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OSCILLATORY PRESSURE DRIVEN FLOW OF HE-XE BETWEEN PARALLEL PLATES IN THE WHOLE RANGE OF THE KNUDSEN NUMBER

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ABSTRACT

Oscillatory rarefied flows are of main technological interest in large gas vacuum systems (e.g. gas exhaust systems in fusion reactors and particle accelerators), as well as in small devices such as pressure sensors, flow controllers and heat transfer enhancement applications. Oscillatory flows in the hydrodynamic limit have been extensively investigated. However, the corresponding work in rarefied gases is very limited and it is focused in single gases [1,2].
Here, the oscillatory pressure-driven fully-developed flow of He-Xe between parallel plates is investigated. Assuming that the amplitude of the oscillation is small, the flow is simulated based on the time-dependent linearized McCormack kinetic model equation [3] subject to diffuse boundary conditions. The main objective is to investigate the effect of the oscillation frequency on the gas separation phenomenon, which in the steady-state configuration has been well analyzed [4,5].
Consider the binary gaseous mixture of He-Xe confined between two parallel plates fixed at $y' = \pm H/2$. The mixture is oscillating due to an imposed harmonically oscillating pressure gradient $d\tilde{P}(x',t')/dx' = \mathbb{R}\left[\exp(-i\omega t')\, dP(x')/dx'\right]$, where $\mathbb{R}$ denotes the real part of the complex expression $i=\sqrt{-1}$, t' is the time independent variable, $dP(x')/dx'$ is the amplitude of the oscillating pressure gradient and ω is the oscillation frequency, caused by a periodically moving membrane or piston. The flow is assumed to be harmonic in time, fully developed (independent of x') and varying in the y'-direction. The flow is characterized by the gas rarefaction parameter δ defined as

$$\delta = \frac{P_0 H}{\mu}\sqrt{\frac{m}{2kT_0}} \tag{1}$$

where P_0 and T_0 are the reference pressure and temperature of the mixture, respectively, μ the viscosity coefficient of the mixture at T_0, k is the Boltzmann is the mean molecular mass of the mixture constant and $m = C_0 m_1 + (1-C_0) m_2$, where $m_\alpha\ (\alpha=1,2)$ is the molecular mass of gaseous species α. In the case of the He-Xe mixture the molecular mass ratio is $m_1/m_2 = 4.0026/131.3$. The molar concentration C_0 of the mixture is defined as $C_0 = n_1/(n_1+n_2)$, where $n_\alpha\ (\alpha=1,2)$ is the number density of gaseous species α. The flow is also characterized by the oscillation parameter

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$$\theta = P_0 / (\mu\omega), \tag{2}$$

which is defined as the ratio of the collision frequency over the pressure gradient oscillation frequency. Furthermore, assuming that the dimensionless amplitude of the local oscillatory pressure gradient $X_P = (H/P)(dP(x',t')/dx')$ is adequately small, linearization is introduced. The main unknown is a complex perturbed distribution function of the form $\tilde{h}_\alpha(t,y,\boldsymbol{c}) = \mathbb{R}[h_\alpha(y,\boldsymbol{c})\exp(-it)]$ where $\boldsymbol{c}_\alpha$ is the dimensionless molecular velocity, $y = y'/H$ and $x = x'/H$ are the dimensionless coordinates and $t = \omega t'$ is dimensionless time. Substituting this expression into the unsteady linearized Boltzmann equation it yields a system of two equations [4,5]

$$i\frac{\delta}{\theta}h_\alpha + c_{\alpha y}\frac{\partial h_\alpha}{\partial y} = \omega_\alpha \sum_{\beta=1}^{2} L_{\alpha\beta} h_\alpha - c_{\alpha x} X_P\,,\ \alpha = 1,2 \tag{3}$$

where $\omega_\alpha = H\sqrt{m_\alpha / 2kT_0}$. In Eq. (2) the exact collision term $L_{\alpha\beta}$ has been replaced by the McCormack model and it is given in detail in [4]. The bulk velocity u_α, the heat flux q_α and the shear stress Π_α, are defined as moments of the perturbation function [4]. Since h_α is complex the macroscopic quantities are also complex and they may be written as $w = w_A(y)\exp[i\, w_P(y)]$, $(w = u_\alpha, q_\alpha, \Pi_\alpha)$, where w_A and w_P are the amplitude and the phase of each quantity.

In the present work the main quantity of practical interest is the oscillatory complex flow rate $J_\alpha = J_{\alpha,A}\exp[iJ_{\alpha,P}]$ of each species, which is obtained by integrating the corresponding bulk velocity over the distance between the parallel plates. More specifically, we are interested at the ratio of the amplitudes $J_{1,A}/J_{2,A}$, which quantifies the intensity of gas separation. The numerical results have been successfully validated with corresponding single gas results [2], as well as with the steady state results, since as the oscillation frequency is reduced the corresponding steady-state binary gas mixture flow is recovered [4,5].

In Fig. 1 computational results of the ratio $J_{1,A}/J_{2,A}$ are provided in terms of the gas rarefaction parameter δ for various typical values of the oscillation parameter θ, with the molar concentration $C_0 \in (0,1)$. It is clearly seen that the oscillation parameter has a very significant effect on the behavior of $J_{1,A}/J_{2,A}$ in terms of δ. At large values of θ (e.g. $\theta = 100$), i.e., when the oscillation frequency is very low, there is a clear resemblance with the corresponding steady-state behavior. However, as θ is reduced, i.e., as the oscillation frequency is increased, the behavior of $J_{1,A}/J_{2,A}$ in terms of δ is gradually modified both qualitatively and quantitatively. In the steady-state and low oscillation frequency regimes the ratio $J_{1,A}/J_{2,A}$ is monotonically reduced with δ, with its largest value the free molecular limit ($\delta = 0$) [5]. Now, at efficient large oscillation frequencies (small values of θ) the behavior is not monotonic and more interesting, gas separation becomes more intense at some value of $\delta > 0$. This is a promising finding indicating that in gas mixtures, oscillatory motion may be introduced in order to intensify and, more general, to control gas separation.

The present work is still under development and recently, in addition to He-Xe, other binary and trinary gas mixtures are investigated in order to have a more complete view of the oscillation frequency effect in gas separation.

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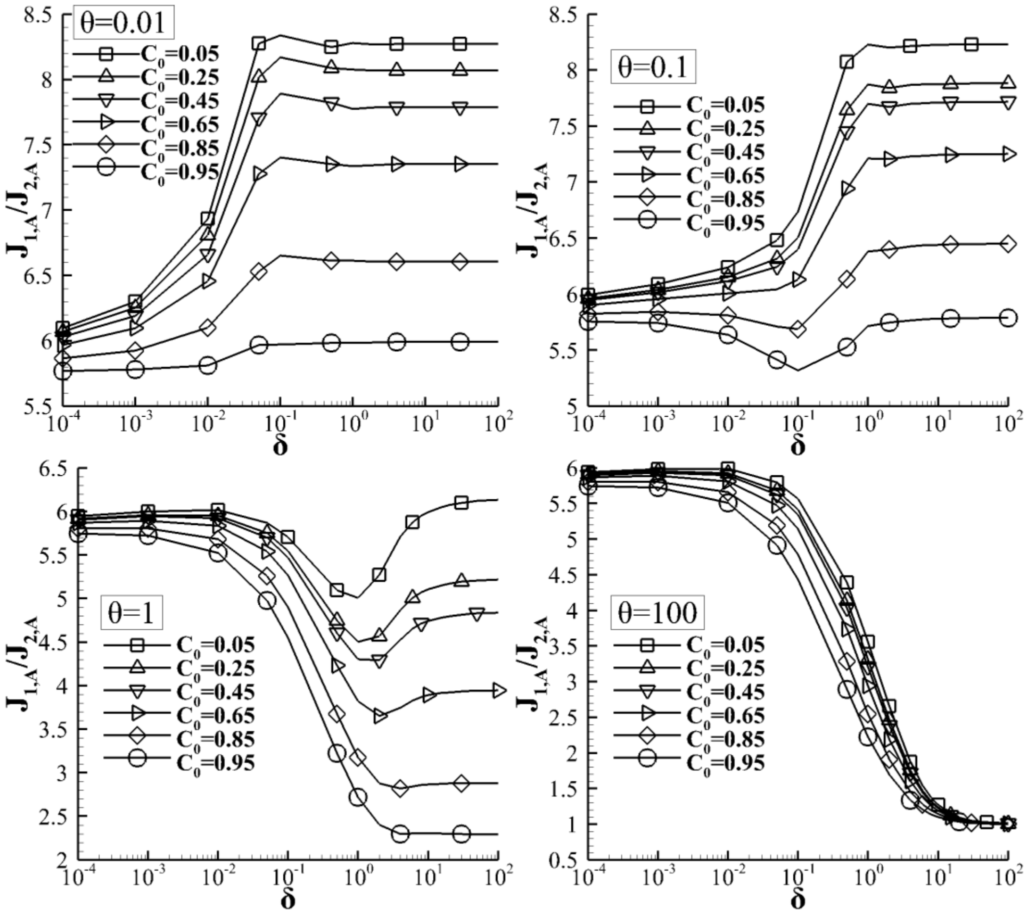

Figure 1: Ratio of flow rate amplitudes $J_{1,A}/J_{2,A}$ over δ for He-Xe mixture, $\theta=\left[10^{-2},0.1,1,10^{2}\right]$ and concentration $C_0=\left[0.05,0.25,0.45,0.65,0.85,0.95\right]$.

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