23. Yu. M. Kolyano, Dokl. Akad. Nauk UkrSSR, Ser. A, No. 9, 34-37 (1984).
24. Yu. M. Kolyano, Mechanics of Inhomogeneous Structures. Materials of the First All-Union Conference [in Russian], Kiev (1986), pp. 96-106.
25. Yu. M. Kolyano, V. I. Gromovyk, and Ya. T. Karpa, Inzh.-Fiz. Zh., 48, No. 2, 312-315 (1985).
26. Yu. M. Kolyano and I. I. Verba, Differents. Uravn., 21, No. 9, 1624-1626 (1985).
27. Yu. M. Kolyano and I. I. Verba, Fiz.-Khim. Mekh. Mater., No. 6, 107-109 (1985).
28. Yu. M. Kolyano, I. I. Verba, and B. V. Koval'chuk, Effect of Concentrated Energy Fluxes on Materials [in Russian], Moscow (1985), pp. 42-54.
29. Yu. M. Kolyano and L. M. Zatvarskaya, Fiz.-Khim. Mekh. Mater., No. 5, 125 (1986).
30. Yu. M. Kolyano, A. N. Kokora, I. I. Bernar, et al., Fiz. Khim. Obrab. Mater., No. 1, 33-42 (1985).
31. Yu. M. Kolyano and I. I. Bernar, Prikl. Mekh., 23, No. 1, 80-86 (1987).
32. Yu. M. Kolyano, I. R. Tatchin, and E. G. Ivanik, Inzh.-Fiz. Zh., 50, No. 1, 120-126 (1986).
33. Yu. M. Kolyano and Yu. A. Muzychuk, Inzh.-Fiz. Zh., 49, No. 5, 839-844 (1985).
34. Yu. M. Kolyano and I. N. Makhorkin, Inzh.-Fiz. Zh., 47, No. 5, 848-854 (1984).
35. Yu. M. Kolyano, I. N. Makharokin, and I. I. Bernar, Fiz.-Khim. Mekh. Mater., No. 2, 96-98 (1985).
36. I. N. Makhorkin, Mechanics of Inhomogeneous Structures, Materials of First All-Union Conf., [in Russian], Kiev (1986), pp. 139-145.
37. Yu. M. Kolyano, I. N. Makhorkin, and M. E. Bitemirov, Means of Utilizing Secondary Resources of Structural Material and Article Production [in Russian], Vol. 2, Abstracts of Reports, All-Union Congr., 971-972, Kaz. Khim.-Tekh. Inst, Chimkent (1986).
38. Ya. S. Podstrigach and Yu. M. Kolyano, Action of Concentrated Energy Fluxes on Materials [in Russian], Moscow (1985), pp. 36-42.
39. Ya. S. Podstrigach and Yu. M. Kolyano, Unsteady Temperature Fields and Stresses in Thin Plates [in Russian], Kiev (1972).
40. I. N. Preobrazhenskii, Yu. M. Kolyano, and O. I. Borisenko, Mekh. Kompositn. Mater., No. 1, 7-12 (1983).
41. A. G. Shashkov, V. P. Kozlov, and A. V. Stankevich, Inzh.-Fiz. Zh., 50, No. 2, 303-309 (1986).
42. A. G. Shashkov, V. P. Kozlov, and V. N. Lipovtsev, Inzh.-Fiz. Zh., 50, No. 3, 458-465 (1986).
43. R. M. Lutsyshin, Inzh.-Fiz. Zh., 50, No. 3, 498 (1986).

PROCESSES OF HEAT, MASS, AND MOMENTUM TRANSFER IN DISPERSE MEDIA

N. I. Syromyatnikov* and G. P. Yasnikov

UDC 536.24:532.5

The first new-concept technological plants to utilize disperse media for intensification of the processes of annealing of zinc concentrates, drying of fine-grained materials, and the combustion of solid fuel in fluidized beds and vibrating fluidized beds were developed on the basis of experimental studies without any incisive theoretical research efforts. This meant that theoretical investigations in the given field were dictated by practice.

However, such a rift between theory and practice quickly led to miscalculations and errors in the development of certain technologies (rapid heating and combustion of fine-grained fuel), which could only have adverse implications for the overall development of the problem.

With these considerations in mind, a research program has been undertaken recently at the Department of Theoretical Heat Engineering of the Ural Polytechnic Institute with a view toward the development of theoretical methods for analyzing the behavior of the indicated

---

* Deceased.

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 5, pp. 868-874, November, 1987. Original article submitted January 30, 1987.

systems, in conjunction with the continuation of traditional investigations in the hydrodynamics of disperse media and of heat- and mass-transfer processes in them.

The research is being carried out by V. S. Belousov, G. P. Yasnikov, and other co-workers. The approaches that they are developing essentially entail the unification of the phenomenological description of transfer processes by the methods of nonequilibrium thermodynamics with statistical averaging over the ensemble of possible states in phase space. Continuous equations for the balance of various types of energy and entropy of a monodisperse suspension of spherical particles have been derived. Linear phenomenological laws governing heat conduction, diffusion, and viscous friction have been obtained on the basis of an analysis of entropy production. The resulting flux equations contain terms that describe the transfer processes in average temperature, concentration, and velocity fields, along with terms that characterize interaction between phases. The relaxation formalism of nonequilibrium thermodynamics [1, 2] has been recommended in order to take into account the contribution of interphase transfer to the effective properties of disperse systems. The effectiveness of relaxation methods in the investigation of transfer processes has been demonstrated in a recent survey [3].

An operator representation of thermodynamic functions of nonquilibrium states such as the specific heats, adiabatic exponent, sound velocity, chemical potentials, etc., has been introduced for disperse and chemically reacting systems on the basis of relaxation methods [4]. This has made it possible to obtain dynamic equations of state for mixtures of gases with solid particles and evaporating droplets and to analyze the processes of compression and expansion of such systems on the basis of the corresponding equations [5, 6].

The relaxation description of interphase transfer in disperse systems yields generalized heat-conduction and diffusion equations, which are reducible to hyperbolic or elliptic equations in special cases [4, 7]. The transport of a fine fraction in a binary fluidized bed has been analyzed on the basis of a hyperbolic diffusion equation [7], and a mathematical model has also been developed for the oxidation of vanadium-containing materials in a fluidized bed.

A hyperbolic heat-conduction equation has been used to analyze thermal fluctuations in a fluidized bed [8, 9]. Expressions have been derived analytically for the temporal correlation functions of the fluctuations of the temperature and heat-transfer coefficient and for the spectral densities of the processes. A relation has been obtained for the mean heat-transfer coefficient [10]. It coincides formally with the well-known equation of Mickley and Fairbanks [10], but differs from it insofar as it contains the decay time of correlations of the heat-transfer coefficient rather than the contact time of "packets" with the surface. The final theoretical results agree with the experimental data.

Relaxation methods have also been used to analyze acoustical phenomena in disperse systems [11]. Corrections to the characteristic relaxation times for intraparticle heat conduction and diffusion are calculated in this paper. It is shown that the dispersion law of the generalized susceptibility of the system at high frequencies can differ significantly from the usual law deduced from acoustical relaxation theory.

The methods used in [1, 2] for the nonequilibrium thermodynamics of suspensions are based on the procedure of averaging the local "microscopic" balance equations over the ensembles of spatial particle configurations, which is equivalent to the very restrictive assumption that the particle velocity is proportional to the acting forces. It has been shown [12] that the previously derived continuous balance equations have a higher degree of generality than is inferred on the basis of the configuration ensemble. This generality can be achieved by utilizing the machinery of Feynman path integrals for the derivation of the continuous balance equations.

Heat- and mass-transfer processes in polydisperse particulate systems have also been analyzed on the basis of statistical method [13, 14]. The calculations are based on the application of a kinetic equation for the particle-size distribution function. Self-similar solutions of this equation have been found, and functional relations describing the kinetics of evaporation and dissolution of polydisperse particles have been obtained. The results of the calculations are consistent with the experimental data.

One of the most troublesome tasks in experimental work is the investigation of internal heat transfer between a fluidizing medium (gas or water) and particles suspended in it [15].

This problem is customarily solved by an unsteady-state procedure [16], which does not afford a reliable assessment of the reliability of the experimental data or the correctness of their approximation. For the elimination of these drawbacks of the unsteady-state procedure it has been suggested that internal heat transfer be investigated under the conditions of a steady field created by the application of high-frequency electromagnetic oscillations to the system so as to compensate the loss of heat from particles to the fluidized flow. This approach has made it possible to establish the existence of an active heat-transfer zone in which the temperature of the medium varies exponentially, and not linearly as had been assumed previously. This meant that the coefficients of heat transfer between the particles and the flow did not depend on the height of the bed. The results simplified the computational procedure and have been instituted in a number of enterprises. It was simultaneously possible to develop and implement a simple method for the protection of thermocouples against the action of magnetic fields; this feature later proved to hold considerable promise for the design of new technological processes operating under conditions where the system is subjected to high-potential magnetic fields.

Investigations of the hydrodynamics and external heat transfer with bodies immersed in a layer have important bearing on the theory and practical application of disperse systems. These investigations, which are concerned primarily with the detailed structure of such disperse systems as gas, liquid, gas—liquid (three-phase), and vibrating fluidized beds, lend insight into the mechanism of the phenomena and make it possible to formulate models of the processes and to intensify heat- and mass-transfer processes on the basis of the models.

A gas-fluidized bed has been studied by V. N. Korolev, A. A. Morilov, and V. M. Kulikov under the direction of N. I. Syromayatnikov [17-25]. It was established that the immersion of a body in a layer leads to reorganization of the velocity field of the gas; the velocity in this case is a minimum in the free volume (core of the bed) and is a maximum near the surface of the body. The local velocities of the gas in the core of the bed decrease [17], and the immersion of a body in the bed results in the cessation of fluidization at fluidization numbers of 1.05-1.1.

The onset of excess gas flows along immersed bodies promotes the intensification of pulsating pseudoturbulent motion of both the individual particles and of entire particle clusters, i.e., results in better mixing. This makes it possible to explain the intensification of external heat transfer in a fluidized bed in comparison with transfer in a single-phase flow and to predict the behavior of the local coefficient of heat transfer along the surface. In particular, it is natural to expect the heat-transfer coefficient to have its maximum values on the part of the surface of plate where bubbles are formed in the vicinity.

The temperature fluctuations in the wall layer were determined experimentally by means of a hot-wire probe, and the porosity fluctuations were determined by x-ray scanning of the layer. The processes of formation of the wall zone were recorded simultaneously on high-speed motion pictures. It was established that the thickness of the wall zone, in which the packets of particles break up and the system virtually loses its macrodispersity, is approximately equal to five particle diameters in an inhomogeneous bed. The porosity in this zone, as opposed to the core of the system, varies continuously rather than discretely (packets of particles — gas voids), as is postulated in the two-phase theory [18]. The computer-calculated cross-correlation coefficients of the porosity and temperature fluctuations for fully developed fluidized beds are close to unity, i.e., a fairly strong stochastic correlation exists between these quantities [19]. The heat-transfer rate is also related to the porosity, and the maximum heat-transfer coefficients correspond to the period of contact between the surface and the hydrodynamic wake of the particles moving after a gas void [20]. When the heat-transfer surface is in contact with dense injected aggregates of low-mobility particles, the instantaneous values of the heat-transfer coefficients are lower than the average. The comparatively high values of the heat-transfer coefficients are mainly attributable to the hydrodynamic unsteadiness of the boundary layer in the disperse system. The boundary layer begins to rearrange at the instant of arrival of the tip of a gas void at the heat-transfer surface, but the small duration of contact with the pure void prevents the boundary layer from forming and causes the transfer rate to be quite high [21].

The structural and hydrodynamic characteristics of the wall zone vary not only in time, but also in space. Three principal zones can be discerned along the height of the body: the lower zone, in which convective heat transfer is dominant since the structure of the layer resembles the structure of a weakly dust-laden flow; the middle or equatorial zone, in which the process closely resembles heat transfer in once-through disperse flows with an elevated particle density; the upper zone, which is typified by conductive heat transfer toward the dense layer of particles [22]. Surface roughness can exert an additional influence on the structure, hydrodynamics, and therefore the heat transfer [23]. It has been shown experimentally that an increase of the roughness for beds of fine particles (with diameters smaller than 0.32 mm) tends to reduce the heat-transfer rate in comparison with a smooth surface. This is associated with an increase in the thickness of the gas interlayer between the surface and the particles and also with an increase in the particle density near the surface due to the slowing action of roughness elements.

Structural and hydrodynamic irregularities around the circumference of the body also impart nonuniformities to the heat transfer. One of the ways to equalize the structure of a fluidized bed in the vicinity of an immersed body is by rotation or spinning [24]. The heat-transfer rate becomes especially high in the vicinity of fluidization numbers close to unity. The maximum heat-transfer rate (for spinning at 4-7 rps) is almost six times higher for particles of diameter 0.18 mm than for a stationary cylinder at a fluidization number of 1.2. This is explained by an increase in the flocculation of the bed in the wall zone of the spinning cylinder, so that drag is reduced, the velocity of the gas increases, and particles near the heat-transfer surface are subjected to additional turbulence.

Studies of heat and mass transfer between the bed and developed surfaces in the form of horizontal or vertical bundles of tubes are of practical interest. The optimum composition of a horizontal bundle immersed in a gas-fluidized bed in the heat-transfer sense has been determined experimentally [25]. Similar hydrodynamic and heat-transfer investigations have been reported for bundles of tubes immersed in a vibrating fluidized bed.

When bundles of horizontal tubes are placed in the bed, where they are rigidly connected to the vibrating surface, the tubular elements comprise additional sources of vibratory action on the friable material, making it possible to vibrate and fluidize beds of considerable height. The nature of the flow around the tubes in a bundle has been investigated by means of x rays and high-speed motion pictures [26, 27]. The heat-transfer rate is determined by the shape and dimensions of the boundary zone; the maximum heat transfer is observed on the side regions of the tubes [28]. Stagnation zones are created in the corridors between mutually facing tube surfaces, so that the heat-transfer coefficients are a minimum in those zones. Stagnation zones do not occur in staggered bundles, and the heat-transfer coefficients are higher on the fore and aft surfaces than on the side regions.

It has also been learned that the heat-transfer rate does not depend on the type of bundle [29] for small vibration parameters. With an increase in the vibration parameters, the heat-transfer rate in a staggered bundle is higher than for a solitary tube [27].

A study of the variation of the rate of heat transfer localized along the height of vertical bundles of tubes has disclosed zones of elevated and reduced heat-transfer coefficients [30]. The reduced zone is observed in the middle part of the bed and increases considerably with the height of the bed. An increase in the vibration parameters only slightly affects the dimensions of this zone; heat transfer is intensified mainly in the upper part of the bed.

The nonuniformity of the heat transfer along the height of vertical tubes and around the circumference of horizontal tubes is preserved with an increase in the moisture content of the bed [31]. The dependence of the average heat-transfer coefficients on the moisture content exhibits a complex behavior, which differs for porous and nonporous materials; this result can be explained within the framework of the model of guided-wave pulse propagation in the vibrating bed.

The heat transfer can be further intensified by using artificially roughened surfaces [32]; the roughness can be regarded as heat-transfer-enhancing microridges.

The behavior and heat transfer of bodies loaded freely into a vibrating fluidized bed have been exhaustively studied [33-35]. It was discovered that the lower surface of a body in the immersed state provides the main contribution to the average heat-transfer coefficient. A kind of disperse cushion is formed beneath this surface, where its properties determine the supporting power, and the heat-transfer rate of free-floating bodies is higher than for bodies fixed in space. The heat-transfer coefficient increases with the vibration parameters and decreases with an increase in the particle diameter.

Experiments on the hydrodynamics and heat transfer of finely disperse materials on a steep-slanted vertically vibrating surface have established the fact that they can exist in the quiescent, vibrating-fluidized, and fountain states [36, 37]. The results of the investigation have been generalized in the form of equations in dimensionless groups and can be utilized in the development of vibration equipment for solid-phase heterogeneous processes.

The intensification of heat transfer in a liquid fluidized bed has been achieved in experimental studies by the injection of a wall jet of liquid and by the application of a water—air mixture as the fluidizing medium (gas—liquid fluidization) [38, 39]. Investigations of the hydrodynamics and heat transfer in a vertical annular duct have shown that the porosity of the bed and the distribution of gas in the liquid are affected by the velocity of the fluidizing components, the particle material, and the particle diameter. Moreover, the injection of gas into the liquid bed can either increase or decrease the height of the bed, depending on the diameter and concentration of the particles. The intensification of heat transfer in a gas—liquid fluidized bed in comparison with liquid fluidization can be attributed to the additional turbulence of the flow as a result of air bubbles transmitted through the bed. The results have been processed in the form of similarity equations and utilized in the design of ore-enrichment equipment.

Investigations have long been underway at the department on the hydrodynamics, heat transfer, and thermodynamics of aerocolloidal flows over a wide range of solid-particle concentrations [40-44]. The structure of the boundary layer in the flow of an aerocolloid over a plate has been studied by heat-ray photography [41]. It was observed by this technique that the heat transfer in low-concentration flows can be intensified by breaking up the trail of particles that forms near the edge of the boundary layer. The particle trail can be broken up and the heat-transfer coefficient tripled by generating a pulsating aerocolloidal flow [42]. The effect is maximized when the frequency of the forced mass-flow pulsations is equal to 1-5 Hz. The presence of solid particles in the flow affects the aerocolloidal flow regime. It has been established experimentally that the critical Reynolds numbers depend on the particle concentration and differ from the values for the pure gas; in particular, laminar flow of a low-concentration aerocolloid in a circular tube is maintained only up to Reynolds numbers equal to half the value for pure air. At concentrations above 5 kg/kg the critical Reynolds numbers increase with the concentration, attaining a value of 5000. At concentrations above 25 kg/kg the transition regime no longer exists, and the laminar regime is superseded by the abrupt onset of turbulence over the entire length of the tube [43, 44].

Studies of jet-fluidization processes, including the heat transfer of planar bodies on an airjet cushion, are of considerable importance [45-48]. Hot-wire anemometer experiments have disclosed that the vibrations of bodies on a gas cushion and their lengthwise motion do not affect the heat-transfer rate. The self-similarity of the motion indicates the absence of resonance effects and accounts for the uniform heat-transfer rate for a body in the free and fixed states on gas jets. The structure of a single impact jet has been investigated by means of miniature velocity-type flowmeters and flow visualization according to Taylor's method; the results show that the basis of turbulence generation in an impact gas jet comprises vortices of the Taylor—Goertler type [46]. The principal difference in the proposed jet model from its predecessors is the introduction of a region dominated by helical motion of the gas. This model can be used to explain the fundamental laws governing local heat transfer in the impact of a jet against a barrier, along with the strong dependence of the heat-transfer rate on artificial turbulence in such systems.

Experiments on jet cooling of the walls of fire tubes for the combustion chambers of gas-turbine power plants have shown that a jet system can provide the required wall temperature for any position of the system relative to the freestream gas flow [47]. The causes of deformation, warping, and premature wear of the fire tubes have been investigated for the combustion chambers of plants operating on a gas-supply compressor, and ways to improve existing cooling systems have been indicated [48].

LITERATURE CITED

1. G. P. Yasnikov, Inzh.-Fiz. Zh., 38, No. 1, 78-84 (1980).
2. G. P. Yasnikov and V. S. Belousov, Inzh.-Fiz. Zh., 46, No. 4, 605-613 (1984).
3. Yu. A. Buevich and G. P. Yasnikov, Inzh.-Fiz. Zh., 44, No. 3, 489-504 (1983).
4. G. P. Yasnikov and V. S. Belousov, Inzh.-Fiz. Zh., 34, No. 6, 1085-1089 (1978).

5. G. P. Yasnikov and V. S. Belousov, Inzh.-Fiz. Zh., 34, No. 5, 833-838 (1978).
6. G. P. Yasnikov and V. S. Belousov, Inzh.-Fiz. Zh., 43, No. 5, 733-740 (1982).
7. G. P. Yasnikov, L. G. Gal'perin, and Z. N. Kutyavin, Inzh.-Fiz. Zh., 39, No. 2, 334-338 (1980).
8. L. K. Vasanova, A. I. Safronov, and G. P. Yasnikov, Inzh.-Fiz. Zh., 41, No. 5, 838-842 (1981).
9. G. P. Yasnikov and F. A. Kuminov, Inzh.-Fiz. Zh., 47, No. 1, 116-124 (1984).
10. H. S. Mickley and D. F. Fairbanks, AIChE J., 1, No. 1, 374-386 (1955).
11. E. M. Tolmachev, Inzh.-Fiz. Zh., 37, No. 4, 609-612 (1979).
12. V. S. Belousov, Yu. A. Buevich, and G. P. Yasnikov, Inzh.-Fiz. Zh., 48, No. 4, 602-609 (1985).
13. L. K. Vasanova, Yu. G. Savinykh, A. I. Safronov, and G. P. Yasnikov, Inzh.-Fiz. Zh., 47, No. 4, 630-635 (1984).
14. G. P. Yasnikov, Inzh.-Fiz. Zh., 42, No. 2, 243-250 (1982).
15. N. I. Syromyatnikov, L. K. Vasanova, and Yu. N. Shimanskii, Heat and Mass Transfer in the Fluidized Bed [in Russian], Moscow (1967).
16. J. S. M. Botterill, Fluid-Bed Heat Transfer; Gas-Fluidized Bed Behavior and Its Influence on Bed Thermal Properties, Academic Press, London—New York (1975).
17. Yu. A. Buevich [Buyevich], V. N. Korolev [Korolyov], and N. J. Syromyatnikov [Syromjatnikov], Preprint of Report at the Sixteenth ICHMT International Symposium on Heat and Mass Transfer in Fized Beds, Dubrovnik, Yugoslavia (1984).
18. V. M. Kulikov, V. N. Korolev, and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 29, No. 2, 220-224 (1975).
19. N. I. Syromyatnikov, V. N. Korolev, and V. M. Kulikov, Dokl. Akad. Nauk SSSR, 219, No. 4, 853-855 (1974).
20. V. M. Kulikov, V. S. Nosov, V. N. Korolev, et al., Inzh.-Fiz. Zh., 30, No. 6, 986-995 (1976).
21. N. I. Syromyatnikov, V. M. Kulikov, V. S. Nosov, and V. N. Korolev, in: Heat and Mass Transfer-5 [in Russian], Vol. 6, Minsk (1976), pp. 107-116.
22. V. S. Nosov, V. N. Korolev, V. L. Gapontsev, et al., in: Heat and Mass Transfer-6 [in Russian], Vol. 6, Part 1, Minsk (1980), pp. 25-29.
23. V. N. Korolev and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 28, No. 6, 977-980 (1975).
24. V. N. Korolev, I. A. Osintsev, and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 52, No. 1, 5-9 (1987).
25. V. N. Korolev and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 38, No. 5, 829-835 (1980).
26. G. D. Kosenko, E. G. Reshetnikov, B. G. Sapozhnikov, and N. I. Syromyatnikov, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1, 161-165 (1979).
27. N. I. Syromyatnikov, V. N. Korolev, and B. G. Sapozhnikov, Izv. Vyssh. Uchebn. Zaved., Énerget., No. 2, 41-50 (1979).
28. B. G. Sapozhnikov, G. D. Kosenko, E. G. Reshetnikov, and N. M. Kharisova, in: Heat and Mass Transfer-5 [in Russian], Vol. 6, Minsk (1976), pp. 275-284.
29. B. G. Sapozhnikov, G. D. Kosenko, and E. G. Reshetnikov, Teor. Osn. Khim. Tekhnol., 11, No. 4, 622-625 (1977).
30. G. V. Sapozhnikov, N. I. Syromyatnikov, and B. G. Sapozhnikov, Inzh.-Fiz. Zh., 47, No. 3, 483-484 (1984).
31. G. V. Sapozhnikov, N. I. Syromyatnikov, and B. G. Sapozhnikov, Izv. Vyssh. Uchebn. Zaved., Énerget., No. 4, 96-99 (1983).
32. B. G. Sapozhnikov, P. V. Khlyupin, and A. M. Sviridov, Zh. Vses. Khim. Obshch., 21, No. 2, 229-230 (1976).
33. A. V. Blinov, B. G. Sapozhnikov, and N. I. Syromyatnikov, Zh. Vses. Khim. Obshch., 27, No. 6, 111-112 (1982).
34. N. I. Syromyatnikov, V. N. Korolev, A. V. Blinov, et al., in: Heat and Mass Transfer-7 [in Russian], Vol. 5, Part 1, Minsk (1984), pp. 48-54.
35. A. V. Blinov, B. G. Sapozhnikov, and N. I. Syromyatnikov, in: Heat and Mass Transfer in Technological Processes and Equipment [in Russian], Minsk (1985), pp. 93-98.
36. V. V. Ogloblin, G. D. Kosenko, E. G. Reshetnikov, and B. G. Sapozhnikov, Zh. Prikl. Khim., No. 4, 805-808 (1984).
37. V. V. Ogloblin, G. D. Kosenko, E. G. Reshetnikov, and B. G. Sapozhnikov, Izv. Vyssh. Uchebn. Zaved., Éneget., No. 11, 88-93 (1978).
38. N. I. Syromyatnikov, L. K. Vasanova, G. P. Yasnikov, et al., in: Heat and Mass Transfer-6 [in Russian], Vol. 6, Part 1, Minsk (1980), pp. 50-57.

39. V. S. Belousov, L. K. Vasanova, A. P. Polozov, et al., in: Heat and Mass Transfer-7 [in Russian], Vol. 5, Part 1, Minsk (1984), pp. 93-97.
40. V. S. Nosov, I. D. Larionov, and V. V. Mamaev, in: Heat and Mass Transfer-5 [in Russian], Vol. 6, Minsk (1976).
41. V. V. Mamaev, V. S. Nosov, and N. I. Syromyatnikov, Izv. Vyssh. Uchebn. Zaved., Énerget., No. 9, 95-98 (1975).
42. V. V. Mamaev, V. S. Nosov, and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 31, No. 5, 815-820 (1976).
43. V. V. Mamaev, V. S. Nosov, and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 37, No. 1, 35-42 (1979).
44. V. S. Nosov, in: Heat and Mass Transfer and Nonequilibrium Thermodynamics of Disperse Systems [in Russian], No. 227, Sverdlovsk (1974), pp. 61-68.
45. B. P. Zhilkin and N. I. Syromyatnikov, Dokl. Akad. Nauk SSSR, 234, No. 4, 784-786 (1977).
46. B. P. Zhilkin and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 33, No. 1, 26-31 (1977).
47. N. I. Syromyatnikov, V. N. Korolev, B. P. Zhilkin, et al., Énergomashinostroenie, No. 12, 35-36 (1979).
48. V. N. Korolev, K. F. Ott, V. V. Startsev, and E. M. Tolmachev, Prom. Teplotekh., 6, No. 4, 64-67 (1984).