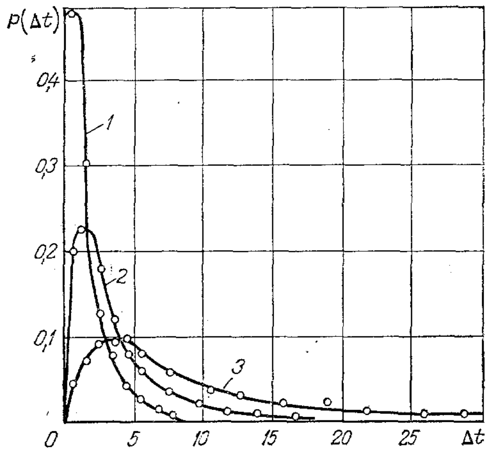

Fig. 4. Density of distribution of time intervals between two successive impacts ($P(\Delta t)$, msec^{-1}; Δt, msec; $\bar{w} = 16.5$ m/sec): 1) $\mu_f = 9.06$ kg/h/kg/h; 2) 2.98; 3) 1.60.

The investigation was carried out on the stabilized segment of an ascending two-phase flow in a pipe with diameter $D = 2R = 50$ mm. The flow-rate concentration and velocity of the carrying medium were varied in the ranges of 0.3-17 kg/h/kg/h and 13-21 m/sec, respectively. As the solid particles, we used a narrow fraction of the total possible range of glass spheres ($d = 1.0$-1.25 mm), with an average diameter $\bar{d} = 1.18$ mm.

The function $\bar{g}/G = \mu(r)$ is shown in Fig. 3 (curve I). As μ_f increases (irrespective of the velocity of the carrying medium), there is an increase in the deviation of $\bar{g}$ from G, reaching approximately 20% in the region of large concentrations.

Earlier (see Fig. 1c) it was shown that for a high frequency of impacts, it is possible to have misses in the count. The fraction of the particles (n'/N) not recorded by the frequency meter was calculated in each experiment on the oscillograph screen by setting the sensor at the radius r_0 corresponding to the average flux $\bar{g}$ (averaged over the cross section of the pipe); the value of r_0 was, of course, found for each g(r) distribution curve. The justification for this method is provided by a special series of experiments with strict averaging of the quantity n'/N over the cross section of the pipe.

The data obtained are shown in Fig. 3 (curve II). Taking account of this correction for the finite response of the piezosensor (curve III), we obtain very good agreement between the flow rates $\bar{g}$ and G:

$$0.93 \leqslant \frac{\bar{g}}{G}\left(1 + \frac{n'}{N}\right) \leqslant 1. \qquad (5)$$

The small imbalance (not exceeding 7% in the range of measurements made) may be due to the disturbance introduced by the sensor into the structure of the turbulent two-phase flow.

The degree to which the sensor disturbs the flow is connected, to a significant extent, with the relative distance between the holder and the end face of the receiving waveguide, l/d_0. According to the data of our measurements, for $l/d_0 < 10$ the role of this factor is quite significant. Thus, for $l/d_0 = 1$, the lower bound of the expression (5) was reduced to 0.65. Qualitatively, the same effect is obtained by a deviation of the axis of the receiving waveguide from the axis of the flow by an angle $\varphi > 15°$.

The particles moving in the two-phase flow, when they interact with the end face of the receiving waveguide set up at radius r, give the piezoelement a momentum characterized by the spectrum of the amplitude of the electrical pulse $a(r)$ with a distribution density $P(a)$.

The amplitude characteristic of the sensor (the variation of the pulse amplitude as a function of the particle velocity) was determined from the impact effect of particles of known mass colliding at a known velocity with the sensitive zone of the sensor at a fixed angle of attack. The velocity of the particles was measured by the time-of-flight method in a tube 2 mm in diameter (for the measuring circuit, see Fig. 2B). The results of the calibration are shown in Fig. 2C. We can observe a weak stratification of the values of the pulses as a function of the mass of the particles. For the purposes of our subsequent analysis, this stratification, as applied to the narrow fraction used, can be disregarded; then it is allowable to postulate that the parameters of the motion of all the particles at a given point of the stream will practically coincide — we can operate with an "average particle" in an "average situation." In particular, the average value of the local axial velocity of a particle, v(r), when we have an experimental curve of the impact amplitude distribution density $P(a)$, can be determined from the formula

$$v(r) = K \int_{a_{min}}^{a_{max}} a(r) P(a)\, da, \tag{6}$$

where K is the coefficient of the amplitude characteristic of the sensor (according to the curve in Fig. 2C, the latter is close to unity).

Another important result of the calibration was the fact that the sensor records only that component of the velocity which is perpendicular to its end-face zone. In this connection, there seems to be some promise in the use of modified designs for a piezosensor which will measure the transverse migration and radial velocity of the solid particles. In addition, a count of the number of collisions with a sensor set up on the wall of the channel will make it possible to determine directly one of the components of the hydraulic losses of the two-phase flow.

The present study is devoted to an investigation and discussion of the possibilities of the piezoelectric method for measuring the hydrodynamic characteristics of solid particles in a two-phase flow and does not present the results of a systematic investigation. We assume that this method will be usable for a very wide range of questions connected with the structure and mechanism of transfer in dispersed systems with solid particles and with the correct interpretation and practical utilization of the experimental data. We shall demonstrate these deductions on one particular question related to two-phase flows.

In Fig. 4 we show the experimental curves of the density of distribution of time intervals between two successive collisions of solid particles with a sensor set up along the axis of the pipe. The curves are asymmetric and have a shape reminiscent of the Poisson distribution. As the flow-rate concentration increases, the spectrum of time intervals becomes narrower and the maximum of the curves is shifted towards the high-frequency region: corresponding to concentrations of 1.6, 2.98, and 9.06 kg/h/kg/h we have dispersions of 64.2, 13.6, and 2.47 msec^2. Thus, increased constriction of the flow is accompanied by a decrease in the mean free path of the solid particles and by an ordering of their motion. For small values of μ_f the region of transverse migration of particles is bounded primarily by the walls of the pipe. For this very reason, the previously described [16] dispersed regime of motion of a two-phase flow is characterized by a more uniform distribution of the particles in the cross section of the pipe and a relatively high frequency of particle collisions with the walls [17, 18]. For a substantial increase in μ_f, the motion of the particles becomes more ordered, so that even though the average concentration is higher, the increase in the frequency of particle collisions with the walls is slowed down [18].

NOTATION

n, number of impacts of solid particles on the end face of the sensor per second; μ_f, flow-rate concentration of two-phase flow; $\bar{w}$, average velocity of the gas in the pipe; v, velocity of the particles; ρ, ρ_s, density of the gas and of the solid particles; d, diameter of particles; $\bar{m}$, average particle mass; f_0, area of the sensitive zone of the sensor; a, amplitude of an impact pulse; r, instantaneous radius; g(r), local density of solid-particle flow; R, radius of pipe; G, flow rate of solid particles; n', number of impacts not recorded by the frequency meter; φ, angle of attack; Δt, time interval between two successive impacts.

LITERATURE CITED

1. Z. R. Gorbis, Heat Exchange and Hydromechanics of Dispersed Straight-Through Flows [in Russian], Énergiya, Moscow (1970).
2. S. Soo, Hydrodynamics of Multiphase Systems [Russian translation], Mir, Moscow (1971).
3. J. D. Doig and G. H. Roper, "Contribution of the continuous and dispersed phases to the suspension of spheres by a bounded gas-solid stream," Ind. Eng. Chem. Fundam., 7, No. 3, 459-470 (1968).
4. K. V. S. Reddy, M. C. Van Wijk, and D. C. T. Pei, "Particle dynamics in solids — gas flow in a vertical pipe," Can. J. Chem. Eng., 8, No. 3, 490-497 (1969).
5. R. Eichhorn, R. Shanin, and U. Navon, Determination of the Velocity of the Solid Phase in Turbulent Flow of a Gas Suspension in Pipes. Heat and Mass Transfer, Vol. 5 [Russian translation], Énergiya, Moscow—Leningrad (1968), pp. 274-291.

6. V. V. Zlobin and A. Z. Rozenshtein, "An optical method for measuring the distribution of a solid admixture in two-phase flows," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, 142-146 (1975).
7. S. L. Soo and J. A. Regalbuto, "Concentration distribution in two-phase pipe flow," Can. J. Chem. Eng., 38, No. 5, 160-166 (1960).
8. C. S. Rao and A. E. Dukler, "Isokinetic probe for measuring the local velocities and concentration of fine particles," Ind. Eng. Chem. Fundam., 10, 520-524 (1971).
9. V. V. Zlobin, "Experimental investigation of the flow of a mixture of gas and particles in a pipe," Inzh.-Fiz. Zh., 33, No. 4, 611-616 (1977).
10. C. E. Capes and K. Nakamura, "Vertical pneumatic conveying: an experimental study with particles in the intermediate and turbulent flow regimes," Can. J. Chem. Eng., 51, No. 1, 31-38 (1973).
11. V. A. Sheiman and V. I. Kasper, "On the question of the motion of a material in a vertical stream of gas," Inzh.-Fiz. Zh., 6, No. 3, 63-71 (1963).
12. R. Busroyd, Flow of a Gas with Suspended Particles [Russian translation], Mir, Moscow (1975).
13. G. F. Hewitt, "Role of experiments in two-phase systems with particular reference to measurement techniques," J. British Nucl. Soc., 12, No. 2, 213-240 (1973).
14. A. P. Klimenko, Methods and Instruments for Measuring the Concentration of Dust [in Russian], Khimiya, Moscow (1978).
15. A. N. Petunin, Methods and Techniques of Measuring the Parameters of a Gas Flow [in Russian], Mashinostroenie, Moscow (1972).
16. N. I. Gel'perin, V. G. Ainshtein, L. I. Krupnik, Z. N. Memedlyaev, and S. V. Efimova, Structure and Heat-Exchange Capacity of a Turbulent Flow of a Gas Suspension. Heat and Mass Exchange 5, Vol. 6 [in Russian], A. V. Lykov ITMO of the Academy of Sciences of the Belorussian SSSR, Minsk (1976), pp. 193-203.
17. N. I. Gel'perin, L. I. Krupnik, Z. N. Memedlyaev, and V. G. Ainshtein, "Interaction of solid particles with the walls of a channel in the vertical flow of a gas suspension," Inzh.-Fiz. Zh., 32, No. 5, 860-864 (1977).
18. V. N. Milyutin and A. A. Shraiber, "Experimental investigation of the interaction of the flow of a gas suspension with the walls of a vertical channel," Teor. Osn. Khim. Tekhnol., 10, No. 2, 239-247 (1976).

PROBLEM OF DETERMINING THE EFFECTIVE TEMPERATURE IN COMBUSTION CHAMBERS OF HEAT AND POWER INSTALLATIONS

V. P. Trofimov, K. S. Adzerikho, and F. D. Lozhechnik

UDC 536.3:535.34

The effect of the dimensions of the constant temperature core in a radiating planar, nonisothermal, nonscattering layer on the magnitude of the effective temperature is examined. Computed effective temperatures of such a layer, obtained with the use of various methods, are also compared.

As studies of the temperature fields in furnaces in modern large-volume boiler systems show, at some distance from the section in which the burners are located, the temperature of the furnace gases is equalized at the center [1]. As the number of burners increases, the probability for realizing a flat temperature profile increases. However, henceforth, the nature of the temperature profile T(x) along the flame in the furnace section changes due to convection, gradually transforming into a Shlikhting-type temperature profile [2]. In this connection, there naturally arises the problem of the effect of the size of the constant temperature core (plateau or "table") on the effective temperature T_{eff} of the radiating space, which has the type of cross-sectional temperature profile indicated.

A. V. Lykov Institute of Heat and Mass Exchange. Institute of Physics. Institute of Mathematics, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 40, No. 1, pp. 109-114, January, 1981. Original article submitted January 11, 1980.

 0022-0841/81/4001-0078$07.50