RESULTS OF A STUDY CONCERNING THE HEAT AND MASS TRANSFER WHEN HELIUM IS PURGED OF NITROGEN IMPURITY BY THE CONDENSATION METHOD

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Results are shown of an experimental study concerning the heat and mass transfer inside a vertical tube between the mainstream and the interphase boundary.

In recent years helium has found many industrial applications as a working medium and as an inert gas. For this reason, it becomes necessary to reduce its waste. In many technological processes helium becomes contaminated and must be purified before re-use.

The process by which concentrated helium is produced is only little understood. The necessary apparatus is designed on the basis of formulas for a vapor–gas (water vapor and air) mixture the properties of which differ very much from those of a nitrogen–helium mixture. The lack of reliable data characterizing the helium concentration process has provided the stimulus for this study.

The test apparatus and procedure have been described in [1, 2]. The data were generalized on the basis of the similarity theory.

In this case the composition of the binary mixture was changing drastically along the channel. Its physical properties were changing too.

A generalization of test data on the basis of the similarity theory is possible, for a given set of physical conditions, if one considers small segments along the partitioning apparatus within which the composition of the vapor–gas mixture varies only slightly and, consequently, the physical properties as well as the process parameters vary only slightly.

An analysis has shown that the criterial relations characterizing the heat and mass transfer during condensation of vapor from the flowing vapor–gas mixture may be presented as follows:

for convective heat transfer

$$\mathrm{Nu} = \varphi\left(\mathrm{Re},\ \mathrm{Pr},\ \pi_\omega,\ \frac{P_\mathrm{M}}{P_\mathrm{cr}},\ \frac{C_\mathrm{V}}{C}\right), \tag{1}$$

for mass transfer

$$\mathrm{Nu}_D = \varphi\left(\mathrm{Re},\ \mathrm{Pr}_D,\ \pi_\mathrm{g},\ \varepsilon_G,\ \frac{P_\mathrm{M}}{P_\mathrm{cr}},\ \frac{R_\mathrm{V}}{R_\mathrm{G}}\right). \tag{2}$$

In addition to the criterial numbers given in [3, 4], we have also introduced in Eqs. (1) and (2) the parameter P_M/P_{cr}. The reason for this is that the relations here apply to a wide range of pressures. Without this parameter, the test points would scatter on account of differences in pressure.

The criterial numbers in (1) and (2) were calculated on the basis of mean parameter values referring to the mainstream along a given channel segment. As the characteristic dimension we chose the inside diameter of the partition tube. The diffusivity was determined according to the formula

$$D_\mathrm{c} = 0.621\cdot 10^{-4}\,\frac{1}{P_\mathrm{M}}\left(\frac{T}{273}\right)^{1.73}\ \mathrm{m^2/sec.}$$

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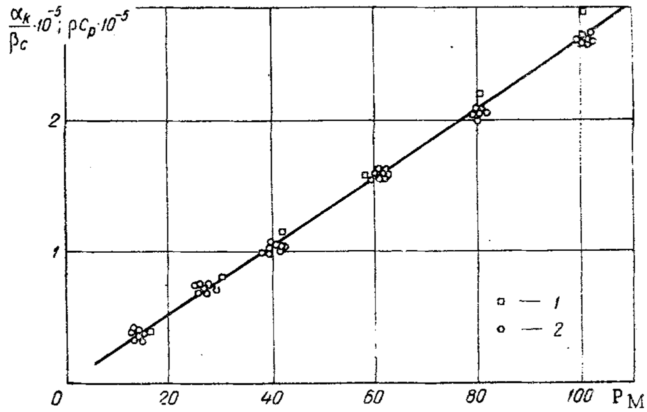

Fig. 1. Comparison of calculated values (ρC_p) (1) with test data (α/β_c) (2) characterizing the analogy between heat and mass transfer. Pressure P_M (bars), α_k/β_c, ρC_p (J/m$^3 \cdot$ °C).

It has been stated in the literature that the effect of diffusion currents in these cases should not be included, i.e., that the universal expressions should not contain the π_ω-number and the π_g-number, but that only the effect of a Stefan current characterized by the criterial parameter P_G/P_M should enter here. An evaluation of our test data has established, however, that the criterial relations must contain the π_ω-number and the π_g-number when applied to high and intermediate concentrations of nitrogen. Only for low concentrations of nitrogen may they be omitted.

A thorough analysis has shown that, for a generalization of test data and for a determination of the relevant quantities, it is worthwhile to divide the total span of concentrations into three zones characterized by different process trends. These three zones will be called here the zone of low, intermediate, and high nitrogen concentration respectively. The high-concentration zone is, moreover, characteristic of high pressures in the mixture and is defined as the zone within which the partial pressure of nitrogen in the mixture is above its critical pressure.

Zone of Low Nitrogen Concentration. It is well known that an approximate analogy between heat transfer and mass transfer exists when the concentration of the active component is within the low range.

When heat and mass transfer occur simultaneously, then the flow equation is common to both and one major factor which would invalidate this analogy when the processes run separately, namely the different hydrodynamic conditions during heat and mass transfer, is eliminated here.

The approximate analogy between heat and mass transfer remains valid if the following conditions are satisfied [3]:

a) the volume concentration of the active component in the mixture is low;

b) the equality

$$a = \frac{\lambda}{\rho C} = D_p R_V T = D_c$$

holds true or, which is equivalent, the Prandtl numbers for heat and diffusion are equal ($Pr = Pr_D$);

c) the temperature field and the pressure field are similar; this requirement is expressed as

$$B = \frac{C_V}{C}\,\frac{R}{R_V} = \frac{\frac{R_G}{R_V} + x}{\frac{C_G}{C_V} + x} = 1;$$

d) the boundary conditions are similar.

An analysis of the test data in [1] has shown that the conditions of approximate analogy between heat and mass transfer apply to low volume concentrations ranging from 0 to 10% nitrogen in the mixture.

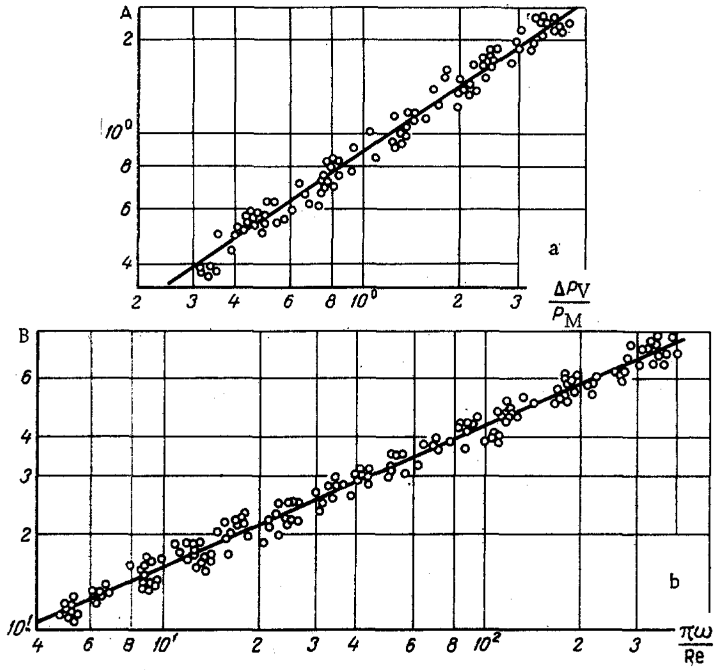

Fig. 2. Mass transfer (a) and heat transfer (b) during condensation of nitrogen from a nitrogen–helium mixture (zones of high and intermediate nitrogen concentrations). $A = Nu_D(P_M/P_{cr})^{-0.5}/Re^{1.0}Pr_D^{0.3}$; $B = Nu(P_M/P_{cr})^{-0.5}/Re^{1.0}Pr^{0.3}$.

Here

$$1 \leqslant \frac{a}{D_c} \leqslant 1.14; \quad 1 \leqslant B \leqslant 1.3.$$

Assuming the approximate analogy between the two processes to be valid in the low-concentration zone, one may expect the Lewis relation

$$\frac{\alpha}{\beta_c} = \rho C_p$$

to be applicable. The $\alpha/\beta_c = f(P_M)$ and $\rho C_p = \varphi(P_M)$ curves are shown in Fig. 1.

The test data agree closely with calculations.

Thus, our test data confirm the existence of an approximate analogy between heat and mass transfer within the range of low nitrogen concentrations.

The test data on mass transfer during a forced flow of a vapor–gas mixture fit the following equation:

$$Nu_D = 6.272 \cdot 10^{-3} Re^{0.89} Pr_D^{0.56} \left(\frac{P_V}{P_M}\right)^{-0.85}. \tag{3}$$

By analogy, for the heat transfer within the same range of concentrations we have obtained

$$Nu = 2.64 \cdot 10^{-3} Re^{0.89} Pr^{0.56} \left(\frac{P_V}{P_M}\right)^{-0.93}. \tag{4}$$

These equations describe the test results within a ±8% accuracy.

Zone of Intermediate Nitrogen Concentrations. At the upper limit of this zone the partial pressure of nitrogen is equal to its critical pressure P_{cr}; at the lower limit the nitrogen concentration is 10%.

The rate of nitrogen condensation from the mixture in this zone is much higher than in the other zone, because both heat and mass transfer are characterized here by high temperature and concentration drops.

An analysis of test data has shown that no analogy between heat and mass transfer exists here.

The generalization of test data in criterial form was based on relations (1) and (2). A further evaluation (Fig. 2a) has yielded the following relation:

$$\mathrm{Nu}_D = 0.434 \cdot \mathrm{Re}^{1.0} \mathrm{Pr}_D^{0.3} \left(\frac{P_M}{P_{cr}}\right)^{0.5} \left(\frac{\Delta P_V}{P_M}\right)^{0.68}, \tag{5}$$

with which all segments of this zone can be described within a ±15% accuracy.

Another data evaluation (Fig. 2b) has yielded for the heat transfer between the vapor–gas stream and the interphase boundary within the zones of high and intermediate nitrogen concentrations:

$$\mathrm{Nu} = 0.116\,\mathrm{Re}^{1.0} \mathrm{Pr}^{0.3} \left(\frac{P_M}{P_{cr}}\right)^{0.5} \left(\frac{\pi_\omega}{\mathrm{Re}}\right)^{0.43}. \tag{6}$$

The effect of mass transfer on heat transfer, as has been pointed out earlier, is accounted for by the additional criterial π_ω-number. Equation (6) describes all segments within a ±16% accuracy.

It is to be noted that Eqs. (3)-(6) reflect the effect of condensate film thickness insofar as the latter influences the temperature trends at the interphase boundary and in the mainstream — measured directly in the tests [2].

Zone of Supercritical Partial Pressure of Nitrogen (range of high nitrogen concentrations in the mixture). As the vapor–gas mixture was cooled at a partial pressure of the active component above critical, the trend of nitrogen condensation from the nitrogen–helium mixture was not evident. Test data have shown that, starting at the critical temperature, the partial pressure of nitrogen drops fast as the mixture is cooled further. This drop is, apparently, due to a splitting of the mixture into liquid nitrogen which concentrates at the cold tube wall and mixture which retains nitrogen within the gaseous helium.

The migration of nitrogen from the bulk of the vapor–gas stream toward the wall can be explained by thermodiffusion which, as is well known, causes heavier molecules to move toward a cold wall. The nitrogen concentration in the mainstream drops fast, i.e., at a very low tube height the drop in partial pressure is large. This indicates that the splitting of the mixture due to thermodiffusion is a violent process which produces large differences between partial pressures of nitrogen in the mainstream and at the liquid film.

Thus, the onset of thermodiffusion brings about a diffusion due to a large partial-pressure difference and the total effect is a high process rate.

Such very complex changes in the physical structure of this zone notwithstanding, and considering that the temperature as well as the partial pressure in the mainstream and at the interphase boundary differ appreciably, one can determine the local heat and mass transfer coefficients on the basis of conventional concepts.

This would not be expedient in this particular case, however, because the high-concentration zone — if it exists — covers only an insignificant part of the apparatus surface. Therefore, it is sufficient to determine the surface covered by the other two zones and to increase the amount by 8-10% accounting for this third zone.

NOTATION

$\mathrm{Nu} = \alpha d/\lambda$	is the Nusselt number for heat;
$\mathrm{Nu}_D = \beta_c d/D_c$	is the Nusselt number for diffusion;
$\pi_g = \Delta P_V/P_M$	is the effect of density in the transverse current on mass transfer;
$\pi_\omega = g_V d/\mu g$	is the effect of the transverse current on heat transfer;
$\varepsilon_G = P_G/P_M$	is the effect of Stefan current on mass transfer;
R_V/R_G	is the ratio of vapor gas constant to inert-gas gas constant;
C_V/C	is the ratio of vapor heat capacity to mixture heat capacity;
α	is the coefficient of heat transfer from the vapor–gas stream to the condensate film;
β_c	is the mass transfer coefficient referred to the concentration gradient;
D_c, D_p	is the diffusivity referred to concentration and to mixture pressure respectively;
ν, μ	are the kinematic and dynamic viscosity respectively;
ΔP_V	is the difference between partial pressure of vapor in the mainstream and at the interphase boundary;

P_G	is the partial pressure of the inert component in the mainstream;
P_M	is the mixture pressure;
P_{cr}	is the critical pressure of active component;
$x = \rho_V/\rho_G$	is the ratio of active component density to gas density;
λ	is the thermal conductivity;
a	is the thermal diffusivity.

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