3. A. J. Klee and R. E. Treyball, AIChE J., 2, No. 4, 444-447 (1956).
4. P. M. Krishna, D. Venkateswarlu, and G. S. R. Narasimhamurty, J. Chem. Eng. Data, 4, No. 4, 340-343 (1959).
5. J. R. Grace, T. Wairegi, and T. H. Nguen, Trans. Inst. Chem. Eng., 54, No. 3, 167-173 (1976).
6. B. M. Grakhovskii and T. A. Pol'skaya, Motion of Gas Bubbles and Drops in Supercritical Region. Paper No. 921 Deposited at VINITI [in Russian], Moscow (1979).
7. H. Tsuge and S. Hibino, J. Chem. Eng., 10, No. 1, 66-68 (1977).
8. F. H. Peebles and H. J. Garber, Chem. Eng. Prog., 49, No. 2, 88-97 (1953).
9. A. Reinhart, Chem. Ing. Tech., 36, No. 7, 740-747 (1964).
10. A. J. Johnson and L. Braida, Can. J. Chem. Eng., 35, No. 4, 165-172 (1957).
11. I. I. Ponikarov, V. V. Kafarov, and O. A. Tseitlin, Zh. Prikl. Khim., 45, No. 7, 1517-1522 (1972).
12. O. A. Tseitlin and I. I. Ponikarov, Teor. Osnov. Khim. Tekhnol., 13, No. 1, 131-134 (1979).
13. I. I. Ponikarov, V. V. Kafarov, and O. A. Tseitlin, Zh. Prikl. Khim., 45, No. 3, 560-564 (1972).
14. O. A. Tseitlin and I. I. Ponikarov, Teor. Osnov. Khim. Tekhnol., 13, No. 2, 301-303 (1979).
15. O. A. Tseitlin and I. I. Ponikarov, in: Abstracts of the Proceedings of the All-Union Conference on Extraction and Separation [in Russian], Vol. 1, Riga (1982), pp. 67-70.

USING THE ISENTROPIC INDEX TO CALCULATE THE PARAMETERS OF TWO-PHASE FLOW

V. V. Fisenko, V. E. Cheremin,
I. A. Ivakhnenko, and O. E. Zoteev

A method of determining the volume vapor content in two-phase mixture is proposed, on the basis of the relation between the isentropic index of the mixture and the "frozen" sound velocity there.

In the gas dynamics of an ideal gas, the isentropic index

$$k = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s \qquad (1)$$

is used as an effective quantity permitting sufficiently fast and reliable calculation, using gas-dynamic functions, of all the necessary parameters of ideal-gas flow: the pressure, temperature, and density [1, 2]. Here k is usually assumed to be constant for each specific gas over the whole of the practical pressure and temperature ranges, and depends basically only on the number of rotational degrees of freedom of the gas molecule [2]. For water vapor ($\delta_{ro} = 3$)

$$k = \frac{5 + \delta_{ro}}{3 + \delta_{ro}} = \frac{8}{6} = 1{,}333 \ldots$$

Taking into account that the gas (vapor) system is only a particular, limiting case of the multiphase liquid–gas (vapor)–solid particle system, it is natural that the scope of use of the isentropic (adiabatic) index of the mixture must be broadened for such systems. In this case, it becomes a function of the temperature, pressure, and gas content [2, 3].

Consider the propagation of a weak perturbation wave in a two-phase mixture, assuming that the distribution of one phase in the other is arbitrary and the mixture may be both in a state of rest and in a state of motion.

An expression is now written for the specific entropy of this mixture at any time

$$s_{mi} = s_{1i}(1 - x) + s_v x.$$

Differentiation gives

$$ds_{mi} = (1 - x)\,ds_{1i} + x\,ds_v - s_{1i}\,dx + s_v\,dx. \tag{2}$$

The conditions under which the propagation of the perturbation in the mixture is always isentropic, regardless of the mixture composition and the character of the perturbing factor, are now determined, setting the right-hand side of Eq. (2) equal to zero. After the necessary algebraic transformations and taking into account that $ds_{1i} = dq_{1i}/dT_{1i}$, $ds_v = dq_v/T_v$, $dq_{1i} = -dq_v = dq$, it is found that

$$\left(\frac{x}{T_v} + \frac{1 - x}{T_v} \right) dq + (s_v - s_{1i})\,dx = 0. \tag{3}$$

The simple trivial solution of Eq. (3) for any x, T_v, T_{1i}, s_v, and s_{1i} corresponds to the condition dq = 0, which leads automatically to dx = 0.

In physical terms, the solution obtained indicates that the propagation of small perturbations in a two-phase mixture is always isentropic if there is no heat or mass transfer between the phases. Note that, apart from the requirement that dq = 0, no constraints at all are imposed on the mechanical and thermal characteristics of the phases, i.e., slipping, temperature disequilibrium, and so on are possible between the phases. As shown below, such a limitingly nonequilibrium process is the propagation of sound waves in two-phase media.

Assuming that $T_v = T_{1i} = T$, Eq. (3) takes the form

$$\frac{dq}{T} + (s_v - s_{1i})\,dx = 0. \tag{4}$$

Substituting the known thermodynamic relations for wet vapor $s_v - s_{1i} = r/T$ and $dq = c_x dT$ into Eq. (4), the result obtained is

$$c_x dT + r\,dx = 0, \tag{5}$$

which describes the change in the parameters in wet vapor in a limiting equilibrium adiabatic process which is simultaneously isentropic [2].

In the context of the above analysis, it becomes clear that, in the context of a two-phase system and, in particular, a two-phase single-component system, the concept of the isentropic (or adiabatic) index takes on a more profound meaning than in the the case of an ideal gas. This complex now becomes not only the most important index of the process in which ds = 0 but also characterizes the interphase state in the mixture. It ceases to be a single-valued function of the volume vapor content, thermodynamic parameters of the phases, etc., and is determined, apart from everything else, by the degree of disequilibrium in the volume processes and, in the general case, may vary over very broad limits with absolutely identical parameters of the phases: from sufficiently large values — in the single and double figures — in the limitingly disequilibrium process to a few tenths in the limitingly equilibrium process [3-5]. The influence of the degree of disequilibrium between the phases on the adiabatic index of two-phase flow was considered in sufficient detail in [6, 7]; this problem is not discussed here.

Assuming that the liquid phase in the mixture is incompressible (dv' = 0) and exchange processes are completely frozen (dx = 0, dq = 0), it may be found that

$$dv = d\,[v'(1 - x) + v'' x] = x\,dv''.$$

The Poisson differential adiabatic equation for the vapor gives

$$dv'' = -\frac{v''}{k_v}\frac{dp}{p}.$$

Substituting these relations into Eq. (1) gives

$$k = -\frac{v}{p}\left(-x\,\frac{v''}{k_v p}\,dp \right)^{-1} dp = \frac{vk_v}{v'' x} = \left[\frac{v'}{v''}(1 - x) + x \right]\frac{k_v}{x}.$$

Since the relation between the volume and mass degrees of dryness in the absence of slip between the phases is expressed as follows

$$\beta = \left[\left(\frac{1}{x} - 1 \right) \frac{v'}{v''} + 1 \right]^{-1},$$

a simple formula is hence obtained for the calculation of the limitingly disequilibrium isentropic index for vapor—liquid and gas—liquid mixtures

$$k = k_{\text{v}}/\beta. \tag{6}$$

If the compressibility of the liquid phase must be taken into account ($dv' = 0$), then [7]

$$k = \left\{ \beta \left[\frac{1}{k_{\text{v}}} + \frac{1}{k_{1\text{i}}} \left(\frac{1}{\beta} - 1 \right) \right] \right\}^{-1}.$$

Expressions for the limitingly equilibrium isentropic index in various forms were derived in [2, 3].

At present, it has been established by numerous theoretical and experimental investigations that, in a broad frequency which is of practical interest, the propagation of small perturbations in a two-phase medium may be regarded as limitingly nonequilibrium [3, 4, 8, 9]. This allows k to be determined using a dependence for the sound velocity which is also valid in a limitingly equilibrium process [2]

$$a = \sqrt{- v^2 \left(\frac{\partial p}{dv} \right)_s} = \sqrt{kpv};$$

this describes the propagation of sound waves in a medium with any degree of compressibility [5]. As shown below, this relation is especially promising for use for two-phase media with a high degree of compressibility [5]. Thus, the problem of finding k in the given cross section and for the given mixture may be reduced to finding the sound velocity in this cross section and then determining

$$k = a^2/pv. \tag{7}$$

In connection with this, it is of special interest to investigate the emission of effervescing liquids and two-phase mixtures through cylindrical outlets and nozzles, where a flow velocity equal to the local "frozen" velocity of sound is established in critical outflow conditions in a cross section close to the outlet cross section [8]. But then, on the basis of the above analysis of Eq. (3), it may be said that there must be sharp reduction in all dissipative losses in the near-outlet section, which may be called the region of "degenerating turbulence," by analogy with gas outflow [1]. For a gas, the reduction in drag coefficient of the smooth tube at Mach numbers close to unity was observed experimentally by Gukhman and Gandel'sman. An analogous result was established in the emission of effesvescing water heat carrier from long pipelines [5]. This permits the hypothesis that, at near-unity Mach numbers, i.e., when the compressibility of the medium begins to play a determining role, ideal-gas properties begin to appear. In fact, the sufficient condition here is that the streamlines be parallel and frictional forces be zero. For two-phase flow, this permits (in the first approximation) the use of isentropic formulas obtained for an ideal gas in calculating the critical pressure ratio [1, 5]

$$\varepsilon_* = \left(\frac{2}{k_{*s} + 1} \right)^{\frac{k_{*s}}{k_{*s}-1}}. \tag{8}$$

The critical pressure p_* may be found sufficiently easily from the point of inflection on the static-pressure curve at the nozzle outlet [5]. Then Eq. (8) takes the form

$$\frac{p_*}{p_0 - \Delta p} = \left(\frac{2}{k_{*s} + 1} \right)^{\frac{k_{*s}}{k_{*s}+1}}. \tag{9}$$

Solving the transcendental Eq. (9) for k_{*s} with a definite form of the function Δp and the experimental value of p_*, the possible scope for use of Eq. (8) may be estimated.

In [5], a method was proposed for determining the limiting nonequilibrium isentropic index in the critical outlet cross section from experimental data on the effervescing-water output of cylindrical nozzles of great length ($L/D > 10$)

$$k_{*e} = (R_e/F + p_{\text{m}} - p_{*e}) p_{*e}^{-1}. \tag{10}$$
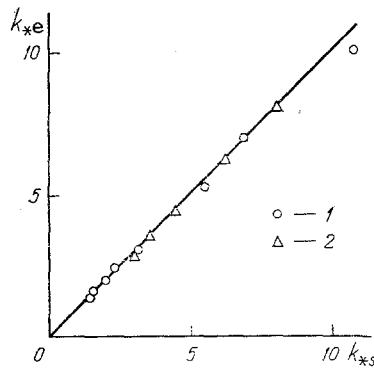
Fig. 1   Fig. 2
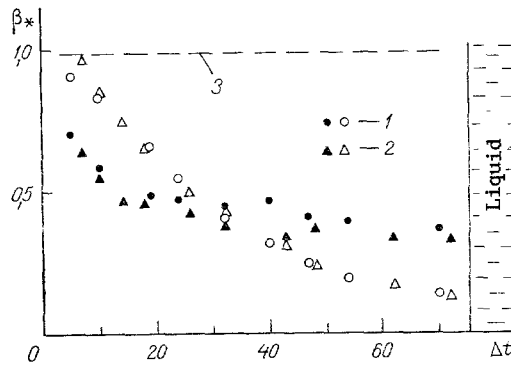
Fig. 1. Comparison of isentropic indices of steam–water flow
in the critical cross section; calculation according to Eqs.
(9) and (10): 1) L/D = 15.8; 2) 10.1.

Fig. 2. Volume vapor content in critical cross section according to Eq. (11) (open points) and Eq. (12) (dark points):
1) L/D = 15.8; 2) 10.1; 3) calculation of β_s according to the
isentropic equilibrium model [2].

A comparison of k_{*s} and k_{*e} is shown in Fig. 1. Two continuous cylindrical nozzles
wit a sharp inlet edge and a relative length L/D = 10.1 and 15.8 are used in the experiments.
The water pressure at the inlet is 1.0 MPa (constant). The temperature varies from 293 K to
~446-448 K. Dissipation is taken into account only in the form of pressure losses at the
sharp inlet edge: $\Delta p = 0.25 j_*^2 v'[1 - (D/D_0)^2]$, where $D_0 = 5 \cdot 10^{-2}$ m; $D = 8 \cdot 10^{-3}$ m.

Detailed description of the experimental apparatus and method and analysis of the results may be found in [5, 10].

As is evident from Fig. 1, the isentropic indices are sufficiently close, even though
they are calculated from formulas representing different approaches to the description of
processes in the critical cross section. This confirms the above hypothesis regarding the
character of the interphase processes occurring in the critical cross section.

The critical pressure ratio determined by Eq. (8) is a monotonically decreasing function of k_{*s}; hence it follows that, since the limitingly nonequilibrium isentropic index in
two-phase flow $k_{*,tp} > k_{*,v}$ [5], correspondingly $\varepsilon_{*,tp} < \varepsilon_{*,v}$. At the same time, experimental data for which $\varepsilon_{*,tp} > \varepsilon_{*,v}$ are fairly common in the literature. In particular, in
[11], it was found that $\varepsilon_{*,tp} = 0.8-0.7$ in investigating the critical outflow of effervescing
water and steam–water mixtures through long tubes; this is larger than the critical pressure
ratio for water vapor: $\varepsilon_{*,v} = 0.546$.

From the perspective of the thermodynamics of two-phase critical flows, this seeming
contradiction may be easily explained, in that in these experiments the critical pressure
was measured not precisely in the critical outlet cross section but some distance from it.
Since the static-pressure gradient in the near-outlet section is very large, this could
easily lead to considerable error in determining p_*. In our view, the critical pressure may
be most accurately found only by drawing a special probe (a capillary with a hole in the side
wall) along the channel and finding p_* as the point of inflection of the static-pressure
curve [5].

Equating the right-hand sides of Eqs. (6) and (10), the integral mean (over the cross
section) volume vapor content may be determined

$$\beta_* = \frac{k_v p_{*e}}{R_e/F + p_m - p_{*e}}. \tag{11}$$

In the method of calculating the critical parameters outlined in [5], a formula for β_*
is proposed on the assumption that $\beta_* \rho_*'' \ll \rho_*'(1 - \beta_*)$

$$\beta_* = 1 - j_{*e}^2 v_{*e}'(R_e/F + p_m - p_{*e})^{-1}. \tag{12}$$

1310

Calculating the dependence of the volume vapor content on the underheating of the water at the nozzle inlet $\Delta t = t_S(p_0) - t_0$ according to Eqs. (11) and (12) shows (Fig. 2) that the method based on the concept of the isentropic index of two-phase flow (open points) gives more reliable results from a physical viewpoint both when $\Delta t \to 0$, where $\beta_* \to \beta_S$, and when $\Delta t \to 80$ K, where $\beta_* \to 0$ (hydraulic flow conditions). The isentropic equilibrium model yields a description of the volume vapor content in the critical cross section which is both qualitatively and quantitatively incorrect, primarily because of the high thermal disequilibrium in the flow [5].

The theoretical vapor content obtained may then be used to find the most important characteristics of two-phase flow in the critical and any other cross section: slipping of the phases, heating of the liquid phase relative to the equilibrium temperature and the flow may be analyzed using the isentropic index in practically any arbitrary cross section of the channel; it is sufficient to know the sound velocity there. This does not present particular difficulties in terms of experimental technique [3, 8, 9]. In this case, the volume vapor content may be found from the equation

$$\frac{a^2}{p}[\rho'(1-\beta) + \rho''\beta] = \frac{k\mathbf{v}}{\beta}, \tag{13}$$

which is valid if the true volume vapor content is equal to the flow-rate value. Assuming that $\rho'(1-\beta) \gg \rho''\beta$ at low pressures and temperatures, Eq. (13) may be reduced to the form

$$\beta^2 - \beta + \frac{k_\mathbf{v}p}{a^2\rho'} = 0, \tag{14}$$

and hence β may be determined.

Passing a beam of directed sound waves in fan-like fashion through a two-phase flow and determining their velocity experimentally, it is evidently possible to proceed to the determination of local characteristics in the cross section.

Probably on account of the pressure pulsations of considerable amplitude and frequency on passing through the upper or lower boundary curve [3], the given method may result in considerable errors in these regions, which have not been taken into account. Therefore, its use may be recommended in the region of developed two-phase flow, where the phases are uniformly mixed and the discontinuous phase is finely disperse (emulsional conditions).

The use of the given method in combination with methods of optical of γ illumination of the flow [3] and with various probes and samplers permits qualitative increase in the diagnostic level for two-phase flows.

NOTATION

s_{li}, entropy of liquid phase; s_v, entropy of vapor (gas) phase; x, mass degree of dryness; dq_{li}, dq_v, elementary heat transfer between liquid and vapor phases; T_{li}, liquid temperature; T_v, vapor temperature; r, specific heat of vaporization; c_x, specific heat in process with x = const; v, specific volume of mixture; v', v'', specific volumes of liquid phase at the left-hand boundary curve and of the vapor phase at the right-hand boundary curve; k_v, k_{li}, adiabatic indices of vapor (gas) and liquid phases; p_*, static pressure of mixture in critical cross section; p_0, initial stagnation pressure; k_{*s}, isentropic index in critical cross section; k_{*e}, isentropic index in critical cross section found experimentally; F_e, reactive force found experimentally; p_m, pressure of surrounding medium; p_{*e}, static pressure of mixture in critical cross section found experimentally; Δp, dissipative pressure loss in channel; $\rho_* = 1/v_*'$, specific density of liquid phase; $\rho_*'' = 1/v_*''$, specific density of vapor phase; j_{*e}, specific mass flow rate of mixture found experimentally; t_0, liquid temperature at channel inlet; L, D, channel length and diameter; D_0, diameter of supply channel.

LITERATURE CITED

1. M. E. Deich, Engineering Gas Dynamics [in Russian], Moscow (1974).
2. M. P. Vukalovich and I. I. Novikov, Thermodynamics [in Russian], Moscow (1972).
3. M. E. Deich and G. A. Filippov, Gas Dynamics of Two-Phase Media [in Russian], Moscow (1981).
4. V. V. Fisenko, Critical Two-Phase Flows [in Russian], Moscow (1978).
5. V. V. Fisenko, Compressibility of Heat Carrier and Efficiency of Operation of Circulatory Systems of Nuclear Power Plants [in Russian], Moscow (1987).

6. G. A. Filippov, E. V. Stekol'shchikov, and M. P. Anisimova, Teploénergatika, No. 3, 41-45 (1968).
7. A. L. Dushkin and A. I. Kolomentsev, in: Operating Process in Elements of Motors and Power Units with Two-Phase Working Medium [in Russian], Moscow (1980), pp. 8-15.
8. V. V. Fisenko, At. Tekh. Rubezh., No. 5, 41-47 (1977).
9. B. G. Pokusaev, in: Hydrodynamics and Heat Transfer in Two-Phase Media [in Russian], Novosibirsk (1981), pp. 81-90.
10. V. V. Fisenko et al., Izv. Vyssh. Uchebn. Zaved., Énerg., No. 1, 73-77 (1987).
11. H. Uchida and H. Nariai, in: Proceedings of Third Heat Transfer Conference, Vol. 5, Chicago (1966), pp. 1-12.

AERODYNAMICS OF A CIRCULATING FLUIDIZED BED

V. K. Maskaev, A. P. Baskakov,
A. G. Usol'tsev, and I. V. Ivanov

The authors present results of an experimental determination of the aerodynamic drag, density, velocity and dwell time of disperse material in a circulating bed.

It is known [1] that the region of stable pneumatic transport is determined by the speeds of the transporting gas, on the order of 10-15 m/sec. According to the data of [2], a reduction of the gas speed leads to increased slip velocity of the solid particles, accompanied by strong mixing of the material throughout the volume, predominantly ascending motion in the center of the channel, and sporadic slipping down motion along the walls.

The special features of the motion and distribution of the disperse material in the circulating bed, in comparison with pneumatic transportation, were studied on the extended experimental facility shown schematically in Fig. 1.

The facility consists of a channel 1 of internal diameter 250 mm, composed of 10 sections of length 950 mm each. The side surfaces of the sections had transparent windows for visual observation. The lowest section had a gas distribution grid 2 and performed the function of an aero chamber 3. The disperse material was supplied to the aero chamber from the storage bunker 4 via one of five interchangeable cantilevered screw-conveyer units 5, of internal diameter from 42 to 144 mm and volume rate up to 16.5 m³/hr. The feed drive was actuated by the motor 6 through a transmission 7 and a safety device 8. The air was supplied from the air blower 9 through one of six standard diaphragms 10-15, and its pressure was regulated by the dump slide-valve 16. At the exit from the experimental channel the gas plus suspension reached the cyclone 17 of the first stage of cleaning. The trapped disperse material was collected in the bunker 18, and passing successively through valves 19 and 20, was routed as need be into the charging bunker 21 or for unloading via the hatch 22 into the box 23. The semi-clean gas was directed via the blower 24 to the cyclones 25 of the second stage of cleaning. The solid particles from the last cyclones were poured into the bunker 26 and unloaded through the hatch 27 and the box 28. The dust-free gas went to the ventilation box 29. In case more cleaning was needed the semi-clean gas was directed by the blower 30 to the bag filter 31, whence it went to the ventilation box 32. The disperse material was returned via valve 33 to the charge bunker. The hopper 34 was used to load fresh material. The operation of all the valves was actuated by the drive 35 from the motor 36. The gases were pumped out by the fan 37.

In the tests as the finely dispersed material we used aluminum hydroxide with a mean-mass diameter of 49 μ, as per GOST 118441-76, from the Polevskyi factory, for which the fractional composition is as follows: