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NUMERICAL INVESTIGATION OF THE EFFECT OF INCLINATION ANGLE ON THE STABILITY OF MECHANICAL EQUILIBRIUM IN Ar–N_2 BINARY GAS MIXTURES

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Abstract. This work presents a numerical study of the influence of the diffusion channel inclination angle on the stability of mechanical equilibrium and mass transfer in a binary Ar–N_2 gas mixture under gravity. Isothermal mixing in a two-flask apparatus is considered, where the loss of mechanical equilibrium results from unstable concentration-induced density stratification during mutual diffusion of components with different molecular weights. The resulting concentration-driven gravitational convection strongly affects both the rate and structure of mass transfer.

The aim of the study is to determine how the channel inclination angle influences diffusion–convective regimes under fixed thermobaric conditions. Numerical simulations were performed in ANSYS Fluent using a three-dimensional formulation with species transport equations and the k–ω turbulence model. The geometry and boundary conditions correspond to laboratory experimental conditions. Calculations were conducted for inclination angles of 0°, 10°, 20°, and 30°, with analysis of concentration fields, velocity distributions, and integral mixing characteristics.

The results show that increasing the inclination angle leads to a gradual weakening of concentration-driven convection due to the reduction of the gravitational acceleration component along the channel axis. This is reflected in lower convective intensity, reduced argon transfer to the lower flask, and smoother temporal concentration variations. At 30°, the system approaches a diffusion-dominated regime. The findings agree with the theoretical dependence of the critical Rayleigh number on cosφ and reproduce experimental trends, confirming the validity of the numerical model and the applicability of the CFD approach for stability analysis in binary gas mixtures.

Keywords: binary gas mixtures, mechanical equilibrium, inclination angle, diffusion–convection transport, numerical modeling

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$Ar–N_2$ БИНАРЛЫ ГАЗ ҚОСПАЛАРЫНДАҒЫ МЕХАНИКАЛЫҚ ТЕПЕ-ТЕҢДІК ТҰРАҚТЫЛЫҒЫНА ҚИҒАШ БҰРЫШТЫҢ ӘСЕРІН САНДЫҚ ЗЕРТТЕУ

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Аннотация. Бұл жұмыс гравитациялық өрістегі екікомпонентті $Ar–N_2$ газ қоспасында диффузиялық арнаның қисаю бұрышының механикалық тепе-теңдік тұрақтылығы мен масса алмасу сипатына әсерін сандық зерттеуге арналған. Бұл жұмыс екі колбалы аппараттағы газдардың изотермиялық араласуын қарастырады, онда молекулалық массалары әртүрлі компоненттердің өзара диффузиясы кезінде тығыздықтың тұрақсыз концентрациялық стратификациясының пайда болуы механикалық тепе-теңдіктің бұзылуына әкеледі. Нәтижесінде пайда болатын концентрацияға негізделген гравитациялық конвекция масса алмасу жылдамдығы мен құрылымына елеулі әсер етеді, сондықтан оның қарқынын анықтайтын факторларды талдау маңызды.

Зерттеудің негізгі мақсаты – берілген термобариялық жағдайларда диффузия-конвективті масса алмасу режимдерінің қалыптасуы мен дамуында каналдың қисаю бұрышының рөлін анықтау. Сандық модельдеу ANSYS Fluent бағдарламалық пакетінде үшөлшемді кеңістікте компонент тасымалдау теңдеулері мен k–ω турбуленттік моделі қолданылып жүргізілді. Құрылғының геометриялық конфигурациясы мен шекаралық шарттары зертханалық тәжірибе жағдайларына сәйкес келеді. Есептеулер 0°, 10°, 20° және 30° еңкіш бұрыштары үшін жүргізіліп, концентрация өрістерінің уақыттық динамикасы, ағын жылдамдықтары және интегралды араласу сипаттамалары талданды.

Еңіс бұрышының ұлғаюы еркін түсу үдеуінің арнаның осіне проекциясының азаюына байланысты концентрациялық гравитациялық конвекцияның біртіндеп әлсіреуіне әкеп соғатыны анықталды. Бұл конвекциялық ағындардың қарқындылығының төмендеуімен, төменгі колбаға өткен аргонның молярлық үлесінің азаюымен және концентрация өзгерістерінің уақыттық динамикасының тегістелуімен көрініс табады. 30° бұрышта жүйе диффузия басым режимге өтуге бейімділікті көрсетеді. Алынған нәтижелер критикалық Рейлей санының φ косинусына тәуелділігінің теориялық заңдылығына сәйкес келеді және белгілі эксперименттік үлгілерді қайталай отырып, сандық модельдің дұрыстығын және екікомпонентті газ қоспаларындағы механикалық тепе-теңдіктің тұрақтылығын талдауда CFD тәсілінің қолданылу мүмкіндігін растайды.

Түйін сөздер: бинарлы газ қоспалары, механикалық тепе-теңдік, көлбеу бұрыш, диффузия-конвективті тасымалдау, сандық модельдеу

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ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ВЛИЯНИЯ УГЛА НАКЛОНА НА УСТОЙЧИВОСТЬ МЕХАНИЧЕСКОГО РАВНОВЕСИЯ В БИНАРНОЙ ГАЗОВОЙ СМЕСИ $Ar–N_2$

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Аннотация. Работа посвящена численному исследованию влияния угла наклона диффузионного канала на устойчивость механического равновесия и характер массопереноса в бинарной газовой смеси $Ar–N_2$ в гравитационном поле. Рассматривается изотермическое смешение газов в двухколбовом аппарате, при котором потеря механического равновесия обусловлена формированием неустойчивой концентрационной стратификации плотности в процессе взаимной диффузии компонентов с различными молекулярными массами. Возникающая при этом концентрационная гравитационная конвекция существенно влияет на скорость и структуру массопереноса, что обусловливает актуальность анализа факторов, определяющих ее интенсивность. Основной целью исследования является установление роли угла наклона канала в формировании и эволюции диффузионно-конвективных режимов массопереноса при фиксированных термобарических условиях. Численное моделирование выполнено в программном комплексе ANSYS Fluent в трехмерной постановке с использованием уравнений переноса компонентов и модели турбулентности k–ω. Геометрическая конфигурация аппарата и граничные условия соответствуют условиям лабораторного эксперимента. Расчеты проведены для углов наклона 0°, 10°, 20° и 30° с анализом временной динамики концентрационных полей, скоростей течения и интегральных характеристик смешения. Установлено, что увеличение угла наклона приводит к последовательному ослаблению концентрационной гравитационной конвекции вследствие уменьшения проекции ускорения свободного падения на ось канала. Это проявляется в снижении интенсивности конвективных течений, уменьшении мольной доли аргона, перешедшего в нижнюю колбу, и сглаживании временной динамики концентрационных изменений. При угле 30° система демонстрирует тенденцию к переходу в диффузионно-доминируемый режим. Полученные результаты согласуются с теоретической зависимостью критического числа Рэлея от cos φ и воспроизводят известные экспериментальные закономерности, подтверждая корректность численной модели и применимость CFD-подхода для анализа устойчивости механического равновесия в бинарных газовых смесях.

Ключевые слова: бинарные газовые смеси, механическое равновесие, угол наклона, диффузионно-конвективный перенос, численное моделирование

Introduction. Due to that mass transfer mechanisms in these systems control the dynamic properties of stratified media, studying binary gas mixtures is vital in both theoretical and applied hydrodynamics. These mixtures play a key role in many technological and physical processes. For areas like astrophysics, climatology, aerodynamics, and chemical and energy technologies, understanding mass transfer in binary gas mixtures is essential (Kossov and Altenbach, 2023; Mialdun et al., 2019; Fedorenko et al., 2024; Kossov et al., 2022).

Under gravitational field conditions, even in the absence of a temperature gradient, isothermal mutual diffusion of gases with different molecular weights can lead to the formation of concentration stratification of density (Valiati et al., 2021; Ankusheva et al., 2010). Such stratification can cause the loss of mechanical equilibrium stability of the system and initiate a transition from the diffusion mode of mass transfer to the mode of concentration gravitational convection. The development of instability is greatly affected by the orientation of the diffusion channel relative to gravity. Changing the inclination angle impacts the effective convection driving force because it alters how free-fall acceleration projects along the channel (Liyanage et al., 2024; Banerjee et al., 2020; Kossov et al., 2023).

The formation of complex convective regimes in binary gas systems is associated with the heterogeneity of concentration fields and changes in gravitational conditions when the channel inclination angle varies. In an inclined configuration, the critical stability conditions are modified, which is reflected in changes in the effective Rayleigh number and the transition boundary between diffusion and convective regimes. Thus, the angle of inclination acts as an external control parameter that can both enhance and suppress the development of concentration-driven gravitational convection (Kosov et al., 2020; Qiu et al., 2025; Dilman et al., 2015).

Despite the existence of experimental studies devoted to the influence of channel orientation on the stability of mechanical equilibrium, the quantitative description of this effect using modern numerical methods remains limited (Kossov et al., 2025; Qui et al., 2025). Modern computational approaches allow for detailed analysis of the structure of flows and concentration fields, but require comparison with reliable experimental data (Kossov et al., 2023).

The aim of this work is to analyze the structure of concentration fields in a binary argon-nitrogen gas mixture at different angles of inclination of the diffusion channel, as well as to develop and verify a numerical model of mass transfer that takes into account the parametric dependence of the mechanical equilibrium boundary on the angle of inclination. Particular attention is paid to determining the critical values of dimensionless parameters characterizing the transition from the diffusion mode of mass transfer to the mode of concentration gravitational convection. The study is conducted within the framework of hydrodynamic stability theory using numerical simulation methods in the ANSYS Fluent software package (Kosov et al., 2025; Qui et al., 2025; Mukamedenkyzy 2025; Zhakebayev et al., 2022). The obtained calculation results are compared with known experimental data and demonstrate satisfactory agreement.

Materials and methods. The experimental results obtained in (Kulzhanov 2002) for a binary Ar–N_2 gas mixture at a pressure of 0.584 MPa and a temperature of 298 K using a two-flask method, the diagram of which is shown in Fig. 1, were used as initial data. The diffusion apparatus consisted of two flasks of equal volume V_u=V_l=69.5 cm³, connected by a cylindrical diffusion channel with a diameter of d=4 mm and a length of L=70 mm. The duration of one experiment was 17 min.

Unlike previous studies, this work focuses on analyzing the effect of the angle of inclination of the diffusion channel relative to the vertical on the nature of mass transfer and the stability of the mechanical equilibrium of the system. In numerical calculations, the geometry of the installation remained unchanged, while the orientation of the channel in the gravitational field was varied, which made it possible to vary the projection of the acceleration of free fall along its axis.

The ANSYS Fluent software package provides the ability to perform three-dimensional modeling of diffusion channels of arbitrary geometry (Kulzhanov 2002), including taking into account the spatial orientation of the system relative to the gravity vector, as well as visualization of the evolution of concentration and velocity fields over time. This allows for a detailed analysis of the effect of the angle of inclination on the development of concentration gravitational convection and the transition between diffusion and convective mass transfer modes.

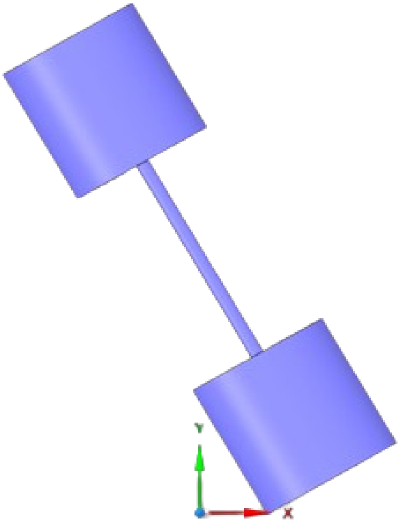


Figure 1 – Three-dimensional model of the diffusion cell and the calculated simulation area inclined at 30º

To model a binary gas mixture, a mixed-method approach was used to create a mesh for discretizing the computational domain. The unstructured triangular mesh represented the cylindrical parts of the installation, and the structured square mesh represented the diffusion channel. This type of mesh adequately represents the geometric features of each area of the installation. Since the characteristic cell size was 1 mm, it creates a correctly represented model geometry and allows for stable convergence of the numerical solution (Ansys, 2025). The total number of elements in the calculation domain is about 425,000. This amount of resolution should provide a reliable representation of mass transfer and mixing phenomena in a binary gas system. The use of triangular and square meshes offers an optimal balance between accuracy and efficiency. The triangular cells in the cylindrical section accurately represent curved surfaces, while the structured mesh in the diffusion channel significantly reduces computation costs. Both of these aspects follow current guidelines for creating computational meshes to simulate processes in binary gas mixtures, where the choice of element type and size balances the complexity of the geometry with the needed accuracy (Kutkan et al. 2021).

Mass transfer modeling in the Ar-N_2 system was done under initial conditions. In this setup, argon sits in the upper flask and nitrogen in the lower one (Kulzhanov, 2002). This arrangement, caused by the difference in molecular weights of the gases, creates a clear gravitational separation of the mixture's density. This allows for the study of how mechanical equilibrium can be disrupted. Within the framework of mathematical modeling, the assumption was made that the physicochemical characteristics of the gas environment are constant. The numerical values of the corresponding parameters were obtained from the built-in database of substances in the ANSYS Fluent software package.

Since the apparatus is modeled as a closed system, impermeability conditions are set at all its boundaries. This type of boundary conditions mathematically excludes the possibility of any mass transfer through the control surface, thereby ensuring the isolation of the system from the external environment in terms of material components. To maintain a constant temperature during the mixing process, suitable thermal boundary conditions were applied. The apparatus was designed with a solid wall made of structural stainless steel. Its thermal and strength properties were sourced from the ANSYS Fluent materials library (Ansys, 2025; Kutkan et al., 2021; Slavinskaya et al., 2023).

Convective flows driven by mechanical equilibrium instability show complex changes during the initial stage. The evolution of convective flows includes a sequence of stages: linear growth of small convective perturbations, nonlinear interaction of instability modes, transition to a turbulent regime with the formation of multiscale vortex structures, and other specific features determined by the parameters of the system (Kulzhanov, 2002). To analyze partial flows in media with convective flows of variable intensity, it is advisable to use the k-ω turbulence model (Kutkan et al., 2021; Slavinskaya et al., 2023; Nouhaila et al., 2024) which allows adequate description of mass transfer processes in a wide range. The initial and boundary conditions were set as follows: at the initial moment of time, the upper and lower chambers of the diffusion apparatus contained different binary gas mixtures. The molar fractions of the components were determined using the patch method for the corresponding grid zones.

In ANSYS Fluent, binary gas mixtures are simulated using component transport equations (mass fractions Y_1 and Y_2) and equations of motion. Mass transfer is described by convective-diffusion equations taking into account molecular and turbulent diffusion, and the density of the mixture is calculated according to the selected state model. The formulas include the transport equation for mass fraction (Ansys, 2025):

$$\frac{\partial(\rho Y_1)}{\partial t} + \nabla(\rho\vec{u}Y_1) = \nabla(\rho D_{eff}\nabla Y_1) + S_1$$
$$\frac{\partial(\rho Y_2)}{\partial t} + \nabla(\rho\vec{u}Y_2) = \nabla(\rho D_{eff}\ \nabla Y_2) + S_2 \quad (1)$$

where D_{eff} is effective diffusion, S_1 and S_2 are generalized source terms that account for possible mass sources or sinks of components. In the context of the problem under consideration, there are no additional mass sources.

The standard k–ω model is based on a system of semi-empirical transport equations, including equations for turbulent kinetic energy k and its specific dissipation rate ω, where ω is interpreted as the ratio of the turbulent energy dissipation rate ε to k (Ansys, 2025).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho\vec{u}k) = \frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k + G_k$$
$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(\rho\vec{u}\omega) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial\omega}{\partial x_j}\right) + G_\omega - Y_\omega + S_\omega + G_\omega \quad (2)$$

G_k – describes the generation of kinetic energy of turbulence caused by mean velocity gradients; ρ – density of the medium; $\vec{u} = (u_x, u_y, u_z)$ – velocity vector; G_ω – characterizes the generation of specific dissipation rate ω. In the presented system of equations, Γ_k and Γ_ω characterize the effective turbulent diffusion for k and ω, respectively; Y_k and Y_ω are dissipation terms; S_k and S_ω are user source terms, which are assumed to be zero in this work (Qui, et al., 2025). The indices *i*, *j* imply summation over the coordinates (i, j=1,2,3).

The effective diffusion coefficients for the k–ω model are given by the formulas

$$\Gamma_k = \mu + \frac{\mu_t}{\sigma_k}$$
$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \quad (3)$$

Prandtl turbulence numbers σ_k and σω determine the efficiency of diffusion transfer of turbulent kinetic energy and the rate of its dissipation. Within the framework of the model used, constant values $\sigma_k = \sigma_\omega = 2$ are assumed. Molecular viscosity μ is supplemented by turbulent viscosity μ_t, which is a function of k and ω:

$$\mu_t = \alpha^* \frac{\rho k}{\omega} \quad (4)$$

where α* is a coefficient that dampens turbulent viscosity and has a constant value of α*=1 (Ansys, 2025).

Diffusion fluxes J_1 and J_2 for substances 1 and 2, respectively, are calculated using the following formulas:

$$\vec{J_1} = -\left(\rho D_{12} + \frac{\mu_t}{Sc_t}\right) \nabla Y_1$$
$$\vec{J_2} = -\left(\rho D_{12} + \frac{\mu_t}{Sc_t}\right) \nabla Y_2 \quad (5)$$

In the presented model: μ_t is the turbulent viscosity; Sc_t is the turbulent Schmidt number, defined as $Sc_t = \mu_t/(\rho D_t)$; the standard value of Sc_t is taken to be 0.7. D_{12} is the binary diffusion coefficient; T is the temperature.

The binary diffusion coefficient D_{12} is determined within the framework of the Chapman-Enskog kinetic theory (Ansys, 2025) by the formula:

$$D_{12} = 0.00186 \frac{\left[T^3\left(\frac{1}{M_{w,1}} + \frac{1}{M_{w,2}}\right)\right]^{\frac{1}{2}}}{p_{abs}\sigma_{12}^2 \Omega_D} \quad (6)$$

where M_w is the molar mass (g/mol), T is the temperature (K), p_{abs} is the absolute pressure (atm), Ω_D is the dimensionless diffusion collision integral, which quantitatively characterizes the intensity of molecular interactions in the system.

An approach based on the pressure method was used for all calculation models. For spatial discretization of computational fluid dynamics equations, the schemes listed in Table 1 were used, which were tested and validated in (Kossov et al., 2025; Mukamedenkyzy, 2025).

Table 1. Solution methods

Quantity	Discretization
Gradient	Least Square Cell Based
Pressure	PRESTO!
Momentum	Second Order Upwind
Turbulent Kinetic Energy	Second Order Upwind
Specific Dissipation Rate	Second Order Upwind
Pseudo Time Method	Off
Transient Formulation	Second Order Implicit

The parameters listed characterize the configuration of the numerical solution in the ANSYS Fluent environment, detailing the methods used to discretize the basic equations, approximation schemes, and computational algorithms involved in the modeling process. The selected and tested combination of discretization schemes guarantees an optimal balance between the accuracy of the numerical solution and computational efficiency, which is particularly critical for problems with the combined influence of convective and diffusion processes, and makes it the preferred choice for this class of problems (Ansys, 2025; Abd Halim et al., 2018).

Results and discussions. Results and discussions. Numerical simulations of the dynamics of a binary gas mixture were performed using Ansys Fluent 2025 R2. The numerical experiments were conducted on a Lenovo LOQ 15IAX9 platform equipped with an Intel Core I5-12450HX processor, 16 GB of RAM, and an NVIDIA GeForce RTX 3050 GPU. Each simulation required between 120 and 180 minutes, depending on the complexity of the scenario and the convergence rate.

Figure 2 shows the dependence of the α parameter on temperature for the Ar–N2 binary gas system at a fixed pressure of $P=0.584$ MPa and a mixing time of $\tau=17$ min. The parameter α is introduced as the ratio of the molar fraction of the component obtained in the experiment to the corresponding value calculated under the assumption of pure diffusion mass transfer based on the Stefan–Maxwell equations. Thus, α is an integral characteristic that allows quantitative assessment of the deviation of the actual mass transfer process from the diffusion regime.

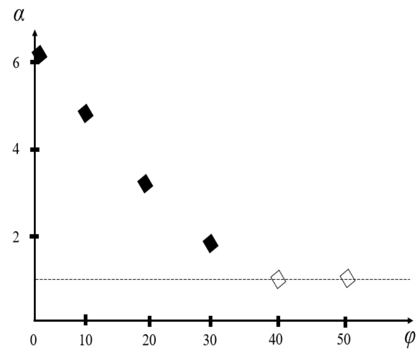


Figure 2 - Dependence of parameter α on temperature for the Ar – N2 system at P = 0.584 MPa, τ = 17 min: ■, □ - experimental data (Kulzhanov, 2002); dotted line - calculation assuming diffusion

Figure 2 shows the experimental dependence of the parameter α on the angle of inclination of the diffusion channel for the Ar–N_2 system at a pressure of P=0.584 MPa and a temperature of T=298 K. The parameter α characterizes the deviation of actual mass transfer from the diffusion regime and allows quantitative estimation of the contribution of concentration-driven gravitational convection. When the channel is in a vertical position (φ=0∘), the maximum value of α is observed, which corresponds to the intensive development of mechanical equilibrium instability and the formation of convective currents.

With an increase in the angle of inclination, the experimental values of α decrease monotonically, which indicates a consistent suppression of the convective transport mechanism. At φ≈30∘, the system approaches the transition boundary to the diffusion regime, and a further increase in the angle leads to an almost complete coincidence of the experimental data with the calculation assuming pure diffusion.

Table 2. Dependence of the diffusion of gas from one flask to another on the angle of inclination of the diffusion cell

Angle of inclination	Ar	N_2
0	0.1367	0.1354
10	0.1055	0.0965
20	0.0738	0.0698
30	0.0401	0.0477

The table shows the results of numerical modeling of the molar fraction of argon that has passed into the opposite flask at angles of inclination of 0°, 10°, 20°, and 30°. The calculated values demonstrate a steady tendency toward a decrease in substance transfer with an increase in φ. Thus, when moving from a vertical position to an angle of 30°, the molar fraction decreases more than threefold. This quantitatively confirms the decrease in the intensity of concentration gravitational convection with a decrease in the effective projection of free-fall acceleration along the channel axis.

The physical mechanism of the observed phenomenon is associated with a change in the component of gravity responsible for the development of density instability. Changing the angle of inclination of the channel affects $g_{eff} = g\cos(\varphi)$, where g_{eff} represents the effective free fall (gravity) of the fluid inside the channel. As the angle of inclination, φ, increases the effective Rayleigh number decreases proportionately to the value of cos(φ), which means the system is moved away from the critical stability state. The effective Rayleigh number decreases through the angle range tested, moving from a convective to molecular regime as the system is diminished in Rayleigh number. The numerical results demonstrate good qualitative agreement with the experimental dependence α(φ). Although the experimental graph is presented without exact numerical values, the nature of the decrease and the position of the critical region are reproduced correctly. This confirms the adequacy of the chosen mathematical model and the correctness of the gravitational vector assignment when modeling an inclined configuration.

Additional analysis of the temporal dynamics of concentrations in the upper and lower flasks shows that as the angle of inclination increases, the amplitude of the initial non-stationary oscillation's characteristic of the stage of convective structure formation decreases. At small angles, a pronounced nonlinear growth of concentration perturbations is observed, while at φ=30∘, the temporal dependencies become smoothed and close to diffusion evolution. This indicates the suppression of vortex structures and a decrease in the intensity of exchange between the flasks. Thus, the angle of inclination of the diffusion channel acts as an effective control parameter for the stability of the mechanical equilibrium of a binary gas mixture. The results obtained confirm the theoretical dependence of the critical Rayleigh number on cosφ and demonstrate that even relatively small deviations from the vertical significantly affect the nature of mass transfer.

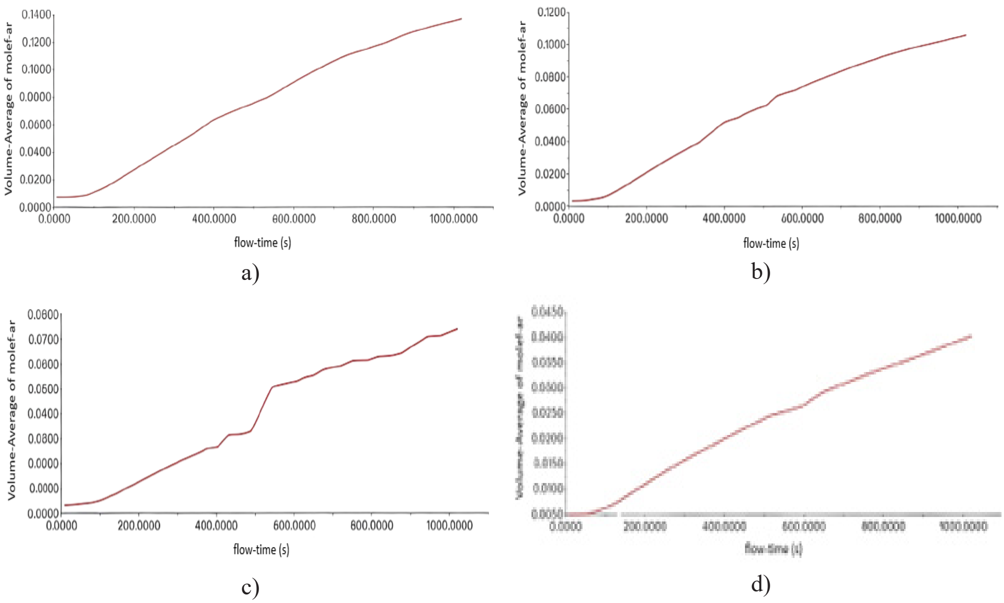
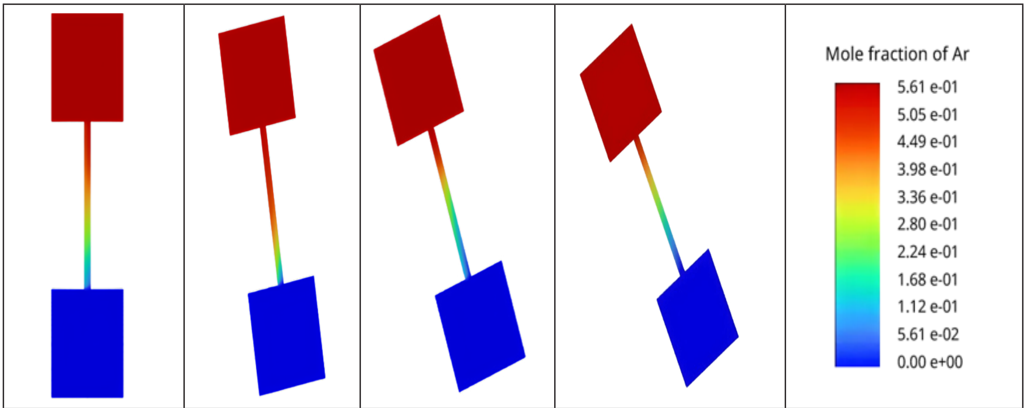


Figure 3 – Dependence of the change in argon concentration in the lower flask on time at different angles of inclination for the system $Ar\text{-}N_2$ at p=0.584 MPa and T=298 K: a) φ=0º; b) φ=10º; c) φ=20º; d) φ=30º

Figure 3 demonstrates that the temporal evolution of argon concentration in the lower flask depends systematically and monotonically on the inclination angle of the diffusion channel. As the inclination increases, the concentration-time curves indicate a progressive reduction in both the rate and total amount of mass transfer from the lower to the upper flask. Configurations closer to the vertical orientation display more pronounced initial concentration increases with evident nonlinear acceleration, attributable to buoyant convective movements combined with molecular diffusion. With increasing inclination angle, the concentration profiles become smoother, indicating a transition from convection-driven to diffusion-dominated mass transfer, as reflected by the increasingly flat slopes of the curves. The decreasing slope signifies a reduction in the effective gravitational force component along the channel axis, thereby diminishing the mechanism responsible for concentrated convection. Additionally, the cumulative concentration change over a given period decreases with increasing angle, confirming that mixing efficiency declines as the inclination increases. The absence of distinct accelerative mixing stages at larger angles suggests that vortex structures are significantly attenuated or insufficiently developed. These results confirm that even moderate deviations from vertical orientation substantially affect mixing kinetics and stabilize the mechanical equilibrium of the binary gas system, consistent with the theoretical cosφ dependence of the effective Rayleigh parameter.



a)	b)	c)	d)	e)

Figure 4 – Convective structures formed in the diffusion channel for the system Ar-N_2 at p=0.584 MPa, T=298 K at the moment t=120 s depending on the channel inclination: a) φ=0º; b) φ=10º; c) φ=20º; d) φ=30º; e) concentration scale for cases (a), (b), (c) and (d) describing numerical values of colors

Figure 4(a–d) illustrates that the inclination angle of the diffusion channel significantly influences the spatial structure of the concentration field. In the vertical position (φ = 0°), gravity aligns with the channel axis, promoting the formation of convective patterns within the diffusion zone. As the inclination increases to φ = 10–20°, the symmetry of the concentration field is gradually restored and convective disturbances weaken. At φ = 30°, the concentration profile becomes notably more uniform along the channel, indicating suppression of large-scale convection. This stabilizing effect results from a reduction in the effective gravitational component along the density gradient, which diminishes buoyancy-driven flow. The numerical results confirm that increasing channel inclination enhances the stability of mechanical equilibrium in the Ar-N_2 system under the examined thermobaric conditions.

Conclusion. Conclusion. This study investigates the influence of diffusion channel inclination on the stability of mechanical equilibrium and mass transfer in an isothermal Ar-N_2 gas mixture under gravity. Transient three-dimensional simulations in ANSYS Fluent were conducted for inclination angles of 0°, 10°, 20°, and 30°. The findings demonstrate that inclination angle is a key parameter governing the interplay between diffusion and convection, with gravitational convection driven by concentration gradients diminishing as the effective vertical gravity component decreases. Quantitatively, the molar fraction of argon transferred decreases by more than threefold as the channel is tilted from vertical to 30°, indicating a substantial reduction in convective mass transfer. This observation aligns with the theoretical criterion that the effective Rayleigh number is proportional to the cosine of the inclination angle. As inclination increases, the system transitions toward a diffusion-dominated regime, and concentration fields become progressively smoother, reflecting reduced convection. Comparison with experimental data shows that the instability parameter decreases monotonically with increasing inclination. The numerical model accurately represents the system's physical processes and may assist in defining stability limits for inclined diffusion channels. Overall, the results confirm that channel orientation significantly affects mass transfer in binary gases and may serve as a passive means to control concentration-driven convection in practical applications.

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