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EFFECT OF DIFFUSION CHANNEL INCLINATION ON STABILITY OF MECHANICAL EQUILIBRIUM IN ISOTHERMAL BINARY GAS MIXTURES

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Instability of mechanical equilibrium in isothermal binary gas mixtures is studied in experiments with different angles of inclination of the diffusion channel with respect to the vertical axis. As the angle of inclination is increased, the intensity of convective mass transfer is found to decrease and decay at a certain value of this angle. Experimental data are demonstrated to be consistent with estimates obtained from the linear stability theory.

Key words: *diffusion, convection, mixing of gases, instability of mechanical equilibrium of the gas mixture, linear stability theory, Rayleigh number, effect of diffusion channel geometry.*

As was demonstrated in experiments [1–3], instability of mechanical equilibrium of the system is observed in the case of isothermal diffusion of a binary gas mixture into the third species in a vertical or inclined channel. The emergence of convective structured flows is affected by various factors considered in [1–6], including the geometric characteristics of the diffusion channel and its inclination [7, 8].

The experiments performed in the present work are aimed at studying alternation of the regimes of diffusion and concentration gravitation convection, which is observed in the isothermal regime of obtaining simple binary Ar–He and Ar–N_2 mixtures with different angles of inclination of the channel. The results obtained are discussed within the framework of the linear stability theory [9, 10].

The experiments were performed by the method proposed in [2, 3] in a two-flask setup with the volumes of the upper and lower flasks $V_{\text{upper}} = 55.5 \cdot 10^{-6}$ m^3 and $V_{\text{lower}} = 54.1 \cdot 10^{-6}$ m^3, respectively. The diameter and length of the diffusion channel were $d = (4.50 \pm 0.01) \cdot 10^{-3}$ m and $L = (64.1 \pm 0.1) \cdot 10^{-3}$ m, respectively [1, 2]. The angle of inclination of the channel with respect to the vertical axis was changed in the range $\varphi = 0$–70°. The measurements were performed at a pressure $p = 0.584$ MPa and a temperature $T = (298.0 \pm 0.1)$ K. In both binary systems, the heavier species (having a greater density) was located in the upper flask, and the lighter species was located in the lower flask (Fig. 1). The pressure of the gases in the flasks was measured by standard pressure gauges. When the procedure of pressure equalization was completed, the diffusion channel was disconnected from the system of gas preparation and was fixed on the setup at a needed angle. The diffusion channel was opened by upraising a rod with a fluoroplastic pellet, and the time corresponding to the process beginning was registered. After the experiment, the flasks were disconnected, and the transfer time was registered. The composition of the gas mixtures in both flasks was analyzed by an ITR-1 interferometer with an error of 0.1% or by a chromatograph with an error of 0.3%. Several measurements were performed under identical test conditions, and the mean values of species concentrations were determined. After that, the diffusion channel was aligned at a different angle, and the procedure was repeated. In all cases, the test time was 17 min.

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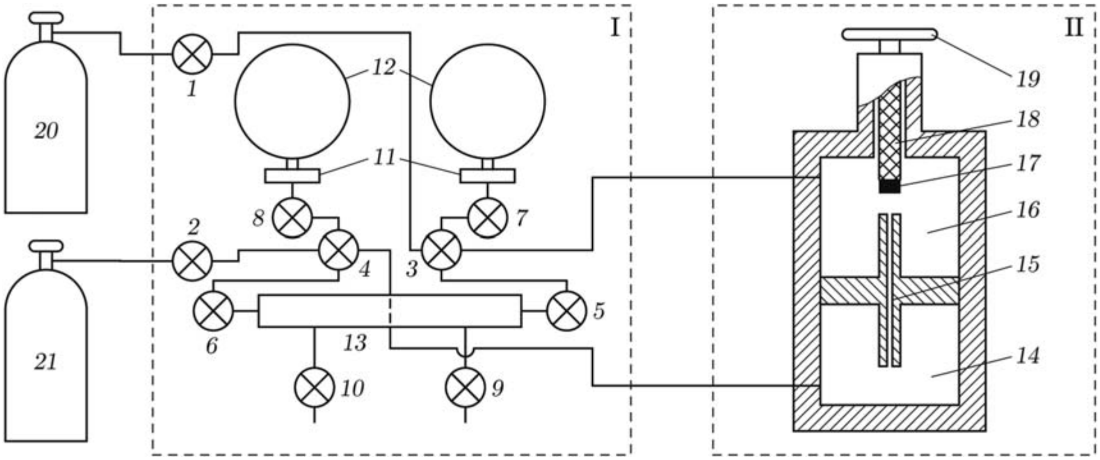

Fig. 1. Experimental setup: the block for gas preparation and the two-flask diffusion setup are indicated by I and II, respectively; valves (1–8), valve connected to the backing vacuum pump (9), valve connected to the interferometer or chromatograph (10), membrane partitions (11), standard pressure gauges (12), equalizing tank (13), lower flask (14), diffusion channel (15), upper flask (16), fluoroplastic pellet (17), rod (18), flywheel (19), and gas holders (20 and 21).

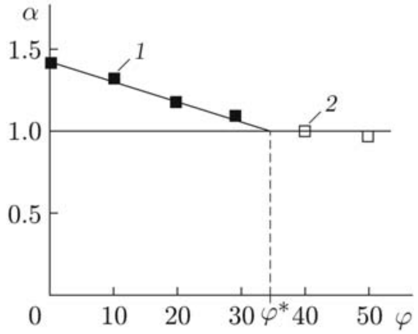

Fig. 2. Parameter α versus the angle of inclination φ for the Ar–N$_2$ mixture at $p = 0.584$ MPa and $T = 298$ K: unstable regime (1) and diffusion regime (2).

The experimentally obtained values (concentrations of the diffused species) were normalized to the values calculated by the formula [2]

$$\frac{\Delta c_t}{\Delta c_0} = \exp\Big[-\frac{(D_0)_{12} p_0 S t}{L p}\Big(\frac{1}{V_{\text{upper}}} + \frac{1}{V_{\text{lower}}}\Big)\Big],$$

where Δc_0 and Δc_t are the differences in species concentrations at the initial time and at the time t, respectively, S is the area of the diffusion channel, t is the time, and $(D_0)_{12}$ is the coefficient of mutual diffusion of the examined pair of gases, which was taken to be $(D_0)_{12} = 0.745 \cdot 10^{-4}$ m^2/sec for the Ar–He mixture and $(D_0)_{12} = 0.211 \cdot 10^{-4}$ m^2/sec for the Ar–N$_2$ mixture. Figure 2 shows the thus-obtained dependence of the ratio $\alpha = \Delta c_{\text{exp}}/\Delta c_{\text{theor}}$ on the angle of inclination φ for the Ar–N$_2$ mixture (Δc_{exp} and Δc_{theor} are the experimental and theoretical differences of concentrations of the mixture in the upper and lower flasks at 17 min after the beginning of their mixing).

It is seen in Fig. 2 that the mechanical equilibrium in the system considered is unstable if the angle of inclination is $\varphi = 0$. As the angle of inclination is increased, the convective flow intensity decreases. At an angle of inclination $\varphi^* \simeq 34^\circ$, the mixing in the system acquires a diffusion character, which is evidenced by the coincidence of the concentrations obtained in experiments and calculated under the assumption that the concentrations are changed owing to diffusion. A similar character of mixing under the conditions considered was also observed for the Ar–He binary mixture.

The dependence of the critical Rayleigh number on the mode of disturbances and on the angle of inclination of the channel has the following form in the first approximation [10]:

$$\mathrm{R}_n = (n\pi)^4/\cos^2\varphi \tag{1}$$

[$n = p/(kT)$ is the concentration of the species and k is the Boltzmann constant].

Using experimental data obtained for a cylindrical channel, we can write the expression for the critical Rayleigh number in accordance with Eq. (1) as

$$\mathrm{R}_1(\varphi) = \mathrm{R}_1(0)/\cos^2\varphi,$$

where $\mathrm{R}_1 = gr^4 n\,\Delta m\,\Delta c/(\rho_0\langle\nu\rangle D_{12}L)$ is the Rayleigh number for the system considered, g is the free-fall acceleration, r is the diffusion channel radius, $\Delta m = m_1 - m_2$ is the difference between the molecular weights of the species, ρ_0 is the mean density of the mixture, $\langle\nu\rangle$ is the mean kinematic viscosity, and Δc is the difference in species concentrations in the upper and lower flasks.

As the transition from convective to diffusion mixing in the experiments performed occurs at $\varphi^* \approx 34°$, we use the value $\mathrm{R}_1 = 115$ obtained in experiments at this angle of inclination and find that $\mathrm{R}_1 = 79$ at $\varphi = 0$. This value is in good agreement with the known critical value of the Rayleigh number for an infinite vertical cylinder $\mathrm{R}_{\mathrm{cyl}} \approx 67.95$ [10]. Thus, the experimental data are consistent with theoretical values predicted by the stability theory.

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