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CONDENSATION HEAT TRANSFER IN THE PRESENCE OF A NON-CONDENSABLE GAS

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Abstract—Potassium vapor is condensed in the presence of various total amounts of argon or helium as non-condensable gases. It is shown that the rate of condensation is governed by the ordinary molecular diffusion equations, the effect of thermal diffusion is negligible. Some influence of natural convection was observed when argon, the heavier of the two non-condensable gases, was present.

NOMENCLATURE

A,	area;
C,	constant;
c_p,	specific heat;
D_{ij},	binary diffusion coefficient;
D_i^T,	thermal diffusion coefficient;
g,	gravitational acceleration;
h,	enthalpy or heat-transfer coefficient;
h_{fg},	latent heat of vaporization;
J_u,	energy flux;
j,	mass flux with respect to mass average velocity;
K,	Boltzmann constant;
k,	thermal conductivity;
k_T,	thermal diffusion ratio;
L,	Avogadro's number or length;
M,	molecular weight;
m,	mass per molecule;
n,	number density;
p,	pressure per unit area;
q_c,	condensation heat flux;
R,	universal gas constant;
T,	temperature;
T_{Av},	average temperature;
t,	effective gas thickness;
$\bar{V}$,	diffusion velocity;
$\bar{v}$,	average molecular velocity;
v_0,	mass average velocity;
W,	mass of non-condensable gas;
w,	mass flux;
X_k,	external forces;
ε_0,	emissivity;
ρ,	density.

Subscripts

i, j,	i-th and j-th components;
l,	liquid;
m,	vapor–gas mixture;
1,	vapor;
2,	non-condensable gas.

THE PRESENCE of a non-condensable gas in a vapor which is condensing on a cold surface presents a diffusional resistance which often is the major resistance in the heat-transfer path. As a result of the mass flow of the vapor toward the surface, this non-condensable gas tends to collect at, or be more concentrated near, the cold surface.

The work described here is an experimental and analytical study of potassium condensing in the presence of non-condensable helium and argon, on the underside of a horizontal cold surface.

EXPERIMENTAL APPARATUS

A detailed drawing presenting the major system components is shown in Fig. 1 [1, 2].

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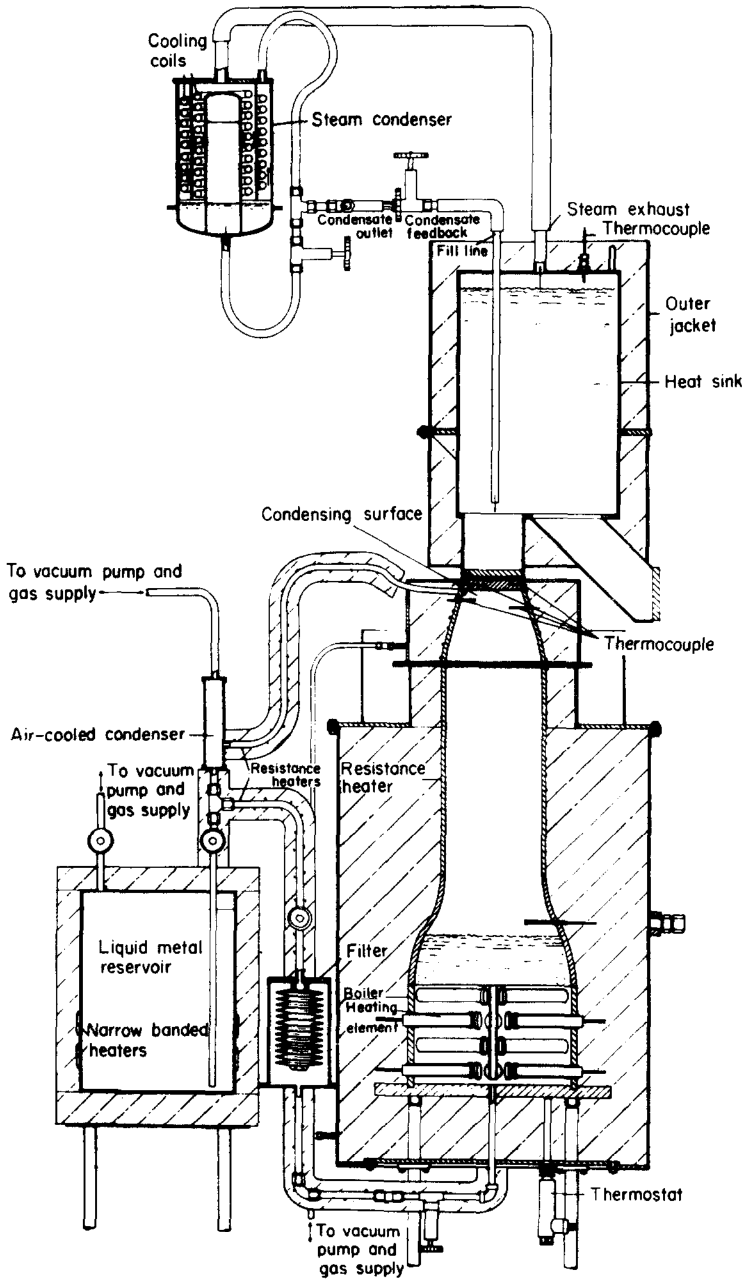

FIG. 1. Apparatus.

Low sodium grade potassium (25 lb) was supplied by the M.S.A. Company in a stainless steel container.

The boiler is fitted with thirty-two radially located, sheathed Watlow Firerod heaters (4-in long, 0·622-in O.D.) with porous welds [3] to ensure stable boiling. Attached to the outside of the vapor space is a resistance heater to compensate for heat losses to the environment.

The vapor is condensed at the top of the vapor space where heat is transferred to boiling water in the upper chamber.

The condensing surface at the top of the vapor space is a 4-in dia., 0·75-in thick horizontal disk of either nickel 200 or stainless steel 316. Two sets of three thermocouple holes (0·063-in dia.) are located radially 0·75 in and 1·50 in. in from the circumferential edge. Two of each set are at $\frac{1}{16}$ in. in from either face and one on the center plane. The thermocouples are 0·062-in sheated chromel–alumel wire. The temperature in the vapor space was measured by three thermocouples at $\frac{1}{4}$ in, $\frac{1}{2}$ in and 1 in below the condensing surface. Two thermocouples were located in the lower chamber immediately above the liquid surface. Also one thermocouple was placed in the liquid itself. In order to check the radial heat flow to the condensing surface, two thermocouples were located in the upper system wall, 0·25 in and 0·625 in from the condensing surface.

To verify that the potassium system was leak-tight, the potassium was boiled and the system purged for 21 h. It was then evacuated to 10^{-3} in Hg and allowed to stand for 4 days. No detectable leakage was observed.

Known amounts of filtered and dried helium or argon were added to the pure potassium vapor by measured volume displacement.

The heat flux was determined by the three thermocouples located 1·50 in. in from the edge of the condensing surface. These readings were extrapolated to determine the surface temperature of the condensing surface.

The radiation heat flux q_r was subtracted from the measured heat flux $q_{c\,\mathrm{exp}}$ to obtain the condensation heat flux reported in Tables 1 and 2. Assuming the vapor to be at the temperature of the liquid surface, T_L at $y = L$, and assuming the liquid condensate running down the side walls is also at this temperature, the radiation heat flux between the cold wall at T_0 and the system is

$$q_r = A\varepsilon_0\sigma(T_L^4 - T_0^4)$$

where ε_0 may be obtained from the data presented by Frehafer [7] which was verified theoretically by Mott and Jones [8]. It was assumed that ε_0 is directly proportional to the absolute temperature with a value of 0·06 at 520°R.

TEST RESULTS

A total of ten test runs were made with helium and fourteen with argon in the potassium vapor as presented in Tables 1 and 2. Here T_L is the temperature of the vapor at the vapor generating surface. The corresponding saturation vapor pressure is obtained from the following equation:

$$\log_{10} p = 4{\cdot}185 - \frac{7797{\cdot}6}{T} \qquad (1)$$

where p is in atmospheres and T in degrees Rankine [4]. The condensing surface temperature is T_0.

Since any non-condensable gas tends to accumulate near the cold surface, this amount of gas was expressed in terms of a layer of effective thickness t of the non-condensable gas at the total pressure and at an average temperature $T_{Av} = 0{\cdot}5\,(T_L + T_0)$

$$t = \frac{WR\,T_{Av}}{AM_2p} \qquad (2)$$

where A is the area of the condensing surface and W the mass of gas.

The test data of Tables 1 and 2 for $T_L = 1300$°F are shown plotted in Figs. 2 and 3 as h_c vs. t for various T_0. The data show the expected pronounced decrease in h_c for the addition of small amounts of non-condensable gas. Test 11

Table 1. Experimental data and results for

Test No.	T_1 (°F)	T_0 (°F)	W ($lb_m \times 10^{-6}$)	t in	$q_{c\,exact}$ (Btu/h ft^2)	$q_{c\,approx}$ (Btu/h ft^2)	q_{exp} (Btu/h ft^2)
1	1108	900	0·70	0·159	19350	19229	25000
2	1293	900	1·55	0·109	34300	33822	29500
3	1305	1129	0·70	0·050	51200	51959	42000
4	1312	886	2·84	0·183	20950	20462	23000
5	1215	674	2·84	0·296	13400	12842	13000
6	1250	517	8·26	0·660	6220	5853	7000
7	1315	616	8·26	0·479	8710	8197	9700
8	1293	640	4·19	0·276	14850	14099	17000
9	1292	630	5·78	0·381	10800	10219	15000
10	1300	1207	0·30	0·023	71000	73100	69000
11*	1218·25	1216·0	0·00	0·000	—	—	29405

$q_{c\,exp} = q_{exp} - q_r$

Table 2. Experimental data and results for

Test No.	T_1 (°F)	$T_{0\,min}$ (°F)	$T_{0\,max}$ (°F)	W ($lb_m \times 10^{-6}$)	t (in)	$q_{c\,exact}$ (Btu/h ft^2)	$q_{c\,approx}$ (Btu/h ft^2)	q_{exp} (Btu/h ft^2)
1	1235	1005	1027	8·82	0·091	8750	8834	18000
2	1304	1062	1095	8·81	0·063	12700	12919	23500
3	1379	1170	1187	8·56	0·042	16740	17196	27500
4	1407	1085	1118	23·87	0·101	8850	8900	25500
5	1325	819	832	61·14	0·359	2850	2796	7000
6	1365	766	770	106·93	0·263	2100	2047	6100
7	1291	920	1005	9·88	0·072	13000	13136	29200
8	1378	870	1030	14·72	0·067	15000	15110	29200
9	1413	898	910	18·69	0·072	14000	14071	29000
10	1414	773	795	31·72	0·117	9000	8878	23000
11	1398	718	733	33·83	0·133	8000	7850	19800
12	1412	1300	1303	6·09	0·027	17000	17541	30000
13	1350	1200	1205	5·26	0·031	19000	19655	32000
14	1300	1250	1252	1·28	0·010	25000	26248	39600

$q_{c\,exp} = q_{exp} - q_r$

of Table 1 shows a measurement with no non-condensable gas present resulting in h_c = 13069 Btu/h ft^2 °F with a $T_L - T_0 = 2{\cdot}25$°F at a $q/A = 29405$ Btu/h ft^2. This suggests that for all of the runs in which gas was present, the temperature drop across the liquid condensate layer and across the liquid–vapor interface is negligible compared with the magnitudes of $(T_L - T_0)$. Also shown in Figs. 2 and 3 are curves representing the predicted results as discussed in the next section.

Figure 4 shows for tests 5 and 7 with helium, the temperature measurements in the vapor space below the condensing surface (as crosses) and in the side wall of the container (as circles). Comparison with the analysis will be made in a later section.

ANALYSIS

Consider a simple one-dimensional model, as shown in Fig. 5, in which potassium vapor is continuously generated at $y = L$, diffuses through a non-condensable gas, and condenses at $y = 0$. The distribution of temperature and *potassium condensing in the presence of helium*

q_r (Btu/h ft^2)	$(q_{\text{exp}} - q_r)$ (Btu/h ft^2)	$\frac{(q_{c\,\text{exact}} - q_{c\,\text{approx}})}{q_{c\,\text{exact}}}$ (per cent)	$h_{c\,\text{exact}}$ (Btu/h ft^2)	$h_{c\,\text{approx}}$ (Btu/h ft^2)	$h_{c\,\text{exp}}$ (Btu/h ft^2)	$\frac{h_{c\,\text{exp}} - h_{c\,\text{exact}}}{h_{c\,\text{exact}}}$ (per cent)
707	24293	0·625	93·0	92·4	117·01	+25·8
1615	27885	1·395	87·3	85·2	71·0	−18·7
1045	40955	−1·485	291·0	295·2	232·0	−20·3
1745	21255	2·330	49·3	48·0	49·8	+1·0
1490	11510	4·170	24·8	23·7	21·3	−14·1
1470	5530	5·900	8·5	8·0	7·5	−11·8
1830	7870	5·900	12·5	11·7	11·3	−9·6
1740	15260	5·060	22·7	21·6	23·4	+3·1
1725	13275	5·380	16·4	15·4	20·0	+21·9
617	68383	−2·960	764·0	786·0	735·0	−3·8
—	—	—	—	—	13069	—

potassium condensing in the presence of argon

q_r (Btu/h ft^2)	$(q_{\text{exp}} - q_r)$ (Btu/h ft^2)	$\frac{(q_{c\,\text{exact}} - q_{c\,\text{approx}})}{q_{c\,\text{exact}}}$ (per cent)	$h_{c\,\text{exact}}$ (Btu/h ft^2)	$h_{c\,\text{approx}}$ (Btu/h ft^2)	$h_{c\,\text{exp}}$ (Btu/h ft^2)	$\frac{h_{c\,\text{exp}} - h_{c\,\text{exact}}}{h_{c\,\text{exact}}}$ (per cent)
1055	16945	−0·96	38·00	38·41	73·8	+94·2
1295	22205	−1·73	52·50	53·38	91·8	+75·0
1400	26100	−2·73	80·00	82·28	124·8	+55·0
1970	23530	−0·57	27·50	27·64	73·1	+166·0
1890	5110	1·90	5·63	5·52	10·2	+81·1
2140	3960	2·52	3·51	3·42	6·6	+88·1
1575	27625	−1·05	35·0	35·41	74·5	+113·0
2170	27030	−0·73	29·50	29·74	53·3	+80·7
2430	26570	−0·51	27·20	27·32	51·7	+90·0
2430	20570	0·24	14·05	13·85	32·1	+128·5
2360	17440	1·88	11·77	11·54	25·7	+118·5
1035	28965	−3·18	152·00	156·62	259·0	+70·4
1025	30975	−3·45	126·00	131·04	206·0	+62·7
353	39247	−5·00	500·00	524·00	784·9	+56·8

of the potassium and gas partial pressure is shown sketched in Fig. 5. In this apparatus L is approximately 18 in. As discussed in the previous section, the temperature drop across the condensate layer and its liquid–vapor interface is negligible compared with measured magnitudes of $(T_L - T_0)$.

For the more modest temperature gradients encountered in condensation heat-transfer problems the effects of thermal diffusion are negligible, as shown in the Appendix, and the following mass diffusion equation is applicable.

$$w = -\frac{DM_1 p}{RT(p - p_1)}\frac{\mathrm{d}p_1}{\mathrm{d}y} \qquad (3)$$

where

$$D = \frac{CT^{\frac{3}{2}}}{p} \qquad (4)$$

and $C = 0·348$ for K–He and $0·091$ for K–A.

For the conditions of these tests the temperature drop across the thin liquid condensate layer is negligible; hence T_0 is taken as the temperature of the liquid–vapor interface.

Integrate equation (3) between p_{10} at $y = 0$ and p_1 at y to obtain

$$\frac{p - p_1}{p - p_{10}} = \exp\left(\frac{wRy}{M_1\, C\, T^{\frac{1}{2}}_{Av}}\right) \tag{5}$$

where T is replaced by $T_{Av} = (T_0 + T_L)\,2$ since the diffusion process is most prominent near the cold surface.

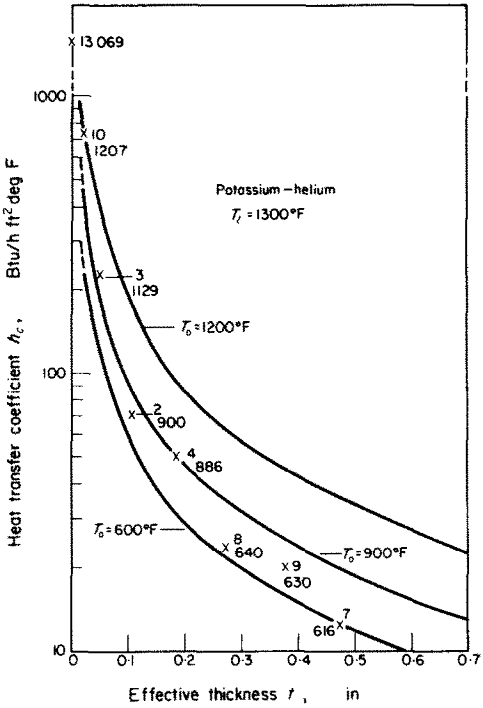

FIG. 2. Heat-transfer coefficient vs. effective gas thickness.

From this equation the average pressure of the non-condensable gas $p_{2m} = (p - p_{1m})$ may be obtained by integrating equation (5) over the total system height and dividing by L.

$$p_{2m} = (p - p_{10})\frac{M_1 C T^{\frac{1}{2}}_{Av}}{wRL} \times \left[\exp\left(\frac{wRL}{M_1 C T^{\frac{1}{2}}_{Av}}\right) - 1\right].$$

In the system studied here the exponential term in the brackets is very small since L is relatively large; therefore

$$p_{2m} = -(p - p_{10})\frac{M_1 C T^{\frac{1}{2}}_{Av}}{wRL}. \tag{6}$$

Note in this coordinate system w is negative for condensation.

For the perfect gas relation the effective thickness t may be expressed as follows

$$t = \frac{p_{2m}}{p} L\,. \tag{7}$$

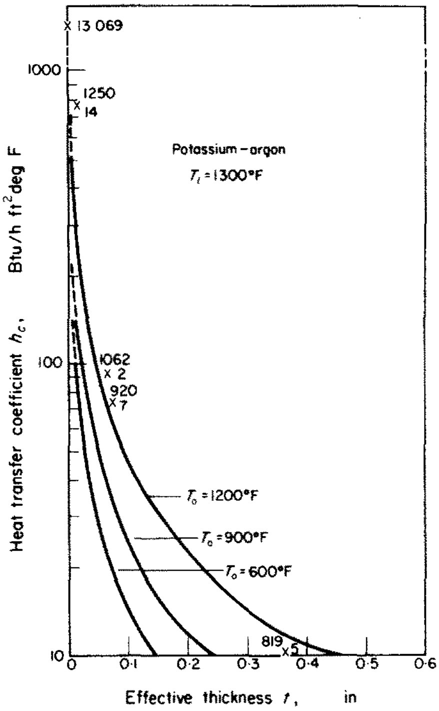

FIG. 3. Heat-transfer coefficient vs. effective thickness.

Substitute this in equation (6) to obtain:

$$w = -\frac{(p - p_{10})\, M_1 C T^{\frac{1}{2}}_{Av}}{pRt}. \tag{8}$$

The condensation heat flux at the cold wall may be expressed in terms of the enthalpy

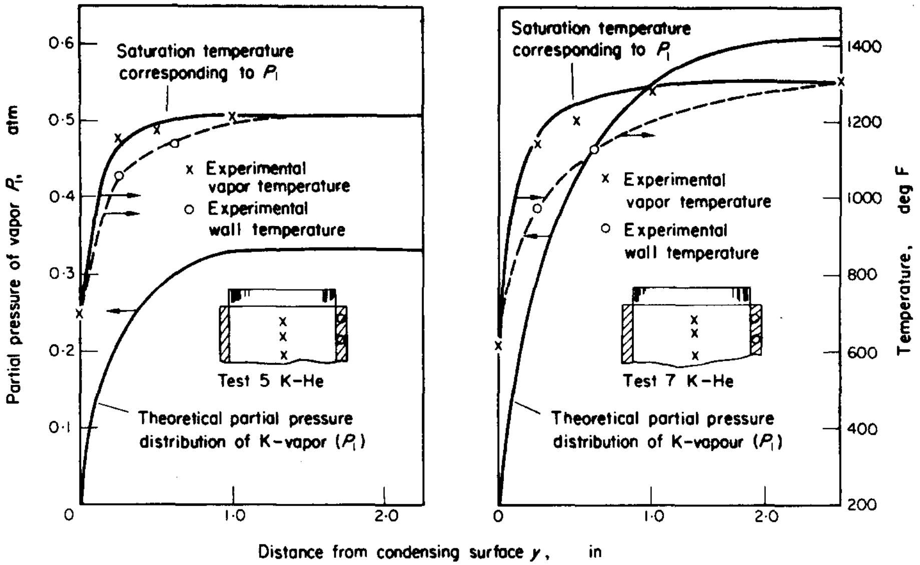

FIG. 4. Partial pressure and temperature distribution vs. distance from condensing surface.

change:

$$q_c = - w[h_{fg} + c_p(T_L - T_0)]. \tag{9}$$

From measurements w is calculated from equation (8) and then q_c from equation (9).

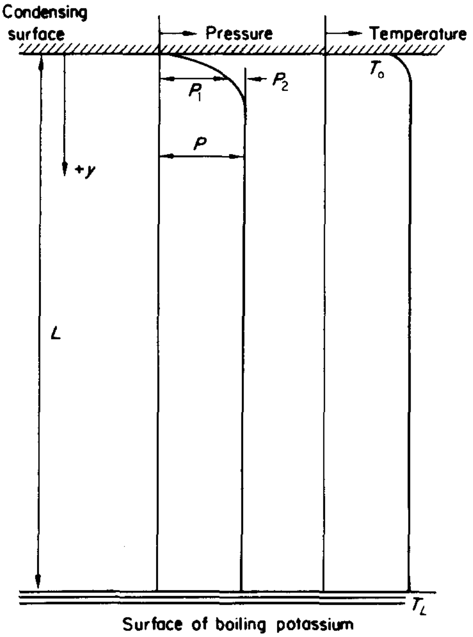

FIG. 5. Condensation of potassium vapor in the presence of a non-condensable gas.

The condensation heat-transfer coefficient may be expressed as

$$h_c = \frac{q_c}{(T_L - T_0)} = \frac{(p - p_{10})}{p} \times \frac{M_1 C T_{Av}^{\frac{1}{2}}[h_{fg} + c_p(T_L - T_0)]}{tR(T_L - T_0)}. \tag{10}$$

This is the equation used to predict h_c from the temperature measurements and with a known quantity of gas present. A more exact analysis of this process is given in the Appendix.

DISCUSSION OF RESULTS

In Tables 1 and 2 magnitudes of q_c calculated from equation (9) are reported and compared with the measured heat flux q_{exp} less the correction for radiation. Very good agreement is obtained for the case of potassium condensing in the presence of helium. The comparison between experiment and prediction is shown in Figs. 6 and 7. (Also included in Tables 1 and 2 are the magnitudes of q_c predicted by the more exact method outlined in the Appendix.)

In Fig. 4 for tests 5 and 7 one of the solid curves represents the calculated distribution of the partial pressure of the potassium vapor near the cold surface. The other solid curve is the saturation temperature corresponding to this partial pressure. The crosses are the temperature measurements taken in the vapor showing good agreement with the calculated results.

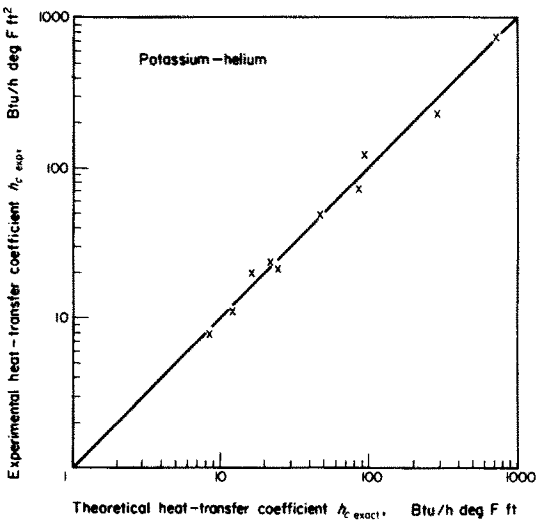

FIG. 6. Comparison of experimental heat-transfer coefficient to theoretical heat-transfer coefficient.

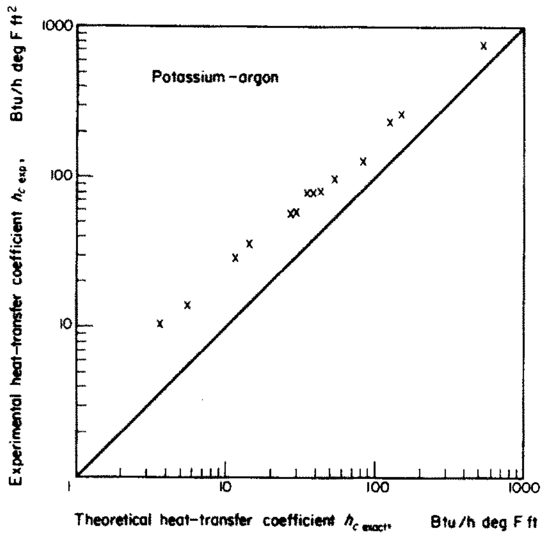

FIG. 7. Comparison of experimental heat-transfer coefficient to theoretical heat-transfer coefficient.

The experimental data and results for a potassium–argon mixture are presented in Table 2. Two values for the wall temperature are given, i.e. $T_{0\,\mathrm{min}}$ and $T_{0\,\mathrm{max}}$. During these experiments a quasi-steady operating state was never attained. Although the liquid temperature T_L and the amount of gas in the system was maintained constant for a specific test, the condensing wall temperature tended to fluctuate significantly throughout the test. For each test the maximum and minimum wall temperature was thus noted over a period of one hour or longer. All calculations were based on the minimum wall temperature reading.

In all cases the experimental heat-transfer coefficient is larger than the theoretical value, Fig. 7, improving slightly for larger values of h_c, i.e. usually for tests having smaller quantities of argon present.

This discrepancy may be ascribed to the following:

(a) Lateral conduction into the cold surface from the side walls could result in flow paths and lines of constant argon concentration as shown in Fig. 8. Although the conduction path between the system walls and condensing plate was made as thin as possible, quantities of potassium condense on the walls which conduct away the resultant heat flux into the disk. This results in a distribution of argon over an area, larger than considered in the calculations, resulting in a smaller effective thickness at the center-line where a greater heat flux may thus be expected.

(b) Because of the diffusion of potassium towards the system wall, as described in (a), there will be a resultant temperature gradient in that direction. Since argon has almost the same molecular weight as potassium, the density near the walls will be greater than at the center giving rise to convective currents as envisioned in Fig. 9. This convective pattern is further encouraged by the condensate film on the walls and the fact that the diffusion coefficient for potassium–argon is low. A further considerable decrease in the effective thickness of argon may thus be expected at the center of the plate. In addition pure potassium vapor is carried towards the condensing surface in the core of the convective current. Both these effects tend to increase the heat flux.

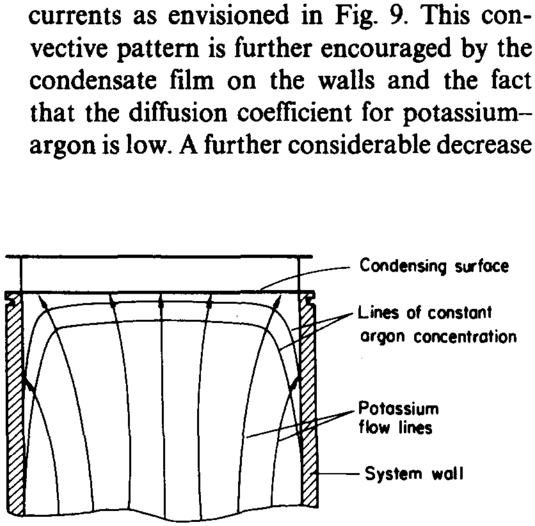

FIG. 8. Potassium condensing in the presence of argon.

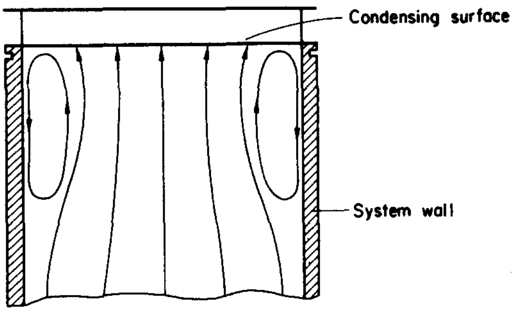

FIG. 9. Convective pattern due to density gradients at the wall.

(c) As was mentioned the temperature at the center of the disk fluctuated continuously. In a typical test the rate of fluctuation was noted. The temperature slowly fell from $T_{0\,\max}$ to $T_{0\,\min}$ in about 3 min. After remaining at $T_{0\,\min}$ for a few seconds, it suddenly rose to $T_{0\,\max}$ in a period of about 18 s. After about 30 s, it again began to fall. Although not all fluctuations in any one test were identical, the times for the different phases were of the same order.

This phenomenon is explained in the following manner. The slow fall in T_0 is due to the accumulation of argon at the condensing surface as a result of diffusion and convection. This results in a corresponding density rise at the condensing surface until the unstable situation so created is disturbed and the argon is suddenly removed, clearing the surface and exposing it to purer and hotter vapor. This immediately results in a larger heat flux, tending to rapidly raise the wall temperature after which the cycle is repeated. It is clear that this mechanism may result in a considerable increase in the average condensation heat-transfer rate.

Parenthetically, we mention here the results of tests performed early in this program on condensing of potassium with the same non-condensable gases on a 4 × 4 in square vertical surface in the same apparatus. In these tests instabilities were also observed. These were attributed to the existence of natural convection effects. In all cases the measured h_c was higher than the predicted magnitude.

CONCLUSIONS

Heat transfer associated with condensation in the presence of non-condensable gases can be predicted by the diffusion analysis outlined in the Appendix and is closely approximated by simpler analysis leading to equation (10).

The effect of superimposed natural convection effects can be significant. These effects generally produced greater heat fluxes than those predicted by the diffusion analysis; in that sense the prediction method is conservative.

ACKNOWLEDGEMENTS

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APPENDIX

Diffusion Analysis

Consider the simple one-dimensional model as shown in Fig. 5 in which saturated potassium vapor, continuously generated at ($y = L$) diffuses through a non-condensable gas and condenses at the surface ($y = 0$). The latter surface may be regarded as being impervious to the gas, but not to the vapor.

According to Hirschfelder and Curtiss [6] the energy flux per unit area through a surface fixed with respect to the condensing surface in this case is given by

$$J_u = -k_m \frac{\mathrm{d}T}{\mathrm{d}y} + \sum_{i=1}^{\nu} h_i n_i m_i (\bar{V}_i + v_0) + \frac{KT}{n} \sum_{i=1}^{\nu} \sum_{\substack{j=1 \\ j \neq i}}^{\nu} \frac{n_j D_i^T}{m_i D_{ij}} (\bar{V}_i - \bar{V}_j) \qquad \text{(A.1)}$$

where k_m is the thermal conductivity of the vapor–gas mixture (see [6]) h_i is the enthalpy per unit mass of the i-th component, K is the Boltzmann constant, n_i, n_j and n are the number densities of the components and the mixture respectively, D_{ij} and D_i^T are the binary diffusion and thermal diffusion coefficients respectively (see [6]), v_0 is the mass average velocity, m_i is the mass of the i-th particle and $\bar{V}_i$ and $\bar{V}_j$ are the diffusion velocities of components i and j respectively.

In the present two-component system, let subscript 1 refer to the vapor and 2 to the gas. The diffusion velocity of the vapor may be expressed as

$$\bar{V}_1 = -\frac{n^2 m_2}{\rho n_1} D_{12} d_1 - \frac{D_1^T}{n_1 m_1 T} \frac{\mathrm{d}T}{\mathrm{d}y} = \bar{v}_1 - v_0 \qquad \text{(A.2)}$$

where ρ is the mass density and $\bar{v}_1$ is the average molecular velocity. The expression for d_1 includes concentration and pressure gradients as well as the effects of external forces X_k acting on the molecules.

$$d_1 = \frac{\mathrm{d}}{\mathrm{d}y}\left(\frac{n_1}{n}\right) + \left(\frac{n_1}{n} - \frac{n_1 m_1}{\rho}\right) \frac{\mathrm{d}\ln p}{\mathrm{d}y} - \frac{n_1 m_1}{p} \times \left[\frac{\rho}{m_1} X_1 - \sum_{k=1}^{\nu} n_k X_k\right]. \qquad \text{(A.3)}$$

In this case the only external force acting on the molecules is that of gravity, i.e. $X_i = m_i g$.

Thus for a two-component system:

$$\sum_{k=1}^{2} n_k X_k = (n_1 m_1 + n_2 m_2) g = \rho g.$$

The external force term in the expression for d_1 thus vanishes.

The gravitational acceleration, however, does lead to pressure diffusion. In the present system the variation in total pressure is less than 0·005 per cent and the second term containing $\mathrm{d}/\mathrm{d}y\,(\ln p)$ may be ignored.

Since the non-condensable gas is stagnant with respect to the fixed reference frame chosen, $\bar{v}_2 = 0$, and it follows from equation (A.2) that the mass average velocity is

$$v_0 = -\left(\frac{n^2 m_1}{\rho n_2} D_{12} \mathrm{d}_1 + \frac{D_1^T}{n_2 m_2 T} \frac{\mathrm{d}T}{\mathrm{d}y}\right).$$

The mass flux of component 1 with respect to the mass average velocity v_0 is

$$j_1 = n_1 m_1 \bar{V}_1 = \frac{n^2}{\rho} m_1 m_2 D_{12} d_2 - \frac{D_1^T}{T}\frac{\mathrm{d}T}{\mathrm{d}y}.$$

Similar expressions may be obtained for component 2. Taking the difference of these two expressions gives

$$\bar{V}_1 - \bar{V}_2 = -\frac{n^2}{n_1 n_2} D_{12}\left[\frac{\mathrm{d}}{\mathrm{d}y}\left(\frac{n_1}{n}\right) + \frac{k_T}{T}\frac{\mathrm{d}T}{\mathrm{d}y}\right] \tag{A.4}$$

where k_T, known as the thermal diffusion ratio is defined by

$$k_T = \frac{\rho}{n^2 m_1 m_2}\frac{D_1^T}{D_{12}}. \tag{A.5}$$

A theoretical first approximation to the thermal diffusion ratio k_T is presented in [6].

According to equation (A.1) energy may be transported through a mixture by three mechanisms: (i) heat conduction; (ii) enthalpy flux; and (iii) a "reciprocal process" due to thermal diffusion.

During steady-state operation almost no gas will be found at the vapor generating surface, thus eliminating temperature and pressure gradients for all practical purposes. This means that the energy flux J_u across a fixed surface in this region will consist solely of the enthalpy flux of the vapor if the kinetic energy may be neglected. Furthermore, due to the conservation of energy, J_u remains constant throughout the system.

$$J_u = h_L w \tag{A.6}$$

where h_L is the enthalpy of the vapor and w is the vapor mass flux per unit area at $y = L$.

Substitute equations (A.2) through (A.5) into equation (A.1) to obtain

$$J_u = -\left[k_m + \left(\frac{k_T}{T}\right)\alpha\right]\frac{\mathrm{d}T}{\mathrm{d}y} - \alpha\frac{\mathrm{d}}{\mathrm{d}y}\left(\frac{n_1}{n}\right) \tag{A.7}$$

where

$$\alpha = \frac{D_{12} n^2}{\rho}\left(h_1 m_1 m_2 + \frac{h_1 n_1 m_1^2}{n_2} + \frac{k_T p \rho}{n_1 n_2}\right)$$

and the total system pressure $p = nKT = p_1 + p_2$ is constant.

According to the equation of state, the following relations exist:

$$n = \frac{pL}{RT}, \qquad n_1 = \frac{p_1 L}{RT}, \qquad n_2 = \frac{p_2 L}{RT}$$

where L is Avogadro's number and R is the universal gas constant. Further

$$m_1 = \frac{M_1}{L}, \qquad m_2 = \frac{M_2}{L}$$

and $\rho = m_1 n_1 + m_2 n_2$ where M_1 and M_2 are the molecular weights of components 1 and 2, respectively. Substitute these relations in (A.7) to obtain

$$J_u = -\left[k_m + \frac{\beta p k_T}{T}\right]\frac{\mathrm{d}T}{\mathrm{d}y} - \frac{\beta\,\mathrm{d}p_1}{\mathrm{d}y} \tag{A.8}$$

where

$$\beta = \frac{p D_{12}}{(p - p_1)}\left[\frac{h_1 M_1}{RT} + \frac{k_T p}{p_1}\right].$$

Another expression relating p_1 and T is obtained by applying the mass conservation equation to the vapor, i.e.

$$m_1 n_1 \bar{v}_1 = m_1 n_1 \bar{V}_1 + m_1 n_1 v_0 \tag{A.9}$$

or

$$w = m_1 n_1 (\bar{V}_1 + v_0).$$

Substitute (A.2) and (A.3) in (A.9), and find

$$w = -D_{12}\frac{m_1 n^2}{\rho}\left(m_2 + \frac{m_1 n_1}{n_2}\right)\frac{\mathrm{d}}{\mathrm{d}y}\left(\frac{n_1}{n}\right) - \frac{D_1^T}{T}\left(1 + \frac{m_1 n_1}{m_2 n_2}\right)\frac{\mathrm{d}T}{\mathrm{d}y}.$$

This is further simplified by introducing k_T and applying the perfect gas relations

$$w = \frac{-D_{12} M_1 p}{RT(p - p_1)}\left[\frac{\mathrm{d}p_1}{\mathrm{d}y} + \frac{k_T p}{T}\frac{\mathrm{d}T}{\mathrm{d}y}\right] \tag{A.10}$$

Equations (A.8) and (A.10) are two simultaneous non-linear differential equations and can be solved numerically to give the temperature and partial pressure distributions in the system. The condensation heat-transfer rate, q_c is given by equation (9).

To find q_c the following procedure is proposed in cases where the film and interfacial resistance is negligible.

Given T_0 and T_L for the system containing a known amount of gas per unit condensing area, a first guess is made for w. Substitute in (A.10) and solve for the temperature distribution with boundary conditions T_0 and T_L and the pressure distribution with boundary conditions $p_1 = p$ at $(y = L)$ and p_{10} the saturation pressure corresponding to T_0 at $(y = 0)$. Knowing the temperature and partial pressure distribution of the gas makes it possible to calculate numerically, from the equation of state, the mass of gas in the system corresponding to the chosen value of w. If this gas mass does not agree with the known quantity in the system, a new value for w is chosen until the agreement is obtained. The final choice of w is then substituted in equation (9) and q_c is found.

For engineering purposes a more approximate but adequate solution for finding the condensation heat-transfer rate is suggested.

Usually for small quantities of gas

$$\frac{k_T p}{T}\frac{\mathrm{d}T}{\mathrm{d}p_1} \ll 1,$$

and the resulting second term in equation (A.10) may be neglected resulting in equation (3) and leading to equation (10). For the K–He tests here Fig. 10 shows that the magnitude of this quantity is always less than 0·05 anywhere in the system.

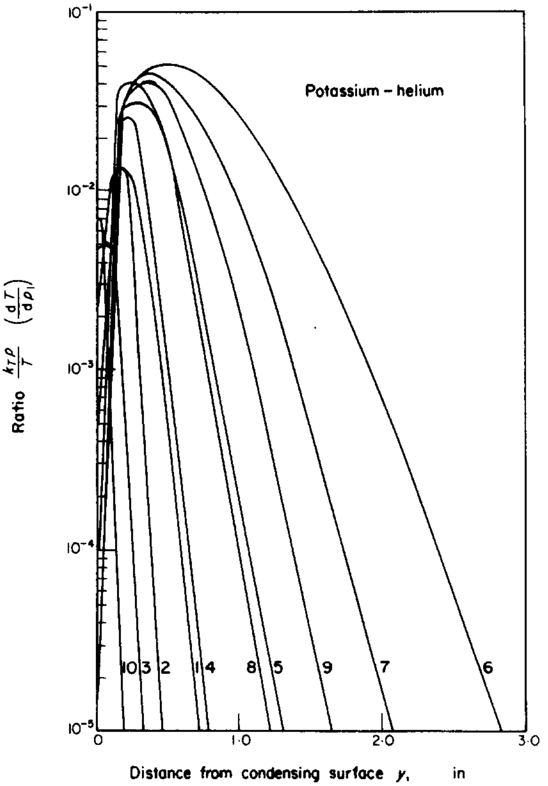

FIG. 10. Ratio $(k_T p/T)(\mathrm{d}I/\mathrm{d}p_1)$ vs. distance from condensing surface for different tests.

Résumé—Du potassium se condense en présence de différentes quantités totales d'argon ou d'hélium qui ne se condensent pas. On montre que le taux de condensation est régi par les équations de diffusion moléculaire ordinaire, l'effet de la diffusion thermique étant négligeable. On a observé une certaine influence de la convection naturelle lorsque l'argon, le plus lourd des deux gaz non-condensables, était présent.

Zusammenfassung—Kalium-Dampf wurde kondensiert in Gegenwart von verschiedenen Mengen Argon oder Helium als Inertgas. Es wurde gezeigt, dass die Kondensationsgeschwindigkeit durch die normalen Diffusionsgleichungen bestimmt wird. Der Einfluss von Thermodiffusion ist vernachlässigbar. Ein Einfluss von natürlicher Konvektion wurde beobachtet, wenn Argon, als schwereres der beiden Inertgase, anwesend war.

Аннотация—Калий конденсировали в присутствии разлияных общих количеств неконденсирующихся газов (аргона или гелия). Показано, что скорость конденсации можно описать обычными уравнениями молекулярной диффузии, где не учитывается термодиффузия. Обнаружено некоторое влияние естественной конвекции при наличии аргона — более тяжелого из двух неконденсирующихся газов.