*Int. J. Heat Mass Transfer.* Vol. 27, No. 10, pp. 1789–1799, 1984
Printed in Great Britain

0017-9310/84 $3.00 + 0.00
Pergamon Press Ltd.

# Investigation of heat transfer in rarefied gases over a wide range of Knudsen numbers

YU. G. SEMYONOV, S. F. BORISOV and P. E. SUETIN
Urals State University, Sverdlovsk, U.S.S.R.

(*Received* 25 *February* 1982)

**Abstract**—The paper presents experimental results on heat exchange of fine metallic filaments with a rarefied gas at different pressures. The investigations were carried out using the transient hot-wire technique in the case of small temperature perturbations. The heat fluxes for a number of inert and some polyatomic gases have been measured under different heat transfer conditions ranging from a molecular to a continuum regime. The experimental results showing the dependence of heat fluxes on the gas rarefaction degree have been compared with the theoretical ones obtained from the solution of the BGK model by the variational method. Under the conditions of molecular heat transfer, the dependence of the energy accommodation coefficients on the kind of material and the state of the filament surface, kind of gas and mean temperature of the system is found. The filaments were made of platinum, nickel, tungsten and tantalum. The surface was cleaned by annealing in high vacuum and in a weak hydrogen atmosphere. Control of the surface state was accomplished by the thermal flash method and by checking a change in the surface emissivity. The degree of filament recrystallization in the process of thermal refining was determined by X-ray structural analysis.

## 1. INTRODUCTION

ACCORDING to the current molecular-kinetic concepts, the heat transfer in a rarefied gas is described as a complex physical process depending on a great number of factors the set of which is specified by the conditions of a particular problem.

An important role in the heat transfer between a gas and a solid body is played by the degree of gas rarefaction or Knudsen number ($Kn$), i.e. the ratio of the molecular mean free path length to the characteristic geometrical dimension of the process [1].

In a dense gas (continuum regime, $Kn \to 0$), the heat transfer is mainly determined by the gas molecule interaction potential and by the frequency of two-body collisions. In the region of high rarefactions (intermediate and, especially, molecular regime, $Kn \to \infty$), a greater effect on heat transfer is exhibited by the frequency of collisions of gas molecules with the surface and the magnitude of the gas–surface interaction potential.

While for the continuum regime it is frequently sufficient to assume the equality of gas and surface temperatures as a boundary condition, for the intermediate and molecular regimes the boundary conditions become more complicated and it is necessary to take into account the nature of energy transfer between the gas molecules and the surface.

Thus, the main problem in the description of heat transfer of moderately and highly diluted gases consists in the assignment of boundary conditions.

At present, the specification of such boundary conditions is based, as a rule, on the concept of energy accommodation coefficient (EAC) which, according to ref. [1], is determined as

$$\alpha = \frac{E_r - E_i}{E_w - E_i} \tag{1}$$

where $E_i$ is the energy of the incident molecules, $E_r$ the energy of reflected molecules, and $E_w$ the energy of reflected molecules that have acquired the surface temperature.

The EAC quantity enters as a parameter into theoretical relationships, some of which (e.g. those obtained on the basis of the temperature jump theory, the moment method with the use of the BGK model) have an analytical form [2, 3], while the others (e.g. those using the variational method of the BGK-model solution) are obtained in a numerical form [4]. In spite of the fact that there is a qualitative agreement between the theoretical relationships obtained by different methods, their quantitative difference is appreciable. For example, for heat transfer in coaxial cylinders the divergence between the values of heat fluxes obtained by the moment and variational methods for the transition regime is 8–12% [4].

In the solution of specific problems, the major difficulty resides in the choice of a numerical EAC value. The EAC is a complicated function of the actual surface properties, kind of gas, temperature and other factors. The available theoretical models of the EAC [5] only approach the real picture of interactions between the gas molecules and the surface.

The uncertainty of the EAC value does not, however, exhaust the whole problem of boundary conditions. The functional relation between the distribution of molecules incident on the surface and reflected from it is usually expressed in the form of Maxwell's diffuse-specular scheme in terms of the EAC. This scheme is virtually the only one, which is widely used, but is far from being adequate. In particular, it does not take into account a change in the nature of interactions of molecules with the surface on variations of the Knudsen number.

In view of this, the experimental investigations may

## NOMENCLATURE

| | |
|---|---|
| $C_p$ | heat capacity of filament material [J kg$^{-1}$ K$^{-1}$] |
| $C_v$ | heat capacity of gas [J kg$^{-1}$ K$^{-1}$] |
| $E_i$ | energy of molecules incident on a surface |
| $E_r$ | energy of reflected molecules |
| $E_w$ | energy of reflected molecules that acquired the surface temperature |
| $k$ | Boltzmann constant [J K$^{-1}$] |
| $l$ | filament length [m] |
| $m$ | filament cooling rate [s$^{-1}$] |
| $m_{rc}$ | filament cooling rate in continuum conditions |
| $m_{fm}$ | filament cooling rate in free-molecular conditions |
| $N_0$ | Avogadro's number [mol$^{-1}$] |
| $P$ | gas pressure [N m$^{-2}$] |
| $q_r$ | radial heat flux between a filament and outer cylinder [W m$^{-2}$] |
| $q_{rc}$ | heat flux in continuum conditions |
| $q_{fm}$ | heat flux in free-molecular conditions |
| $R_1$ | filament radius [m] |
| $R_2$ | inner radius of outer cylinder [m] |
| $r$ | rarefaction parameter, $\frac{2}{3}\delta$ |
| $T_0$ | mean gas temperature [K]. |

Greek symbols

| | |
|---|---|
| $\alpha$ | energy accommodation coefficient (EAC) |
| $\alpha_1$ | EAC on filament surface |
| $\alpha_2$ | EAC on outer cylinder surface |
| $\beta$ | heat transfer coefficient [W m$^{-2}$ K$^{-1}$] |
| $\gamma$ | filament surface emissivity |
| $\delta$ | rarefaction parameter, $(\pi^{1/2}/2)(1/Kn)$ |
| $\kappa$ | electric resistivity of filament [$\Omega$ m] |
| $\lambda$ | thermal conductivity of gas [W m$^{-1}$ K$^{-1}$] |
| $\mu$ | molecular weight of gas [kg mol$^{-1}$] |
| $\rho$ | density of filament material [kg m$^{-3}$] |
| $\phi$ | Stefan–Boltzmann constant [W m$^{-2}$ K$^{-4}$] |
| $\omega$ | thermal conductivity of filament material [W m$^{-1}$ K$^{-1}$]. |

conduce, on the one hand, to the derivation of more quantitatively correct theoretical relationships and, on the other, may relate, by the EAC quantity, the heat fluxes to the microscopic processes occurring on the gas–solid-body interface.

Some experimental works on heat transfer of rarefied gases are available [6–8] which cover a wide range of *Kn*. These studies were made with the use of the stationary hot-wire technique. The method has a number of drawbacks due to rather a considerable heating of the wire (5–10% of the mean gas temperature) causing the onset of convection and making it difficult to determine the mean temperature at which the heat fluxes are measured. Moreover, in the case of a mixture of gases, the undesirable phenomenon of thermal diffusion occurs.

The transient methods of measuring heat fluxes in a rarefied gas [9, 10] have a number of advantages as compared with the stationary ones (convection and thermal diffusion diminish, the process of measurements becomes more rapid and simple). However, because of the complex functional dependence of heat flux on time and the absence of reliable and precise enough instruments for measuring the quickly varying temperature of the filament, the transient measurements involve rather large errors in comparison with the stationary methods.

The analysis of experimental results obtained by the stationary method [6–8] shows a considerable (up to 30%) discrepancy in the data on heat fluxes reported by different authors for the same conditions, as well as the difference, in dimensionless coordinates [3], of points for different gases. This hampers a comparison between the theory and experiment, especially in the region of transition from the continuum to the molecular regime and in the molecular regime region, where the scatter in the experimental data is especially marked. It can be assumed that the spread of the data is associated with inaccurate measurements of small pressures and, as a consequence, with improper determination of the EAC. It can also be assumed that the reason for this can be traced back to the absence of checking the state of the heated surfaces that participate in the process of heat transfer. The latter circumstance plays an especially important role in the case of EAC investigations by the method of low pressures.

Vast experimental data obtained with the use of the low-pressure method [11–14] are available in the published literature on the EAC of gas molecules on metal surfaces. However, in the majority of cases the information on the control of the surface purity is lacking. As a rule, the authors merely report on the temperature of the surface cleaning by thermal desorption and the degree of vacuum.

In the process of thermal refining of surfaces, the oxidic deposits on the surface disintegrate and the impurities are disposed of. Simultaneously with cleaning, the annealing of polycrystalline bodies leads to recrystallization of the material which qualitatively changes the state of the surface. A thermally refined surface may again, partially or fully, cover itself with a layer of residual gas molecules during the process of measurements, just after the cleaning. Thus, an uncertainty in the measurement of the EAC arises due to the physical, chemical and induced inhomogeneities of the surface.

The aim of this paper is the measurement of heat fluxes in a rarefied gas and also of the EAC at the lowest temperature disturbances in the gas medium tested and under the conditions of controlled cleanness of heated surfaces. This is done with the aid of a device which is based on the RC-oscillator and which is able to record small changes in the filament temperature. The use of the RC-oscillator made it possible to substantially increase the accuracy of the transient method, preserving its main advantages.

## 2. EXPERIMENTAL INSTRUMENTATION AND MEASUREMENT TECHNIQUE

The block-diagram of an experimental set-up is presented in Fig. 1. A measuring cell (1) in the form of a hollow stainless steel cylinder, with a metallic filament (2) stretched along its axis, is the main element of the measuring scheme. A test gas is fed into the interior of the cylinder. The metallic filament (2) is connected to a source (3) and a resistance thermometer is switched into the frequency-setting negative feedback circuit of an RC-oscillator the scheme of which (4) was published earlier [15]. The frequency of the RC-oscillator is a function of the filament temperature. It is recorded at regular intervals by a digital frequency meter (5) with the results fed to a numerical printer (6). The tested gas pressure within the cylinder is measured with a capacitance micromanometer (7), the design and operating principle of which are described in detail elsewhere [16].

The frequency signal of the micromanometer is recorded by a digital frequency meter (9) with the information fed to a numerical printer (6). The pressure of the residual gases (after preliminary evacuation of gas from the measuring cell) is determined with a magnetic-ionization vacuum gauge (10). Efficient evacuation of the measuring cell is achieved by a discharge pump NMDO-250 through a branch pipe (11). The zero cavity of the capacitance micromanometer is pumped out through a branch pipe (12). The measuring cell contains also a device in the form of a cryostat filled with liquid nitrogen to sustain low temperatures. Copper–constantan thermocouples for the measurement of the mean gas temperature are attached to the ends of the cell. These elements are not shown on the diagram.

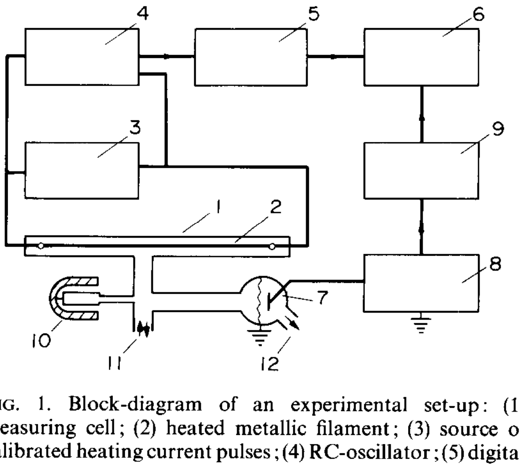

FIG. 1. Block-diagram of an experimental set-up: (1) measuring cell; (2) heated metallic filament; (3) source of calibrated heating current pulses; (4) RC-oscillator; (5) digital frequency meter; (6) numerical printer; (7) capacitance micromanometer; (8) LC-oscillator of capacitance micromanometer; (9) digital frequency meter; (10) magnetic-ionization vacuum-gauge; (11) branch pipe for evacuating the measuring cell and feeding of test gases; (12) branch pipe for evacuating zero cavity of capacitance micromanometer.

The transient hot-wire technique with the use of the RC-oscillator has a number of advantages over similar stationary methods. First, a high sensitivity of the RC-oscillator to the filament temperature ($10^3$ Hz $K^{-1}$) makes it possible to set up an initial temperature difference between the filament and the gas of less than 1°C (less than 0.3% relative to the mean gas temperature) thus excluding convection and also thermal diffusion in the case of gas mixture and ensuring consistency of the system mean temperature Second, the use of the digital frequency meter secures the recording of the cooling process time coordinate with the precision controlled by a quartz oscillator ($\pm 10^{-9}$). Third, the digital data read-out and the speed of the scheme response (each individual measurement in 20 s) allow measurements even at ever changing temperatures and pressures of the gas.

The use of the capacitance micromanometer with a sensitivity of $10^6$ Hz mm $Hg^{-1}$ considerably accelerates the process of pressure measurement as compared with mercury or oil manometers traditionally used for the measurements of the EAC and also allows one to prevent contamination of the measuring cell with mercury or oil vapours.

In the present work, a mean relative error of the measurement of the EAC does not exceed 2%, a relative error of the measurement of heat fluxes does not exceed 0.7% within the whole range of the pressures studied.

The experiment was carried out as follows. After having exhausted the cavity of the measuring cell at a pressure of $1 \times 10^{-9}$ mm Hg, it was filled with a test gas. A 1–2 s heating current pulse was applied to the filament (2) from the source (3). This heated the filament up to some excess temperature and then allowed it to relax to the initial state.

The basic measured quantity in the experiment was chosen to be the rate of filament cooling, $m$, i.e. the logarithmic rate of change of its relative temperature. If at some zero instant of time the difference between the filament and gas temperatures was $\Delta T_0$ and was $\Delta T_i$ ($\Delta T_i < \Delta T_0$) at a subsequent time $t_i$, then in the case of a regular heat transfer regime the following relationship will be valid for the cooling rate [17]

$$\frac{\Delta T_i}{\Delta T_0} = \exp(-mt_i). \tag{2}$$

At small temperature differences, $\Delta T_i$, the relationship between a change in the frequency of the RC-oscillator and the filament temperature is linear and can be presented in the form

$$\frac{\Delta T_i}{\Delta T_0} = \frac{\Delta F_i}{\Delta F_0} = \exp(-mt_i). \tag{3}$$

Here $\Delta F_i$ is the frequency change of the RC-oscillator corresponding to the temperature difference $\Delta T_i$; $\Delta F_0$ is the drop in oscillator frequency corresponding to the initial heating of the filament.

After logarithmic operation, equation (3) yields the expression for the filament cooling rate

$$m = -\frac{1}{t_i}\ln\frac{\Delta F_i}{\Delta F_0}. \tag{4}$$

In the course of the experiment, the frequency drops, entering into equation (4), and the values of time $t_i$, corresponding to these drops, were determined. In order to estimate the regularity of change, plots of the following functions were constructed

$$\ln\frac{\Delta F_i}{\Delta F_0} = f(t_i). \tag{5}$$

Figure 2 shows curves of the above function for a 50 $\mu$m diameter platinum filament in a $CO_2$ gas medium at a temperature of about 300 K. The linear segment indicates the development, in the measuring cell, of the regular heat transfer regime and, consequently, the validity of equation (2). The treatment of the experimental relationships of the form of equation (5) by the least-squares method, employing the quadratic trinomial approximation, made it possible to determine the value of the cooling rate with regard for the deviation from the linear law. The relative nonlinearity of the cooling rate for the whole range of gases and pressures investigated did not exceed 0.5%. The relative variance of the cooling rate was within 0.001–0.05% depending on the degree of gas rarefaction. In the low-pressure region, the relative variance was at a minimum. This can be explained by the fact that at lower pressures a larger number of experimental points can be obtained over a time interval than in the case of high pressures. In Fig. 2, straight line 1 corresponds to a pressure of about 0.2 mm Hg and straight line 3, to a pressure of about 0.03 mm Hg. Correspondingly, the cooling rate for straight line 1 was determined with a relative variance of 0.04% at the relative nonlinearity of 0.3% and for straight line 3, with the relative variance of 0.001% at the relative nonlinearity of 0.05%. Thus, the main error in the experiment was due to the relative nonlinearity of the cooling rate.

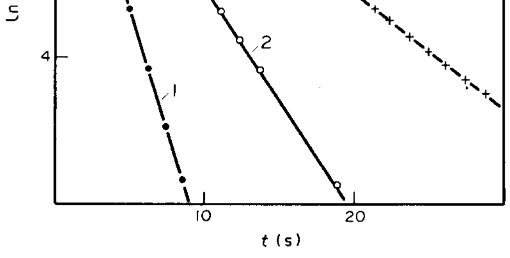

FIG. 2. The logarithm of relative drop in RC-oscillator frequencies vs time: (1) $\delta = 0.133$, $P = 0.199$ mm Hg, $m = 0.672 \pm 0.002\ s^{-1}$; (2) $\delta = 0.0509$, $P = 0.0760$ mm Hg, $m = 0.3067 \pm 0.0006\ s^{-1}$; (3) $\delta = 0.0220$, $P = 0.0329$ mm Hg, $m = 0.1583 \pm 0.000\ s^{-1}$.

As a follow-up to refs. [10–17], it is not difficult to show that the value of the filament cooling rate is associated with the heat transfer coefficient $\beta$ and the radial flux $q_r$ as

$$m = \frac{\beta}{\rho C_p \pi R_1^2 l}; \quad \beta = q_r/\Delta T_i. \tag{6}$$

The relationship between the cooling rate and the EAC or the thermal conductivity of the gas can be obtained by expressing the heat transfer coefficient in terms of the thermophysical parameters of the gas medium. Likewise it is possible to find the corrections for the heat removal from the filament ends and for heat radiation.

According to ref. [18], the value of the EAC is associated with the value of the filament cooling rate and gas pressure by the formula

$$\alpha_1 = \frac{C_p \rho R_1 (2\pi\mu/N_0 k T_0)^{1/2}}{2(C_v \mu/N_0 + k/2)} \cdot \frac{m_1}{P} \tag{7}$$

where $m_1 = m - m_0$.

The quantity $m_0$ is the cooling rate in high vacuum due to heat radiation and heat losses at the ends of the filament. The relationship between the quantity $m_0$, the filament surface emissivity $\gamma$, the filament thermal conductivity $\omega$ and mean gas temperature $T_0$ is expressed as [15]

$$m_0 = \frac{\omega\pi^2}{\rho C_p l^2} + \frac{8\gamma\phi T_0^3}{\rho C_p R_1}. \tag{8}$$

The relationship between the filament cooling rate and the thermal conductivity of the gas for a continuum heat transfer regime is given in ref. [15] in the form

$$\lambda = \tfrac{1}{2}\rho C_p m_1 R_1^2 \ln(R_2/R_1). \tag{9}$$

In order to determine the value of the EAC, a relationship of the following form was constructed

$$m = f(P). \tag{10}$$

The upper pressure limit was chosen from the condition of the heat transfer regime molecularity for each specific gas according to $\delta < 0.05$ $[\delta = (\pi^{1/2}/2)(1/Kn)]$. The treatment of relationship (10) by the least-squares method, with equations (7) and

(8) taken into account, allowed the determination of the EAC and the emissivity.

The ratios of heat fluxes to the continuum limit were constructed, according to ref. [19], on the basis of the heat conduction coefficient for each gas with conversion to the quantity $m_{rc}$ by formula (9), i.e.

$$q_r/q_{rc} = m_1/m_{rc}. \tag{11}$$

The ratios of heat fluxes to the molecular limit were constructed on the basis of the values of the EAC found experimentally with conversion to the quantity $m_{fm}$ by formula (7), i.e.

$$q_r/q_{fm} = m_1/m_{fm}. \tag{12}$$

For the measurement of heat fluxes in a wide range of *Kn*, two measuring cells were used which had the form of cylinders. The cylinders were made from stainless steel about 700 mm in length and 13.0 mm in diameter. The inner cylinder of the first cell was a platinum filament about 50 $\mu$m in diameter ($R_2/R_1 = 260$), while that of the second cell, a nickel filament with a diameter of about 200 $\mu$m ($R_2/R_1 = 65$). The lengths of the filaments were almost the same and were about 680 mm long. Measurements were made at a temperature of about 300 K. In order to preclude the possibility for the convection onset, the measuring cells were positioned horizontally. Before being inserted into the measuring cell, the filaments were treated in a weak solution of nitric acid and then rinsed with alcohol. The outgassing was achieved by keeping the filaments in high vacuum (about $1 \times 10^{-9}$ mm Hg) for 48–72 h. Measurements were made with high-purity gases. Additional refining of the gases was made with the aid of adsorptional traps mounted along the path of gas delivery.

For the determination of the EAC on nickel and platinum surfaces by the low-pressure method, the wires studied were inserted into a 60 mm diameter and 300 mm long measuring cell made of stainless steel. These dimensions of the cell made it possible to exclude the effect of accommodation, occurring on the external cylinder, on the magnitude of the heat flux.

For the measurement of the EAC on tungsten and tantalum surfaces, filaments of about 50 $\mu$m in diameter were used. Before being inserted into the cell, the filaments were rinsed with alcohol. The filaments were cleaned by heating up to 3000 K in a vacuum of about $1 \times 10^{-9}$ mm Hg and in a weak atmosphere of hydrogen at $10^{-4}$–$10^{-5}$ mm Hg. The reduction of tungsten and tantalum oxides by a monatomic hydrogen, being formed on an incandescent surface, and the decomposition of carbides and organic impurities [20] provided additional cleaning of the surface.

The thermal refining of filaments sharply diminished the emissivity. This effect was used to control the degree of surface cleaning from the traces of oxides and graphite greasing (Aquadag).

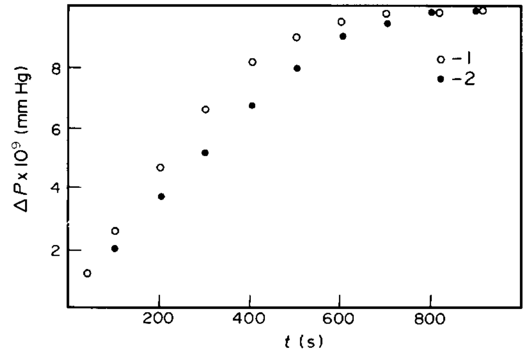

FIG. 3. The diagram obtained by the thermal flash method on tungsten (1) and tantalum (2) filaments at $T_0 \simeq 300$ K.

The emissivity of the surface impurities was assumed to be close to unity. The calculation of the emissivities of pure tungsten and tantalum $\gamma_0$ was made by the formula [21]

$$\gamma_0 = 7.54(\kappa T_0)^{1/2} - 63.5(\kappa T_0) + 673(\kappa T_0)^{3/2}. \tag{13}$$

The emissivity of pure tungsten was compared with that of the sample before and after the cleaning of the latter. A fraction of the surface, $x$, covered with impurities was calculated by the formula

$$x = \frac{\gamma - \gamma_0}{1 - \gamma_0} \tag{14}$$

where $\gamma$ is the emissivity found experimentally in the course of the determination of the EAC.

Since the cleaned surface can again be covered with a layer of adsorbed molecules of residual gases, the time of monolayer filling-up was determined in the present work by the thermal flash method. The technique of this type of measurements is described elsewhere [22]. The filament was supplied with electric pulses, each of which heated it to a temperature of about 3000 K. The duration of intervals between the pulses increased successively. The magnetic ionization vacuum gauge recorded the pressure fluctuations in the measuring cell that were caused by thermal desorption of gases from the filament surface. The resulting diagram is presented in Fig. 3. As follows from the diagram, the time of monolayer filling-up for both filaments was 700–800 s. Since the time for each individual measurement of the EAC did not exceed 30 s, it can be assumed that the experiments were carried out with the surface covered with adsorbed films of molecules of residual gases by no more than 5%.

An X-ray structural analysis of the samples of filaments was made before and after the thermal refining. Comparison of the data obtained did not reveal a substantial recrystallization of the filament material which can be explained by the very short time (< 20 s) of refining.

## 3. THE RESULTS OF MEASUREMENTS

The measured heat fluxes for a number of inert and some bi-atomic gases, reduced to a continuum limit, are

Table 1. The measured radial heat fluxes related to the continuum limit ($R_2/R_1 = 260$)

| *He* | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 55.9 | 0.0193 |
| 62.4 | 0.0173 |
| 68.1 | 0.01613 |
| 87.7 | 0.01255 |
| 108 | 0.01031 |
| 140 | 0.00799 |
| 176 | 0.00632 |
| 216 | 0.00512 |

| Ne | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 8.25 | 0.107 |
| 10.63 | 0.0876 |
| 15.15 | 0.0656 |
| 18.68 | 0.0539 |
| 24.00 | 0.0424 |
| 28.34 | 0.0350 |
| 40.39 | 0.0249 |
| 61.52 | 0.0166 |
| 81.43 | 0.0126 |

| Ar | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.571 | 0.531 |
| 0.679 | 0.489 |
| 0.849 | 0.459 |
| 1.121 | 0.416 |
| 0.412 | 0.378 |
| 1.702 | 0.347 |
| 1.925 | 0.325 |
| 2.229 | 0.298 |
| 2.583 | 0.272 |
| 3.903 | 0.208 |
| 6.004 | 0.150 |
| 7.81 | 0.121 |
| 9.68 | 0.0993 |
| 11.67 | 0.0849 |
| 14.62 | 0.0692 |
| 22.1 | 0.0470 |
| 27.1 | 0.0387 |
| 52.1 | 0.0203 |
| 75.9 | 0.0140 |
| 116.1 | 0.00898 |
| 244 | 0.00435 |

| Kr | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 4.59 | 0.1930 |
| 5.36 | 0.1716 |
| 6.06 | 0.1554 |
| 7.01 | 0.1375 |
| 8.60 | 0.1158 |
| 10.62 | 0.0962 |
| 13.61 | 0.0756 |
| 15.71 | 0.0674 |
| 18.03 | 0.0591 |
| 21.6 | 0.0498 |
| 26.7 | 0.0407 |
| 34.9 | 0.0312 |
| 48.0 | 0.0225 |
| 76.1 | 0.0139 |

| Xe | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.414 | 0.653 |
| 0.454 | 0.642 |
| 0.502 | 0.638 |
| 0.658 | 0.594 |
| 0.781 | 0.554 |
| 1.021 | 0.508 |
| 1.182 | 0.473 |
| 1.362 | 0.451 |
| 1.95 | 0.365 |
| 2.38 | 0.322 |
| 3.12 | 0.271 |
| 4.03 | 0.224 |
| 5.30 | 0.184 |
| 8.94 | 0.1149 |
| 11.65 | 0.0902 |
| 15.22 | 0.0703 |
| 22.9 | 0.0472 |
| 28.5 | 0.0386 |
| 36.6 | 0.0297 |
| 74.4 | 0.0230 |

| $D_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 54.2 | 0.0199 |
| 62.9 | 0.0173 |
| 74.2 | 0.0145 |
| 89.2 | 0.0123 |
| 103 | 0.0107 |
| 132 | 0.00844 |
| 192 | 0.00573 |
| 462 | 0.00225 |

| $N_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 6.987 | 0.144 |
| 10.46 | 0.1011 |
| 14.41 | 0.0761 |
| 23.4 | 0.0503 |
| 158 | 0.00728 |

| Air | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 7.49 | 0.1345 |
| 8.79 | 0.1175 |
| 10.6 | 0.0989 |
| 13.4 | 0.0809 |
| 19.8 | 0.0563 |
| 26.3 | 0.0428 |
| 39.1 | 0.0290 |
| 72.1 | 0.0158 |
| 182 | 0.00572 |

| $CO_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 3.64 | 0.230 |
| 4.50 | 0.195 |
| 5.46 | 0.167 |
| 6.82 | 0.139 |
| 8.10 | 0.120 |
| 9.29 | 0.1062 |
| 11.74 | 0.0863 |
| 13.19 | 0.0781 |
| 15.41 | 0.0682 |
| 18.36 | 0.0586 |
| 22.01 | 0.0502 |
| 27.13 | 0.0419 |

presented in Table 1 (for the outer to inner cylinder radii ratio of about 260) and in Table 2 (for the outer to inner cylinder radii ratio of about 65). The measurements were made at a temperature of about 300 K. The values of heat fluxes are given without regard for the finite length of the measuring cell, so that within the region of the intermediate and continuum regimes a systematic overestimation of heat fluxes by about 2% is possible. The column on the LHS contains the numerical value of $A$ for each gas, which corresponds to the solution of the BGK equation by the moment method for a coaxial geometry [3]

$$q_r/q_{rc} = \frac{1}{1+A};$$
$$A = \left[\frac{1}{\alpha_1} + \frac{R_1}{R_2}\left(\frac{1}{\alpha_2} - 1\right)\right]\frac{15}{8}\sqrt{\pi}\,\frac{1}{\delta}\,\frac{1}{\ln(R_2/R_1)}. \tag{15}$$

The values of the EAC for the internal surface were measured separately by the low-pressure method with a mean relative error of 2%. The results are presented in Table 3. Using these values and assuming that $\alpha_1 = \alpha_2$ (the surface is screened by a layer of impurities), the numerical values of quantity $A$ were calculated. Figure 4 presents some results from Tables 1 and 2 and also the results of other authors for comparison. As is seen from Fig. 4, there is a small spread for different gases, but in the intermediate regime region the results obtained lie somewhat above the theoretical curve plotted on the basis of equation (15). A more detailed comparison of the experimental data of the present work with the theoretical results obtained in ref. [4] was made.

Figure 5 gives the experimental values of heat fluxes for Ar, Xe and $CO_2$ gases related to the molecular limit for $R_2/R_1 = 65$. Here $r$ is equal to $2/3\delta$. The Ar, Xe and $CO_2$ gases were chosen because the value of $\alpha_1$ for these (Table 3) is close to unity which is convenient when comparing with the results of ref. [4] where the numerical calculation was made for $\alpha_1 = 1$. The solid curve in Fig. 5 shows a theoretical dependence at $\alpha_1 = 1$ [4].

Figure 6 presents the deviation of test points from the theoretical curve of Fig. 5. It is seen from Fig. 6 that the experimental data are higher than the theoretical

Table 2. The measured radial heat fluxes related to the continuum limit ($R_2/R_1 = 65$)

| He | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 9.57 | 0.1014 |
| 11.60 | 0.0878 |
| 14.77 | 0.0728 |
| 18.33 | 0.0558 |
| 25.3 | 0.0429 |
| 45.8 | 0.0247 |
| 57.8 | 0.0169 |
| 71.8 | 0.0152 |
| 86.2 | 0.0116 |
| 124 | 0.00837 |
| 200 | 0.00537 |

| Ne | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 2.194 | 0.314 |
| 2.724 | 0.277 |
| 3.150 | 0.235 |
| 4.955 | 0.186 |
| 6.169 | 0.156 |
| 8.052 | 0.1201 |
| 9.992 | 0.1032 |
| 14.13 | 0.0787 |
| 21.53 | 0.0454 |
| 28.50 | 0.0353 |
| 35.50 | 0.0280 |
| 51.76 | 0.0186 |
| 82.79 | 0.0150 |

| Ar | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.1902 | 0.7827 |
| 0.2261 | 0.7570 |
| 0.2828 | 0.7266 |
| 0.3734 | 0.6916 |
| 0.4702 | 0.6463 |
| 0.5674 | 0.6315 |
| 0.6409 | 0.6129 |
| 0.7418 | 0.5780 |
| 0.8596 | 0.5591 |
| 1.030 | 0.5241 |
| 1.299 | 0.4731 |
| 1.641 | 0.3972 |
| 1.999 | 0.3575 |
| 2.60 | 0.3107 |
| 3.22 | 0.2320 |
| 3.88 | 0.2026 |
| 4.87 | 0.1706 |
| 5.91 | 0.1547 |
| 7.37 | 0.1276 |
| 9.04 | 0.1077 |
| 12.10 | 0.0834 |

| Kr | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.131 | 0.877 |
| 0.153 | 0.838 |
| 0.181 | 0.830 |
| 0.230 | 0.821 |
| 0.298 | 0.805 |
| 0.384 | 0.784 |
| 0.483 | 0.747 |
| 0.591 | 0.684 |
| 0.718 | 0.631 |
| 0.916 | 0.583 |
| 1.142 | 0.549 |
| 1.304 | 0.506 |
| 1.53 | 0.460 |
| 1.78 | 0.413 |
| 2.02 | 0.370 |
| 2.86 | 0.294 |
| 3.53 | 0.249 |
| 4.63 | 0.205 |
| 5.23 | 0.186 |
| 6.00 | 0.164 |
| 7.17 | 0.147 |

| Xe | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.0286 | 0.971 |
| 0.0333 | 0.985 |
| 0.0375 | 0.964 |
| 0.0427 | 0.950 |
| 0.0499 | 0.962 |
| 0.0583 | 0.943 |
| 0.0673 | 0.926 |
| 0.0747 | 0.919 |
| 0.0851 | 0.899 |
| 0.0982 | 0.886 |
| 0.109 | 0.871 |
| 0.123 | 0.857 |
| 0.182 | 0.827 |
| 0.218 | 0.816 |
| 0.340 | 0.782 |
| 0.454 | 0.744 |
| 0.651 | 0.660 |
| 1.34 | 0.478 |
| 1.76 | 0.424 |
| 2.79 | 0.330 |
| 5.41 | 0.230 |

| $D_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 7.36 | 0.1206 |
| 8.60 | 0.1073 |
| 10.44 | 0.0920 |
| 14.4 | 0.0734 |
| 17.9 | 0.0605 |
| 24.3 | 0.0451 |
| 33.2 | 0.0341 |
| 40.1 | 0.0268 |
| 50.5 | 0.0214 |

| $N_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 1.05 | 0.504 |
| 1.39 | 0.467 |
| 1.73 | 0.426 |
| 2.25 | 0.342 |
| 3.38 | 0.266 |
| 4.64 | 0.217 |
| 7.22 | 0.150 |
| 20.1 | 0.0547 |
| 50.9 | 0.0240 |

| $CO_2$ | |
|---|---|
| $A$ | $q_r/q_{rc}$ |
| 0.251 | 0.765 |
| 0.486 | 0.672 |
| 0.657 | 0.612 |
| 0.896 | 0.543 |
| 1.21 | 0.458 |
| 1.50 | 0.407 |
| 1.82 | 0.361 |
| 2.27 | 0.319 |
| 2.70 | 0.282 |
| 3.91 | 0.212 |
| 4.39 | 0.193 |
| 5.13 | 0.174 |
| 6.11 | 0.152 |
| 7.32 | 0.140 |
| 9.03 | 0.116 |
| 12.6 | 0.0867 |

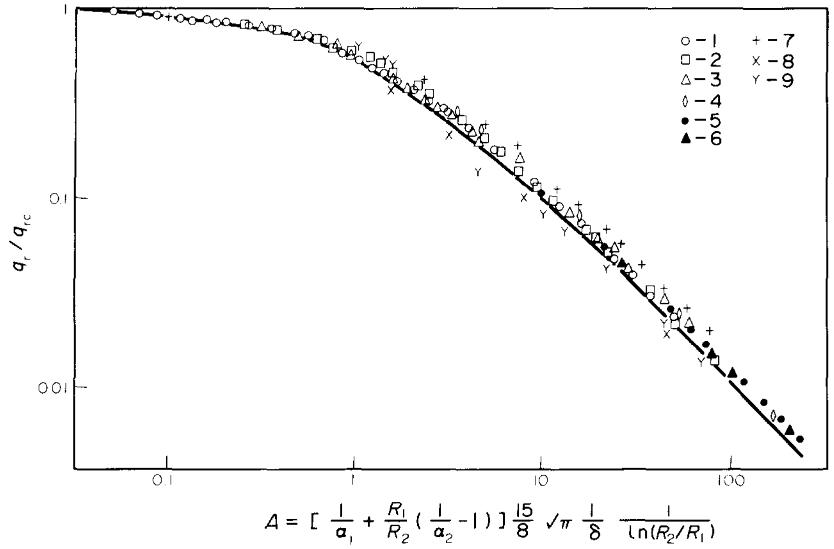

FIG. 4. The radial heat flux $q_r$, relative to its continuum limit $q_{rc}$, vs $A$ for the gases Xe(1), Kr(2), $CO_2$(3), $N_2$(4), He(5), $D_2$(6). The solid line shows the theoretical dependence [3]. The data for He(7) and Xe(8) are taken from ref. [6], for He(9) from ref. [8].

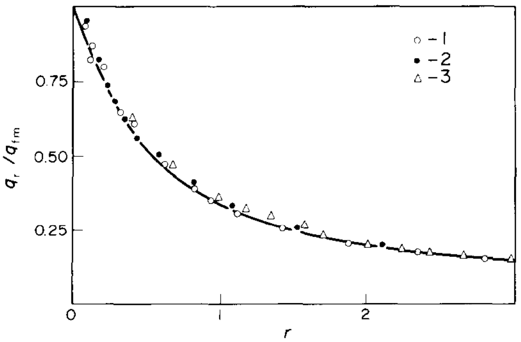

FIG. 5. The radial heat flux $q_r$, relative to its free-molecular limit $q_{fm}$ ($R_2/R_1 = 65$), vs $r$ for the gases Ar(1), $CO_2$(2) and Xe(3) at $\alpha_1 = 1$. The solid curve is constructed on the basis of the numerical solution [4].

results in the region close to the molecular regime on the average by 5%, while in the intermediate regime the experimental results lie somewhat below the theoretical ones.

Figure 7 compares the experimental heat fluxes obtained in the molecular regime region with the molecular limit calculated theoretically for $R_2/R_1 = 65$ and 260. The shaded circles denote the results obtained for $R_2/R_1 = 260$ on a platinum filament of about 50 $\mu$m in diameter. The mean scatter in the points for a platinum filament is markedly (two or three times) less than for a nickel filament. This can be attributed to the fact that the nickel filament has a radius four times as large as the platinum filament, while the cooling rate [according to equation (7)] is inversely proportional to the radius. In the region of low pressures the rate of cooling of a thicker filament will be smaller and, consequently, a relative error caused by the RC-oscillator instability and thermal fluctuations in the measuring cell should be larger. Therefore, to carry out the measurements of the EAC by the low-pressure method within the framework of the present procedure, it is more expedient to make use of filaments of small diameters ($\leqslant 50$ $\mu$m).

Measurements of the EAC were carried out on uncleaned surfaces of nickel, platinum, tungsten and tantalum, and also on thermally refined (in the hydrogen atmosphere) surfaces of tungsten and tantalum. In the molecular regime, an experimental dependence of the cooling rates on the tested gas pressure was plotted. The form of this dependence for He and Ar gases on the tungsten filament of 50 $\mu$m in diameter at a temperature of about 300 K is presented in Fig. 8. The EAC was determined from the tangent of the slope of the lines $m = f(P)$ fitted by least squares. In

Table 3. The measured EAC on uncleaned surfaces of tungsten, tantalum, platinum and nickel at a temperature of 300 K

| | | | | | Gas | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Metal | He | Ne | Ar | Kr | Xe | $D_2$ | $N_2$ | $CO_2$ | Air |
| W | 0.393 | 0.796 | 1.00 | 1.01 | 1.02 | 0.451 | 0.983 | 1.00 | 0.99 |
| Ta | 0.493 | 0.848 | 0.974 | 0.991 | 0.979 | 0.463 | 0.991 | 1.01 | 1.02 |
| Pt | 0.446 | 0.816 | 1.01 | 0.973 | 0.992 | 0.470 | 0.975 | 1.00 | 1.00 |
| Ni | 0.457 | 0.831 | 1.02 | 1.00 | 1.00 | 0.479 | 0.978 | 1.02 | 1.00 |

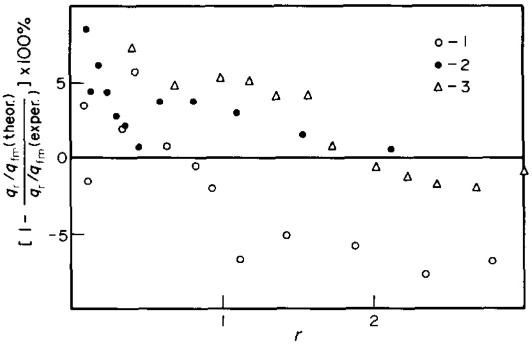

FIG. 6. The scatter of experimental points for heat fluxes about the theoretical curves [4] for the gases Ar(1), $CO_2$(2), Xe(3) at $\alpha_1 = 1$ ($R_2/R_1 = 65$).

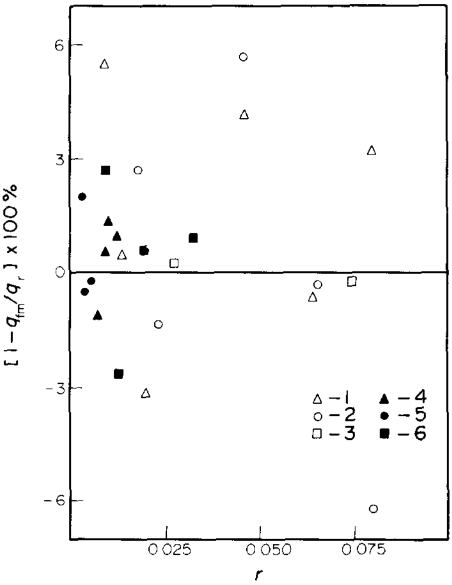

FIG. 7. The scatter of experimental values of heat fluxes relative to the value of the molecular limit for the gases He(1), Ne(2), $N_2$(3) ($R_2/R_1 = 65$) and Ar(4), Ne(5) and Xe(6) ($R_2/R_1 = 260$).

this case, the segment cut off on the ordinate axis ($m_0$ at $P = 0$) was used to determine the emissivity of the filament surface.

It is seen from the plots of Fig. 8 that on thermal refining of tungsten filaments in the hydrogen atmosphere the rate of cooling in vacuum decreased by about six times which corresponds to a 10-fold reduction of the emissivity. It was found from equation (14) that the fraction of the surface covered with impurities amounted to about 40% before annealing of filaments. After the annealing in the hydrogen atmosphere, this fraction was only 0.9%. It should be noted that the annealing in vacuum makes it possible to diminish the fraction of impurities on the tungsten surface only to 4%. As a result, the EACs of inert gases have values different from those obtained by measurements after the annealing in a hydrogen atmosphere. The results, which were obtained on thermally refined (in vacuum and in a hydrogen atmosphere) tungsten and tantalum surfaces at 300 and 77 K are presented in Table 4. For the calculation of the EAC by formula (7), the heat capacity $C_p$ for tungsten and tantalum at 77 K was taken from ref. [23]. The correction for the value of the thermomolecular difference of pressures between the cooled measuring cell and the working cavity of the capacitance micromanometer at room temperature was calculated by the data of ref. [24].

Figure 9 presents the experimental values of the EAC of inert gases on uncleaned and on thermally refined (in a hydrogen atmosphere) surfaces of metals. The abscissa is the quantity which characterizes the magnitude of the potential of interaction between molecules of the same gas. The data on the parameter of the potential well depth $\varepsilon/k$ for the potentials of interaction between the molecules of inert gases are taken from ref. [25].

It is seen from the plot of Fig. 9 that the EAC on the uncleaned surfaces of metals differ little from one another for different types of surfaces which seems to be due to the screening of a surface by a layer of impurities that annihilate the influence of individual properties of the surface on the value of the EAC. The cleaning of the surfaces leads to a sharp decrease in the values of the EAC and to the exposition of differences in the values of the EAC for tungsten and tantalum surfaces. Figure 9 also contains the data of ref. [11] on the EACs for inert gases on a clean tungsten surface. One can see a strong (three-fold) discrepancy between EAC values for He and Ne obtained in the present work and in ref. [11]. This appears to be due to different degrees of roughness of surfaces.

Table 4. The measured EAC on thermally cleaned (in vacuum and hydrogen atmosphere) surfaces of tungsten and tantalum at temperatures of 77.4 and 300 K

| Temperature (K) | Method of cleaning | Metal | Gas | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | He | Ne | Ar | Kr | Xe | $H_2$ | $D_2$ | $N_2$ | $CO_2$ |
| 77.4 | Annealing | W | 0.058 | 0.141 | 0.707 | 0.846 | 0.989 | 0.283 | 0.571 | 0.846 | — |
| 77.4 | in | Ta | 0.060 | 0.166 | 0.725 | 0.895 | 1.01 | 0.287 | 0.571 | 0.843 | — |
| 300 | hydrogen | W | 0.055 | 0.131 | 0.434 | 0.552 | 0.728 | 0.215 | 0.260 | 0.562 | 1.00 |
| 300 | atmosphere | Ta | 0.058 | 0.156 | 0.491 | 0.618 | 0.760 | 0.245 | 0.292 | 0.592 | 1.00 |
| 300 | Annealing in vacuum | W | 0.105 | 0.218 | 0.356 | 0.518 | 0.595 | — | — | — | — |

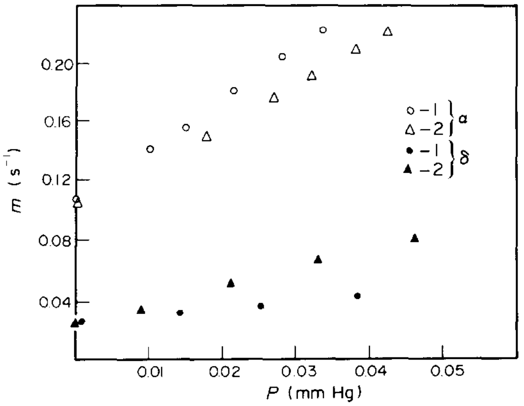

FIG. 8. The cooling rate of a 50 $\mu$m diameter tungsten wire vs the gas pressure in the molecular regime at $T_0 \simeq 300$ K: (a) He(1), Ar(2) before thermal refining; (b) He(1), Ar(2) after thermal refining in a hydrogen atmosphere.

## 4. CONCLUSIONS

(1) The heat fluxes of inert and some polyatomic gases in a coaxial geometry have been measured in a wide range of *Kn*. The measured heat fluxes for Ar, Xe and $CO_2$ gases have been compared with the theoretical results obtained by the variational method with the use of the BGK-model. A good coincidence between theory and experiment has been obtained.

(2) The EACs of molecules of a number of gases on platinum, nickel, tungsten and tantalum surfaces have been measured. A monotonous dependence of the value of the EAC of gases on the potential well depth of the intermolecular interaction potential has been established experimentally.

(3) The effect of the kind of surface and its purity on the value of the EAC is investigated. A substantial effect of surface impurities on the value of the EAC is shown.

(4) In the measurements of the EAC by the low-pressure method, the state of the surface was controlled with the aid of the thermal flash method and emissivity of the sample. The effectiveness of these methods for the determination of the purity of hard-melting metallic filaments has been demonstrated.

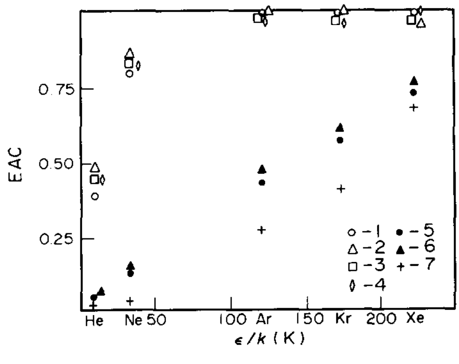

FIG. 9. The EAC vs the given potential well depth $\varepsilon/k$ for the filaments W(1), Ta(2), Pt(3) and Ni(4) without thermal refining and W(5), Ta(6) after thermal refining in a hydrogen atmosphere. The data of the EAC on W(7) are taken from ref. [11].

## REFERENCES

1. M. N. Kogan, *The Dynamics of a Rarefied Gas*. Izd. Nauka, Moscow (1967).
2. F. M. Devienne, *Frottement et Echanges Thermiques dans les Gaz Rarefies*. Gauthier-Villars, Paris (1958).
3. Yu. A. Koshmarov and Yu. A. Ryzhov, *The Applied Dynamics of a Rarefied Gas*. Izd. Mashinostroenie, Moscow (1977).
4. P. Bassanini, C. Cercignani and C. D. Pagani, Influence of the accommodation coefficient on the heat transfer in a rarefied gas, *Int. J. Heat Mass Transfer* **11**, 1359–1369 (1968).
5. F. O. Goodman and H. Y. Wachman, *Dynamics of Gas–Surface Scattering*. Academic Press, New York (1976).
6. A. D. Terekhov and E. N. Frolova, An experimental comparison between the methods of determining the thermal accommodation coefficient, *Prikl. Mat. Tekh. Fiz.* No. 4, 173–176 (1972).
7. A. Koshmarov and A. E. Ivanov, An experimental investigation of heat transfer through a rarefied gas between coaxial cylinders, *Izv. Akad. Nauk SSSR, Energ. Transp.* No. 4, 99–103 (1971).
8. A. Dybbs and G. S. Springer, Heat conduction experiments in rarefied gases between concentric cylinders, *Physics Fluids* **8**(11), 1946–1950 (1965).
9. Yu. A. Gorshkov, V. V. Korolyova, A. E. Umansky and D. L. Timrog, Pulse method measurement of gas thermal conductivity, in *Thermophysical Properties of Gases* (*Proc. 3rd All-Union Thermophysical Conf. on the Properties of Substances at High Temperatures*), pp. 2–6. Izd. Nauka, Moscow (1970).
10. I. F. Golubev, A bicalorimeter for the determination of the thermal conductivities of gases and liquids at high pressures and different temperatures, *Teploenergetika* No. 12, 78–82 (1963).
11. J. Kouptsidis and D. Menzel, Accommodation of the rarefied gases on clean tungsten surfaces between 77 and 380 K, *Ber. Bunsenges. Physik* **74**, 512–520 (1970).
12. F. W. Reiter, J. Camposilvan and R. Nehren, Accommodation coefficient of noble gases on Pt surface from 80 K up to 450 K, *Wärme- und Stoffübertragung* **5**(2), 116–122 (1972).
13. L. B. Thomas, A collection of some controlled surface thermal accommodation coefficient measurements, *Proc. Int. Symp. Rarefied Gas Dynamics*, Vol. 1, Part 2, pp. 155–162. New York Press (1967).
14. B. J. Jody, S. C. Saxena, A. G. Shashkov, F. P. Kamchatov and O. A. Kolenchits, Thermal accommodation coefficient for helium on partially gas covered platinum in the temperature range 300–1400 K, *Proc. 7th Symp. on Thermophys. Prop.*, pp. 760–765, Gaitherbury (1977).
15. Yu. G. Semyonov, B. A. Kalinin, S. F. Borisov and P. E. Suetin, A transient hot-wire method with the use of a RC-oscillator for the investigation of heat transfer in rarefied gases, *J. Engng Phys.* **37**(2), 269–272 (1979).
16. S. F. Borisov, B. A. Kalinin, B. T. Porodnov and P. E. Suetin, A micromanometer with digital data output, *Pribory Tekh. Eksp.* No. 4, 209–210 (1972).
17. V. P. Isachenko, V. A. Osipova and A. S. Sukomel, *Heat Conduction*. Izd. Energiya, Moscow (1969).
18. S. F. Borisov, S. A. Litvinenko, Yu. G. Semyonov and P. E. Suetin, An experimental investigation of the temperature dependence of energy accommodation coefficients for the gases He, Ne, Ar and Xe on the Pt surface, *J. Engng Phys.* **34**(5), 880–885 (1978).
19. N. B. Vargaftik, *Handbook of Thermophysical Properties of Gases and Liquids*. Izd. Nauka, Moscow (1972).

20. S. Dushman, *Scientific Foundations of Vacuum Technique.* New York (1949).
21. A. E. Sheidlin, *Radiative Properties of Solid Materials (Handbook).* Izd. Energiya, Moscow (1974).
22. M. Kaminsky, *Atom and Ion Collisions on a Metal Surface.* Izd. Mir, Moscow (1967).
23. L. A. Novitsky and I. G. Kozhevnikov, *Thermophysical Properties of Materials at Low Temperatures.* Izd. Mashinostroenie, Moscow (1975).
24. B. T. Porodnov, A. N. Kulev and F. T. Tuchvetov, Thermal transpiration in a circular capillary with a small temperature difference, *J. Fluid Mech.* **88**(4), 609–622 (1978).
25. J. O. Hirshfelder, C. F. Curtiss and R. B. Bird, *Molecular Theory of Gases and Liquids.* Wiley, New York (1954).

## ETUDE DU TRANSFERT THERMIQUE DANS DES GAZ RAREFIES SUR UN LARGE DOMAINE DE NOMBRES DE KNUDSEN

**Résumé**—On présente des résultats expérimentaux sur l'échange thermique de filaments fins métalliques avec un gaz raréfié à différentes pressions. On utilise la technique du fil chaud dans le cas de petites perturbations de température. Les flux de chaleurs pour quelques gaz inertes ou polyatomiques sont mesurés sous différentes conditions variant du régime moléculaire au régime continu. Les résultats montrant la dépendance des flux thermiques au degré de raréfaction sont comparés avec ceux théoriques, solutions du modèle B G K par la méthode variationnelle. Les filaments sont en platine, nickel, tungstène et tantale. La surface est recuite dans le vide poussé et dans une atmosphère légère d'hydrogène. Le contrôle de l'état surface est obtenu par la méthode flash thermique et par essai de changement d'émissivité. Le degré de recristallisation du filament dans le processus thermique est déterminé par l'analyse de structure aux rayons X.

## UNTERSUCHUNG DES WÄRMEÜBERGANGS IN AUSGEDÜNNTEN GASEN IN EINEM WEITEN BEREICH DER KNUDSEN-ZAHL

**Zusammenfassung**—Der Aufsatz stellt experimentelle Ergebnisse für den Wärmeaustausch zwischen feinen Metallfäden und einem Gas von geringer Dichte bei unterschiedlichen Drücken vor. Die Untersuchungen wurden unter Anwendung der instationären Hitzdraht-Technik für den Fall geringer Temperaturstörungen durchgeführt. Für eine Anzahl von Inertgasen und vielatomigen Gasen wurde die Wärmestromdichte unter verschiedenen Wärmeübergangsbedingungen gemessen, die sich vom molekularen Wärmetransport bis zu dem im Kontinuum erstrecken. Die Versuchsergebnisse, die die Abhängigkeit der Wärmestromdichte vom Ausdünnungsgrad des Gases zeigen, wurden mit theoretischen Ergebnissen verglichen, die sich aus der Lösung des BGK-Modells mit Hilfe der Variationsrechnung ergeben. Unter den Bedingungen des molekularen Wärmetransports zeigt sich die Abhängigkeit des Akkommodations-Koeffizienten von der Art des Materials und dem Zustand der Fadenoberfläche, von der Art des Gases und von der mittleren Systemtemperatur. Die Fäden waren aus Platin, Nickel, Wolfram und Tantal. Die Oberfläche wurde durch Ausglühen im Hochvakuum und in einer dünnen Wasserstoff-Atmosphäre gereinigt. Die Überprüfung des Oberflächenzustandes wurde mit Hilfe der "thermal flash"—Methode und durch das Beobachten von Veränderungen des Emissionsvermögens der Oberfläche durchgeführt. Der Grad der Rekristallisation des Fadens während der thermischen Reinigung wurde mittels Röntgen-Strukturuntersuchung festgestellt.

## ИССЛЕДОВАНИЕ ТЕПЛООБМЕНА В РАЗРЕЖЕННЫХ ГАЗАХ В ШИРОКОМ ДИАПАЗОНЕ ЧИСЕЛ КНУДСЕНА

**Аннотация**—В работе излагаются результаты экспериментального исследования теплообмена тонких металлических нитей с разреженным газом, находящимся при различных давлениях. Исследования выполнены нестационарным методом нагретой нити для случая малых температурных возмущений. При различных режимах теплообмена от молекулярного до континуального измерены тепловые потоки для ряда инертных и некоторых многоатомных газов. Проведено сравнение экспериментальных зависимостей тепловых потоков от степени разреженности газа с теоретическими, полученными на основе решения БГК-модели вариационным методом. В условиях молекулярного теплообмена получены зависимости коэффициентов аккомодации энергии от рода материала и состояния поверхности нити, рода газа и средней температуры системы. В качестве материала нитей использовались платина, никель, вольфрам и тантал. Очистка поверхности производилась термическим отжигом нитей в глубоком вакууме и в слабой атмосфере водорода. Контроль за состоянием поверхности осуществлялся методом тепловой вспышки и по изменению ее излучательной способности. Степень рекристаллизации нитей при отжиге выявлялась методом рентгеноструктурного анализа.