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INVESTIGATION OF FLOW REGIMES OF AIR-HELIUM MIXTURES DEPENDING ON MICROCHANNEL RADIUS WITH LARGE PRESSURE GRADIENT

Показано актуальність існуючої в хімічній та машинобудівній галузях промисловості проблеми надійної герметизації установок, агрегатів та об'єктів, які експлуатуються протягом тривалого часу та працюють з агресивними середовищами . Наведено різновиди основних типів приладів для виявлення течії з використанням тестової речовини; показано переваги використання гелію. Сформульована задача дослідження течії газів крізь мікроканал з урахуванням зміни режимів течії. В роботі визначено границі переходу молекулярного та в'язкісного режимів течії для повітряно-гелієвих сумішей в залежності від радіусу мікроканалу та перепаду тиску, а також встановлено залежність зміни границь молекулярного та в'язкісного режимів від відсоткового вмісту повітря і гелію. Дослідження проведено в ізотермічній постановці для двох варіантів складу повітряно-гелієвої суміші, п'яти значень радіусів мікроканалу та перепаду тиску, що варіювався в широких межах: з тиском на виході з мікроканалу $P_2 = 1 \cdot 10^5 Па$ та тиском на вході $P_1 = (1.2 \div 81) \cdot 10^5$ $Па$. Наведено метод розрахунку з посиланням на оригінальні джерела літератури Пуазейля, Хагена, Кнудсена та інших авторів, які досліджували означену проблему. З метою визначення границь переходу течії газу в мікроканалі від одного режиму течії до іншого наведено методику визначення границь переходу режимів, за якою побудовано графіки, наведені в роботі. В результаті дослідження отримано, що при зменшенні радіуса каналу границя переходу від молекулярного режиму течії до проміжного зміщується в бік зменшення величини потоку; таким же чином, в бік зменшення величини потоку відбувається також зміщення границі переходу від проміжного режиму течії до в'язкісного. Одержані результати дозволяють провести аналіз характеру впливу радіусів мікроканалів на режими течії сумішей через мікроканал в залежності від параметрів потоку. На основі отриманих даних при контролі приладів та установок на герметичність можна обирати повітряно-гелієву суміш, яка контактує з агресивними середовищами при великих перепадах тиску.

Ключові слова: потік, в'язкісний та молекулярний режим, повітряно-гелієва суміш, циліндричний мікроканал, в'язкість суміші, об'ємна доля, перехідний режим, перепад тиску, радіус мікроканалу.

Introduction. The existence of chemical and machine-building industries requires a solution to the problem of reliable sealing of plants, units and facilities that are operated for a long time and work with aggressive environments. Experience shows that with prolonged contact with such devices with aggressive or toxic substances may leak gases through micro-leaks in welded or detachable joints, as well as – leakage through the walls of the base material. Evaporation of aggressive substances penetrating through the micro-leaks leads to air pollution production facilities, acceleration of corrosion processes and

failure of devices and units of technological equipment, as well as poses a threat of poisoning working staff.

The advent of sophisticated vacuum and refrigeration equipment has led to the emergence of accurate instrumental methods for detecting leaks using test substances; there are two main types of devices: freon and helium.

Helium is an inert gas that provides not only accuracy, but also the durability of the leak detector, as well as a high level of safety in operation. Due to the low density of the gas and the small diameter of the molecules, high fluidity, this gas can penetrate into holes with radii of the order of some microns. It should be noted also one more advantage of use of helium: in air its maintenance is very small therefore on results of measurements the external environment will not affect.

Thus, it is important to study the change in the flow regimes of air-helium mixtures in microchannels depending on the radius of the channel, as well as construction of dependences of the influence of flow boundaries and the magnitude of the pressure drop on the radius of the channel.

Formulation of the problem. The limits of transition of molecular and viscous flow regimes for air-helium mixtures depending on flow parameters (microchannel radius and pressure drop), as well as the dependence of changes in the boundaries of molecular and viscosity modes on percentage of air and helium are obtained.

Given a cylindrical channel with a constant length $l = 3.3 \cdot 10^{-3} м$ and at constant temperature $T = 300^0 K$ and at different pressure drops $\Delta P = P_1 - P_2$: with the pressure at the outlet of the microchannel $P_2 = 1 \cdot 10^5 Па$ and inlet pressure $P_1 = (1.2 \div 81) \cdot 10^5$ $Па$. It is necessary to determine the degree of influence of the radius of the microchannel on the change of the boundaries of the transition of flow regimes.

The composition of the air-helium mixture varied as follows:

a) 90% air + 10% helium;

b) 70% air + 30% helium.

In the calculations, the radii of the microchannels were:

$$3.5 \cdot 10^{-7} \text{m},\ 5 \cdot 10^{-7} \text{m},\ 7 \cdot 10^{-7} \text{m},\ 1 \cdot 10^{-6} \text{m},\ 1.5 \cdot 10^{-6} \text{m}.$$

Physical properties of helium and air:

helium: $\mu = 4.003 \ \frac{kg}{kmole}$; $\eta = 1.9 \cdot 10^{-5} \frac{H \cdot c}{m^2}$;

air: $\mu = 28.986 \frac{кg}{кmole}$; $\eta = 1.81 \cdot 10^{-5} \frac{H \cdot c}{m^2}$.

Calculation method. The first theoretical study of the motion of a viscous fluid in channels and pipes of small diameter was performed by Poiseuille [7, 8] and Knudsen [6], as well as in parallel and independently – Hagen [5]. The relations for the calculation of costs in the viscous mode were obtained by Poiseuille, and in the molecular and transient mode – by Knudsen. In this case, Knudsen studied the movement of gases at low pressure (below atmospheric), while in practice there is a need to expand the range investigated flows at high excess pressures (10^6 Pa and more).

It has been experimentally established [4] that the flow of gas through the microleakage depends on several factors: the pressure in the microleakage channel, the

pressure external environment, physical properties of gases, geometry and size of micro-leaks, as well as modes of gas flow in microchannels.

The parameters of gas flow in the channels for a wide range of pressure drops are determined by both the physical properties of the gases and the magnitude of the effective pressure. There are several different flow modes, which are characterized by the Knudsen test ($Kn = \lambda / r$), which is the ratio of the free path length gas molecules λ to the characteristic size of the channel, such as its radius r.

There is the following classification of modes depending on Knudsen's number:

1) $Kn < 0.01$ – viscous flow;
2) $Kn \ge 1$ – molecular flow;
3) $0.01 < Kn < 1$ – intermediate mode.

In turn, the intermediate is divided into:

1) $0.01 \le Kn \le 0.5$ – gas flow regime with sliding;
2) $0.5 \le Kn \le 1$ – transient (from sliding mode to molecular).

Knudsen's formula [4] was used for calculations, which was obtained semi-experimentally for the transient mode, namely:

$$Q^n = \left(\frac{\pi \cdot r^4}{8 \cdot \eta \cdot l} \cdot P_{mid} + \frac{1 + \dfrac{d}{\eta \cdot \sqrt{(R_{ун} \cdot T)/\mu}} \cdot P_{mid}}{1 + \dfrac{1{,}235 \cdot d}{\eta \cdot \sqrt{(R_{ун} \cdot T)/\mu}} \cdot P_{mid}} \right) \cdot \frac{4}{3} \frac{r^3}{l} \sqrt{2 \cdot \pi \cdot T \cdot R}(P_1 - P_2) \qquad (1)$$

or

$$Q^n = Q^B + z \cdot Q^M \, , \qquad (2)$$

where $z = \dfrac{1 + \dfrac{d}{\eta \cdot \sqrt{(R_{ун} \cdot T)/\mu}} \cdot P_{mid}}{1 + \dfrac{1{,}235 \cdot d}{\eta \cdot \sqrt{(R_{ун} \cdot T)/\mu}} \cdot P_{mid}}$.

To determine the magnitude of the gas flow at viscous and molecular flow regimes used the formulas [2, 3]:

$$Q^B = \frac{\pi \cdot d^4}{128 \cdot \eta \cdot l} \cdot P_{mid} \cdot (P_1 - P_2), \qquad (3)$$

$$Q^M = \frac{d^3}{6 \cdot l} \sqrt{\frac{2 \cdot \pi \cdot R_{mid} \cdot T}{\mu}} (P_1 - P_2). \qquad (4)$$

The molar mass of the mixture μ was determined by the formula [1]:

$$\mu = \sum_{i=1}^{2} r_i \cdot \mu_i = r_{He} \cdot \mu_{He} + r_{air} \cdot \mu_{air} ,$$

where r_{He} , r_{air} – the proportion of helium and air in the mixture, respectively;

μ_{He}, μ_{air} – molar masses of helium and air, respectively.

Mann's formula was used to calculate the viscosity of the mixture η :

$$\eta = \frac{1}{\sum_{i=1}^{2} \frac{r_i}{\eta_i}} = \frac{1}{\frac{r_{He}}{\eta_{He}} + \frac{r_{air}}{\eta_{air}}},$$

where η_{He}, η_{air} – are the coefficients of dynamic viscosity of helium and air, respectively.

At a constant temperature of the gas in the microchannel for two different pressure drops ΔP_1 and ΔP_2 (with the corresponding P_{cp1} and P_{cp2}), using (3, 4), will be true correlation:

$$\frac{Q_2^B}{Q_1^B} = \frac{P_{cp2}(P_1 - P_2)_2}{P_{cp1}(P_1 - P_2)_1} = \frac{P_{cp2}\Delta P_2}{P_{cp1}\Delta P_1}, \tag{5}$$

$$\frac{Q_2^M}{Q_1^M} = \frac{(P_1 - P_2)_2}{(P_1 - P_2)_1} = \frac{\Delta P_2}{\Delta P_1}. \tag{6}$$

Methods for determining the boundaries of the transition regimes. To determine the boundaries of the transition from one flow regime to another, the dependence was built logarithmic scale $Q = f(\Delta P)$, then set the sequence of values of pressure and pressure drops. To find the boundary of the transition from viscous to transient mode, the upper end of the curve was constructed dependence (5), where

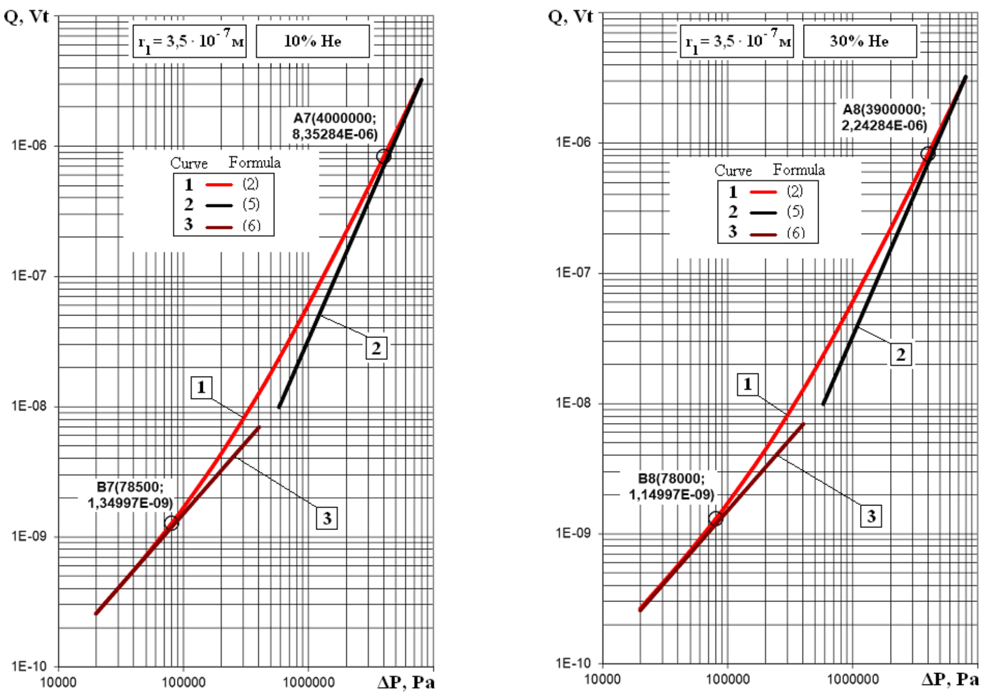
$$P_{cp} = \frac{P_1 + P_2}{2}, \tag{7}$$

and P_2– a given constant value. For another pressure drop from this dependence we find Q_2 , because all other quantities are known. Knowing the coordinates of the second point ($Q_2, \Delta P_2$), plot it on the graph. Similarly, find Q_3 and determine the third point ($Q_3, \Delta P_3$) for the next pressure drop. Through the found points we build a straight line, which will be tangent to the curve describing the dependence of the flow power on the pressure drop in the viscosity mode. When the error between them begins to grow and reaches one tenth, we can consider the flow regime transient, and the point with these coordinates will be the point of divergence of the calculated curve with the dependence (5), which is the boundary of the transition from viscous to transient mode.

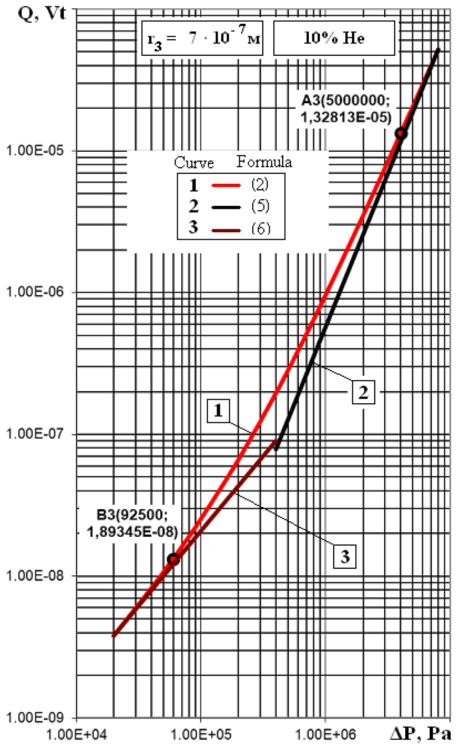
To determine the boundary of the transition from the molecular to the transient mode from the lower end of the curve, the dependence (6) was constructed, where the starting point the first point of the curve with coordinates ($Q_1, \Delta P_1$) was chosen. Knowing also the value of the pressure drop ΔP_2 , we find Q_2 . Similarly, we find the third point,

then build straight. The point where the discrepancy of the dependence (6) on the calculated curve begins will be the boundary of the transition from the molecular to the transition mode.

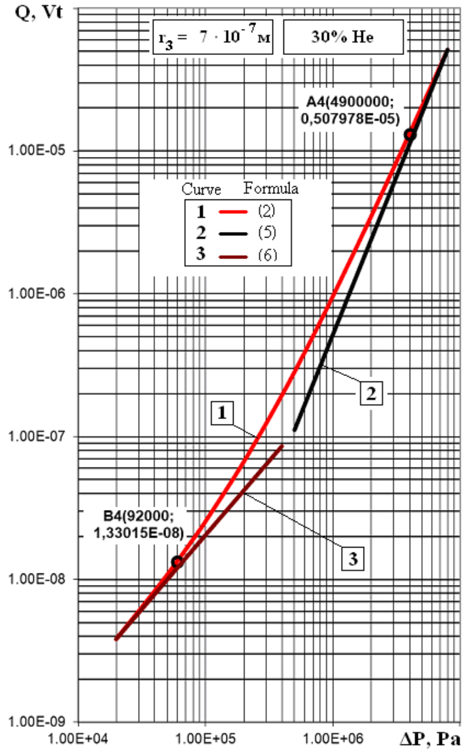
Results. In Fig. 1 and Fig. 2 in logarithmic coordinates are graphs of the dependence of the flow rate Q on the pressure drop ΔP for the studied two variants of air helium mixture when varying the radius of the microchannel: $r_1 = 3{,}5\cdot10^{-7}$m; $r_3 = 7\cdot10^{-7}$m (Fig. 1) and $r_5 = 1{,}5\cdot10^{-6}$m (Fig. 2). Curve 1 corresponds to the calculations for ratio (2); curves 2 and 3 are calculated using relations (5) and (6), respectively. The method of constructing curves in Fig. 2 is similar to construction curves in Fig. 1.



a) b)

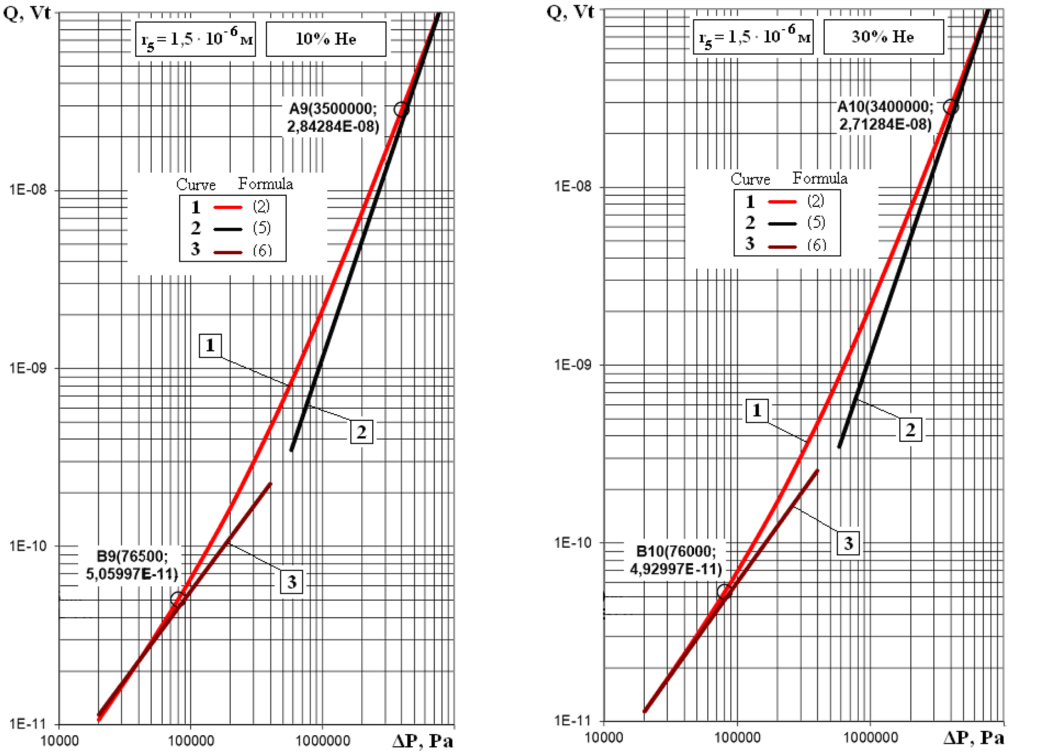


c)



d)

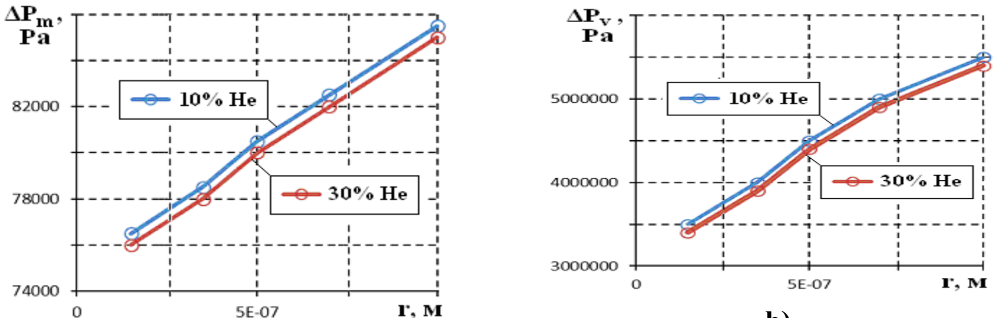
Fig.1. Graph of the dependence of the flow Q on the pressure drop for:
a, c – 90% air + 10% He; b, d – 70% air + 30% He;
a, b – $r_1 = 3{,}5\cdot10^{-7}$m; c, d – $r_3 = 7\cdot10^{-7}$m



a) b)

Fig.2. Graph of the dependence of the flow rate Q on the pressure drop for $r_5 = 1{,}5\cdot10^{-6}$m: a – 90% air + 10% He; b – 70% air + 30% He

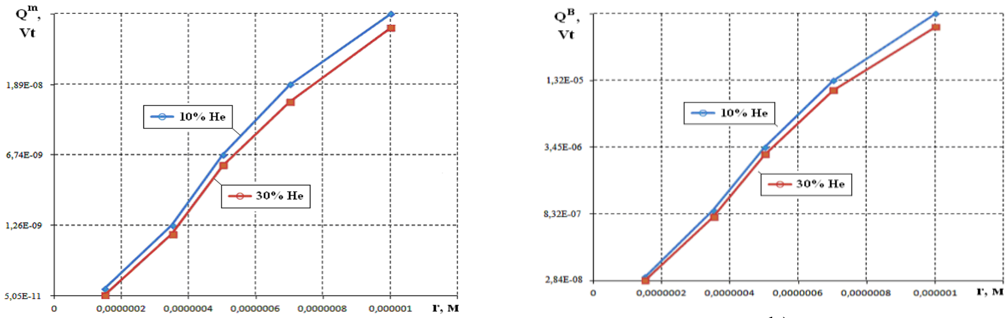
Figure 3 illustrates the curves of the pressure drop on the radius of the microchannel r : $\Delta P_m = \Delta P_m(r)$ – at the molecular regime and $\Delta P_V = \Delta P_V(r)$ – at the viscous flow regime for two variants of air-helium mixture.



a) b)

Fig.3. Graph of the pressure drop dependence on the radius of the microchannel for 10% and 30% of the mixture by He: a – at the molecular mode; b – in viscous mode

Figure 4 presents graphs of the dependence of the mode boundary on the percentage of helium in the mixture for the values Q^B and Q^M, where $Q^в$ is the final value of the molecular flow, in which the molecular flow regime becomes intermediate; Q^M – the initial value of the viscosity flux at which the intermediate the flow regime changes to viscous.



a) b)

Fig.4. Graph of the dependence of the flow rate on the radius of the microchannel for 10% and 30% of the mixture by He: a – Q^M **; b –** Q^B

Conclusions. The analysis of the conducted researches (Fig. 1–4) shows that at decrease in radius of the channel there is a shift towards decrease in size of a stream Q: the boundaries of the transition from the molecular flow regime to the intermediate, as well as the boundaries of the transition from the intermediate flow regime to the viscous. The pressure difference at decreasing the radius of the channel is shifted in the direction of its reduction.

The obtained results allow to analyze the nature of the influence of the radii of microchannels on the modes of flow of mixtures through the microchannel depending on flow values.

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