Int. J. Heat Mass Transfer. Vol. 30, No. 7, pp. 1269–1274, 1987
Printed in Great Britain

0017–9310/87 \$3.00+0.00
Pergamon Journals Ltd.

Kinetic boundary layer treatment in the problem of a rarefied gas flow through a perforated wall by the method of moments

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(*Received* 8 *June* 1983 *and in revised form* 26 *June* 1986)

Abstract—Gas flow from one chamber to another through a plane wall perforated with cylindrical channels is investigated. Gas flow close to the surface of a wall is studied by the methods of kinetic gas theory. The molecule velocity distribution function is found from the Boltzmann equation as a result of its solution by the method of moments. Intermolecular collisions in the channels are supposed to be absent. Molecules collide in the Knudsen layer near the perforated wall. This leads to the formation of a uniform flow far from the wall.

1. INTRODUCTION

GAS FLOW through a thin wall with practically zero permeability was considered in refs. [1, 2]. A good agreement between theory and experiment was found. The data obtained by the method of moments [1] and numerically [2] are also in agreement. The method of moments proved to be valid in analogous problems of the shock wave structure [3] and gas evaporation from a flat surface [4]. All this allows this method to be used in a more general case when gas flows through a wall with cylindrical holes. The results of the solution can be used in the problems of gas flow within perforated boundaries.

The ratio of the area occupied by holes to the total area of the wall cross-section will be referred to as porosity q. The gas to the left of the wall (Fig. 1) is considered to be in equilibrium and is described by the distribution function f_0

$$f_0 = \frac{n_0}{(2\pi R T_0)^{3/2}} \exp\left(-\frac{\xi_x^2+\xi_y^2+\xi_z}{2RT_0}\right) \quad (1)$$

where n_0 and T_0 are the number density and gas temperature in the chamber to the left of the wall, respectively; $\xi(\xi_x, \xi_y, \xi_z)$ is the velocity of molecules. Gas particles do not collide with each other inside the channels and are reflected by the wall with complete energy and momentum accommodation. Gas flows through the channels in the wall at low speeds into the second, low-pressure chamber where $p_\infty = n_\infty k T_\infty$ (n_∞ and T_∞ are the number density and gas temperature in the chamber to the right of the wall). At a distance of several mean free paths from the wall the Maxwellian velocity distribution of molecules is established [3]

$$f_\infty = \frac{n_\infty}{(2\pi R T_\infty)^{3/2}} \exp\left\{-\frac{(\xi_x-u_\infty)^2+\xi_y^2+\xi_z^2}{2RT_\infty}\right\} \quad (2)$$

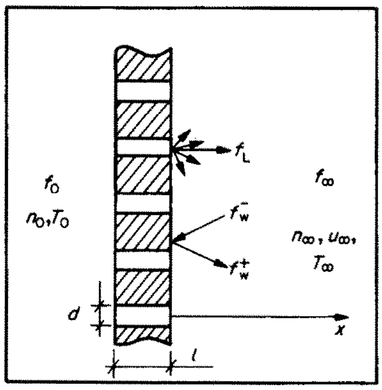

FIG. 1. Schematic of a gas flow through a perforated wall.

where u_∞ is the mean velocity of gas particles. The behaviour of the macroscopic gas parameters will be considered.

2. BOUNDARY CONDITIONS

To solve this problem, it is necessary to determine the distribution function f_+ of molecules escaping from the channels. Each channel has a length l and a diameter d. Suppose that to the left and to the right of the channel the gas is also described by the Maxwellian distribution functions with parameters n_0, T_0 and n_1, T, respectively. In a free molecular flow regime the density distribution of molecular collisions with the walls of the channel $\nu_0(x)$ can be presented as a sum of the solution of two problems of gas expansion into vacuum [5]

$$\nu_0(x) = (1-\nu_1)\left[\frac{1}{2} - A\left(L+2\frac{x}{d}\right)\right] + \nu_1 \quad (3)$$

where $\nu_1 = n_1/n_0$. The coefficient A depends on the relative length of the channel $L = l/d$

NOMENCLATURE

- d diameter of the channels in a wall
- f distribution function
- f_∞ Maxwellian distribution function
- F angular distribution of gas flow
- F_0 angular distribution of gas flows escaping into vacuum
- k Boltzmann constant
- l length of channels in the wall
- L relative length of channels, l/d
- n number density of molecules
- n_0 number density of molecules in the chamber to the left of the wall
- n_∞ number density of molecules far from the wall
- p_0 gas pressure in the chamber to the left of the wall
- p_∞ pressure far from the wall
- q wall porosity
- q_w/q_L ratio of the heat flux passing through a layer to the heat flux entering the kinetic layer from the wall
- R gas constant
- S velocity ratio
- T temperature
- T_0 gas temperature in the chamber to the left of the wall
- T_∞ gas temperature far from the wall
- u mean gas velocity at the point with the x-coordinate
- u_∞ mean gas velocity far from the wall
- W probability of the passage of molecules through the kinetic layer
- W_0 probability of the passage of molecules through the channel
- x coordinate.

Greek symbols

- θ angle
- λ kinetic layer thickness
- λ_0 mean free path of molecules in the source chamber
- ν_0 density distribution of collisions of molecules with the walls of the channel
- ξ velocity of a molecule in a laboratory coordinate system
- ξ_x, ξ_y, ξ_z components of velocity $\boldsymbol{\xi}$.

$$A = \frac{L^3-2+(2-L^2)\sqrt{(1+L^2)}}{3(L\sqrt{(1+L^2)}-\operatorname{Arsh} L)}. \tag{4}$$

Knowing the distribution function of molecules reflected from the channel walls $\nu_0(x)f_0$, it is possible to calculate the angular distribution of the flows of molecules escaping from the channel $F_1(\theta)$. This quantity is equal to the ratio of the gas flow emanating from the channel at an angle θ to the x-axis in a single solid angle to the flow in the axial direction [6]

$$F_1(\theta) = \frac{\iint_S \mathrm{d}S \int_0^{\pi/2} f(\theta)\cos\theta\,\xi^3\,\mathrm{d}\xi}{\iint_S \mathrm{d}S \int_0^{\pi/2} f(\theta=0)\xi^3\,\mathrm{d}\xi} \tag{5}$$

where integration is made over the cross-section of the channel exit S, $\mathrm{d}S$ is an element of the area of this cross-section, $f(\theta)$ is the distribution function of molecules escaping at an angle θ to the channel axis. The calculation of the integrals yields

$$F_1(\theta) = (1-\nu_1)F_0(\theta)+\nu_1\cos\theta. \tag{6}$$

Here $F_0(\theta)$ is the angular distribution of gas flows expanding into vacuum [7].

Based on the mass conservation law for the molecules escaping from the channel, the distribution function of molecules f_+, averaged over the channel exit cross-section is set in the form

$$f_+ = \frac{F_1(\theta)}{\cos\theta}f_0 \tag{7}$$

which is valid at large distances from an isothermal microcapillary. In a particular case, when gas expands into vacuum ($\nu_1 = 0$), the following expression is obtained [8]:

$$f_+ = \frac{F_0(\theta)}{\cos\theta}f_0. \tag{8}$$

To obtain the explicit solution, the unknown distribution function at a wall must be taken in the form f^- as is the case in any moment method.

Now, the form of the distribution function on the surface of the wall ($x = 0$) and in the far developed flow ($x = \infty$) will be assigned [1]

$$x=0: \begin{cases} f = f_0^+ = qf_+ + f^+, & \xi_x > 0; \\ f = f^- = \alpha f_* + \beta f_\infty, & \xi_x \leqslant 0; \end{cases}$$

$$x = \infty: f = f_\infty \begin{cases} \xi_x > 0 \\ \xi_x \leqslant 0 \end{cases}. \tag{9}$$

Here f^+ is the distribution function of molecules reflected from the impenetrable areas of the wall. In the case of diffuse reflection of molecules from the wall

$$f^+ = (1-q)\nu f_0 \tag{10}$$

where ν is determined by the density of collisions of gas particles with the wall. The term αf_* allows for the molecules which returned to the wall on having collided with each other [1]

$$f_* = \frac{n_*}{(2\pi RT_*)^{3/2}} \exp\left\{-\frac{(\xi_x-u_*)^2+\xi_y^2+\xi_z^2}{2RT_*}\right\} \quad (11)$$

where $n_* = qn_0/2$, $u_* = 2u_0$, $u_0 = \sqrt{[RT_0/(2\pi)]}$, $T_* = T_0[1-2/(3\pi)]$. The coefficient α can be chosen arbitrarily, for example

$$\alpha = \zeta\beta \quad (12)$$

where $\zeta \leqslant 1$.

The functions of the distribution of molecules over the wall and in the developed flow (9) are the boundary conditions for the Boltzmann equation

$$\xi_x \frac{\partial f}{\partial x} = \int (f'f'_1 - ff_1) gb \, \mathrm{d}b \, \mathrm{d}\varepsilon \, \mathrm{d}\boldsymbol{\xi}_1 = J(f, f_1). \quad (13)$$

3. PARAMETERS OF A KINETIC BOUNDARY LAYER

To determine the coefficients ν and β, the mean velocity u_∞ and the gas temperature T_∞ in the developed flow, the conservation equations will be used. The balance equation of the number of particles on the impermeable areas of the wall can be written as

$$\int_{\xi_x>0} f^+ \xi_x \mathrm{d}\boldsymbol{\xi} + (1-q) \int_{\xi_x<0} f^- \xi_x \mathrm{d}\boldsymbol{\xi} = 0. \quad (14)$$

Averaging the Boltzmann equation (13) with the weight $Q_j(\boldsymbol{\xi})$ in the velocity space yields the equations for the macroscopic gas characteristics

$$\frac{\partial}{\partial x}\int \xi_x Q_j(\boldsymbol{\xi}) f \, \mathrm{d}\boldsymbol{\xi} = \int Q_j(\boldsymbol{\xi}) J(f, f_1) \, \mathrm{d}\boldsymbol{\xi} = \Delta Q_j(\boldsymbol{\xi}). \quad (15)$$

At $Q_j = 1, \xi_x, \xi^{2/2}$, the right-hand side of equation (15) vanishes. The conservation equations of mass, momentum and energy are obtained which can be written as

$$\left.\int \xi_x Q_j(\boldsymbol{\xi}) f \, \mathrm{d}\boldsymbol{\xi}\right|_{x=0} = \left.\int \xi_x Q_j(\boldsymbol{\xi}) f \mathrm{d}\boldsymbol{\xi}\right|_{x=\infty}; \quad (j = 1, 2, 3). \quad (16)$$

After calculating the integrals in equations (14) and (16), it is possible to obtain a set of equations for the main parameters of the kinetic boundary layer

$$p = q\frac{p_0}{p_\infty} = q\frac{n_0 T_0}{n_\infty T_\infty}, \; T_2 = \frac{T_\infty}{T_0}, \; S = \frac{u_\infty}{\sqrt{(2RT_\infty)}}, \nu, \beta. \quad (17)$$

Generally, in this system of four equations (14) and (16) it is assumed that the quantity p is known and that quantities T_2, S, ν, and β are unknown. However,

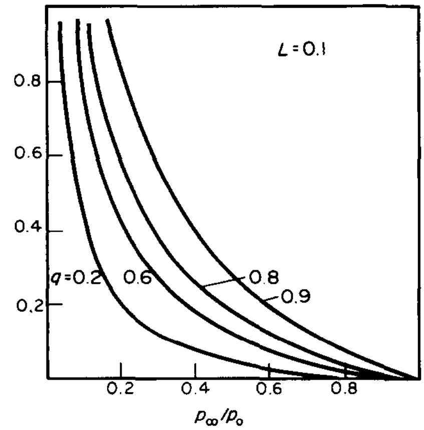

FIG. 2. Velocity ratio as a function of pressure ratio.

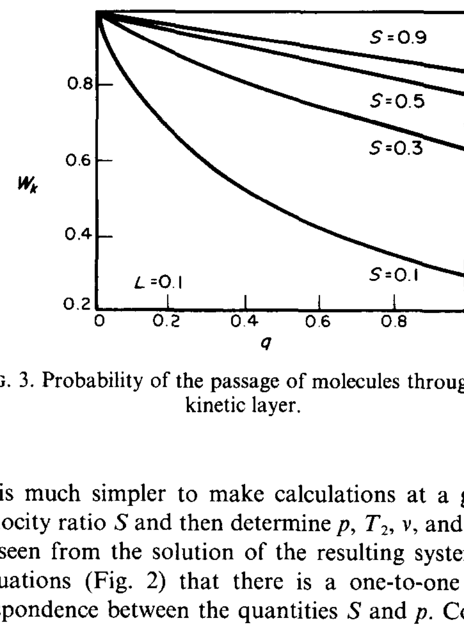

FIG. 3. Probability of the passage of molecules through the kinetic layer.

it is much simpler to make calculations at a given velocity ratio S and then determine p, T_2, ν, and β. It is seen from the solution of the resulting system of equations (Fig. 2) that there is a one-to-one correspondence between the quantities S and p. Consequently, the quantity S can be taken as the determining parameter.

Knowing the solution of equations (14) and (16), one can calculate heat and mass fluxes through the kinetic boundary layer. The mass flux is determined by the probability that molecules would pass through the kinetic layer W (Fig. 3). This parameter is equal to the ratio of the gas flow passing through the layer to the gas flow entering the kinetic layer through the channels and that formed as a result of the reflection from the impermeable areas of the wall

$$W = \frac{2\sqrt{\pi}S}{p\sqrt{T_2}[(1-\nu)W_0+\nu]}, \qquad W_0 = 2\int F_0(\theta)\sin\theta \, \mathrm{d}\theta. \quad (18)$$

The quantity W_0 is the probability of the passage of molecules through a channel.

The heat flux through the Knudsen layer can be

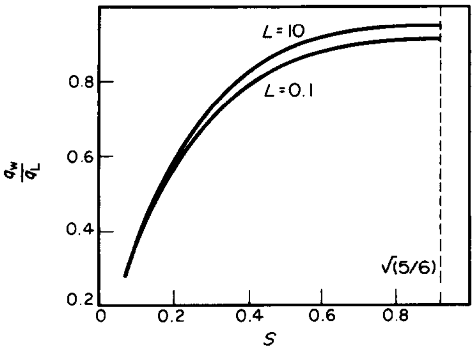

FIG. 4. Heat flux ratio.

characterized with the aid of a similar ratio q_w/q_L (Fig. 4)

$$\frac{q_w}{q_L} = \frac{\sqrt{\pi}S\sqrt{T_2}(5/2+S^2)}{p[(1-\nu)W_0+\nu/q]}. \tag{19}$$

4. KINETIC LAYER STRUCTURE

Represent the molecular distribution function at any point of the kinetic boundary layer as a linear combination of the Maxwellian distribution functions

$$f = \sum_{i=1}^{4} a_i(x) f_i$$
$$f_1 = f_0^+(\xi_x > 0),\quad f_2 = f_\infty(\xi_x > 0),$$
$$f_3 = f_\infty(\xi_x < 0),\quad f_4 = f_*(\xi_x < 0) \tag{20}$$

where $a_i(x)$ are the unknown coefficients. According to the present authors' assumptions about the form of the distribution function of molecules at the boundaries, the corresponding conditions for the coefficients $a_i(x)$ are

$$x = 0: \begin{cases} a_1 = 1, & a_2 = 0; \\ a_3 = \beta, & a_4 = \alpha; \end{cases}$$
$$x = \infty: \begin{cases} a_1 = 0, & a_2 = 1 \\ a_3 = 1, & a_4 = 0 \end{cases}. \tag{21}$$

To determine the values of $a_i(x)$, three conservation equations will be used, the fourth equation is obtained for $Q_4 = \xi_x^2$

$$\sum_{i=1}^{4} c_{1i} a_i(x) = n_\infty u_\infty;$$
$$\sum_{i=1}^{4} c_{2i} a_i(x) = n_\infty RT_\infty(2S^2+1);$$
$$\sum_{i=1}^{4} c_{3i} a_i(x) = n_\infty u_\infty RT_\infty(S^2+5/2);$$
$$\sum_{i=1}^{4} c_{4i} a_i(x) = \Delta\xi_x^2 \tag{22}$$

where coefficients c_{ki} are the moments of functions f_i

$$c_{ki} = \int \xi_x Q_k f_i \,\mathrm{d}\xi \quad (k = 1,2,3,4). \tag{23}$$

These coefficients depend on the parameters of the kinetic boundary layer. The integral of collisions on the right-hand side of the latter equation (21) for Maxwellian molecules is [3]

$$\Delta\xi_x^2 = -\frac{\pi u_0 n}{\lambda_0 n_0}\left[\int(\xi_x-u)^2 f\,\mathrm{d}\xi - \frac{1}{3}\int(\xi-\mathbf{u})^2 f\,\mathrm{d}\xi\right] \tag{24}$$

where λ_0 is the mean free path of molecules in the source chamber, n and u are the number density and mean gas velocity at the point with the x coordinate, respectively.

The first three equations of (22) will be used to express the coefficients a_1, a_2, a_4 by a_3

$$a_1 = \frac{a_3-1}{\beta-1},\quad a_2 = \frac{\beta-a_3}{\beta-1},\quad a_4 = \alpha\frac{a_3-1}{\beta-1}. \tag{25}$$

Substituting these expressions into the fourth equation of system (21) the differential equation for determining function $a_3(x)$ is obtained

$$\frac{\mathrm{d}a_3(x)}{\mathrm{d}x} = \frac{Aq}{\lambda_0}(a_3-1)(a_3-1+r). \tag{26}$$

Here, the following designations are used

$$A = \frac{\pi\Phi_1\Phi_2}{12Bp^2T_2},\quad r = \frac{2}{\Phi_1} - \frac{4S^2}{\Phi_2}.$$

The quantities B, Φ_1 and Φ_2 depend on the parameters of the kinetic boundary layer

$$B = -\left[(1-\nu)W_2 + \frac{\nu}{q}\right] + \frac{\sqrt{T_2}}{p}[E^+(S) + (\beta-1)E^-(S)] + \frac{\alpha}{2}\left(\frac{T_*}{T_0}\right)^{3/2}E^-(S_*),$$

$$\Phi_1 = \frac{1}{\beta-1}\left\{\frac{qn_0}{n_\infty}\left[(1-\nu)W_3 + \frac{\nu}{q}\right] - 1 - \operatorname{erf} S + \alpha\frac{qn_0}{2n_\infty}\operatorname{erfc} S_*\right\} + \operatorname{erfc} S,$$

$$\Phi_2 = \frac{1}{\beta-1}\left\{p\left[(1-\nu)W_4 + \frac{\nu}{q}\right] - 1 - \operatorname{erf} S + \alpha p\frac{T_*}{2T_0}\operatorname{erfc} S_*\right\} + \operatorname{erfc} S. \tag{27}$$

Functions E^+ and E^- depend on the velocity ratios S, $S_* = u_*/\sqrt{(2RT_*)}$

$$E^\pm = (1+S^2)\exp(-S^2) \pm \sqrt{\pi}S(1\pm\operatorname{erf} S)(S^2+3/2). \tag{28}$$

Coefficients W_2, W_3 and W_4 are determined by the length of the channels

$$W_2 = 4\int_0^{\pi/2} F_0(\theta)\cos^2\theta\sin\theta\,\mathrm{d}\theta,$$

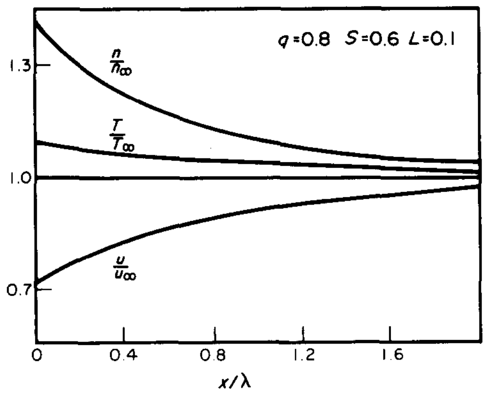

FIG. 5. Number density, mean gas velocity and temperature of gas in the kinetic layer.

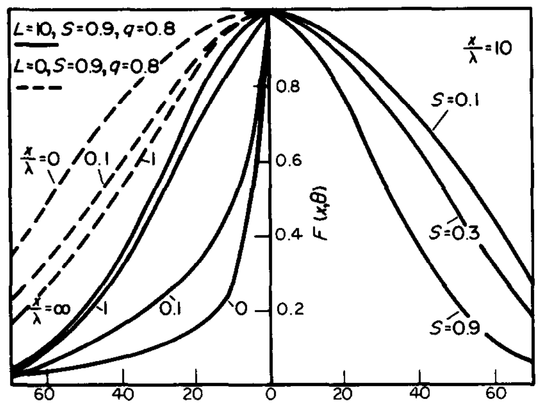

FIG. 6. Angular distribution.

$$W_3 = \int_0^{\pi/2} \frac{F_0(\theta)}{\cos\theta} \sin\theta \, d\theta, \tag{29}$$

$$W_4 = \frac{3}{2}\int_0^{\pi/2} \frac{F_0(\theta)}{\cos\theta} \sin^3\theta \, d\theta.$$

The non-linear differential equation (26) for $Ar \geqslant 0$ has the solution [9]

$$a_3 = 1+(\beta-1)\frac{\dfrac{r}{\beta-1}\exp\left(-\dfrac{x}{\lambda}\right)}{1+\dfrac{r}{\beta-1}-\exp\left(-\dfrac{x}{\lambda}\right)}. \tag{30}$$

The inequality $Ar \geqslant 0$ is fulfilled under the conditions of the subsonic gas flow regime $S \leqslant 5/6$. Equation (30) involves the notion of the kinetic boundary layer thickness

$$\lambda = \frac{\lambda_0}{Ar\, q}. \tag{31}$$

The main macroscopic gas parameters (number density n, mean velocity u and temperature T) in the kinetic boundary layer can be expressed by the already known quantities (27)

$$\frac{n}{n_\infty} = 1+\frac{\Phi_1}{2}(a_3-1), \quad \frac{u}{u_\infty} = \frac{n_\infty}{n},$$

$$\frac{T}{T_\infty} = \frac{u}{u_\infty}\left[1+\frac{\Phi_2}{3}(a_3-1)+\frac{2}{3}\left(1-\frac{u}{u_\infty}\right)S^2\right]. \tag{32}$$

As is shown in Fig. 5, in the kinetic boundary layer the number density and the temperature of the gas decrease and the mean velocity increases with an increase of the x-coordinate.

In the problem of the formation of molecular beams by packets of channels, the direction of gas flows is of great importance. The angular distribution of flows can be calculated from relation (5). After calculating the integrals of the distribution function $f^+ = a_1 f_0^+ + a_2 f_\infty^2$ $(\xi_x > 0)$, the required relation is obtained

$$F(x,\theta) = \frac{\left[(1-v)\dfrac{F_0(\theta)}{\cos\theta}+\dfrac{v}{q}\right]a_1 + \dfrac{1-a_1}{p\sqrt{T_2}}\exp(-S^2\sin^2\theta)E^+(S\cos\theta)}{\left(1-v+\dfrac{v}{q}\right)a_1+\dfrac{1-a_1}{p\sqrt{T_2}}E^+(S)}\cos\theta. \tag{33}$$

Near the surface of the perforated wall the angular distribution depends on both its porosity and thickness and also on the intensity of the flow of returning molecules

$$F(0,\theta) = \frac{(1-v)\dfrac{F_0(\theta)}{\cos\theta}+\dfrac{v}{q}}{1-v+\dfrac{v}{q}}\cos\theta. \tag{34}$$

In particular, when the wall is thin, then $F_0(\theta) = \cos\theta$ and the wall gives off molecules according to the known law $\cos\theta$. In downstream flow the angular distribution depends on the velocity ratio only

$$F(\infty,\theta) = \frac{E^+(S\cos\theta)}{E^+(S)}\exp(-S^2\sin^2\theta)\cos\theta. \tag{35}$$

The calculated data for angular distribution are given in Fig. 6.

5. DISCUSSION OF RESULTS

The solution is obtained for the problem of rarefied gas flow through a penetrable wall of arbitrary porosity and thickness. In a more accurate statement of the problem it is possible to take into account that for the solution of the problem for one channel the molecules to the right of it have the distribution function f_∞. The violation of the distribution function in the chamber to the left of the wall is also possible because of the gas flow origination. The assumptions adopted in this work correspond to the case of the evaporation of molecules from the bottom of channels.

Relations have been derived that connect the conditions of gas flow in the source chamber with the developed downstream flow. The kinetic boundary layer parameters calculated at $\alpha = 0$ depend on the porosity of the wall (Fig. 2). The probability of the passage of molecules through the kinetic boundary layer increases with an increase of the velocity ratio in a developed flow and decreases with an increase of the wall porosity (Fig. 3). The heat flux does not depend on the wall porosity (Fig. 4).

The angular distribution of the flows of molecules which characterizes the direction of the flow has been calculated. In the developed flow the angular distribution depends on the velocity ratio only. With an increase of the x-coordinate, the angular distribution becomes narrower for thin, and wider for thick, walls (Fig. 6).

In the case of low porosity of a thin wall the data corresponding to effusion are obtained [1]. When impermeable areas on the wall are absent, the results coincide with the solution of the problem of evaporation from a flat surface [4].

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TRAITEMENT PAR LA METHODE DES MOMENTS DE LA COUCHE LIMITE CINETIQUE DANS LE PROBLEME D'UN ECOULEMENT DE GAZ RAREFIE A TRAVERS UNE PAROI PERFOREE

Résumé—On étudie l'écoulement d'un gaz d'une chambre à une autre à travers une paroi plane perforée avec des canaux cylindriques. L'écoulement proche de la paroi est étudié par les méthodes de la théorie cinétique des gaz. La fonction de distribution de vitesse de la molécule est trouvée à partir de l'équation de Boltzmann par la méthode des moments. On suppose qu'il n'y a pas de collision entre molécules dans les canaux. Les molécules se rencontrent dans la couche de Knudsen près de la paroi perforée. Ceci conduit à la formation d'un écoulement uniforme loin de la paroi.

ANWENDUNG DER KINETISCHEN GASTHEORIE AUF DIE STRÖMUNG EINES VERDÜNNTEN GASES DURCH EINE PERFORIERTE WAND

Zusammenfassung—Die Gasströmung von einer Kammer in eine andere durch eine mit zylindrischen Kanälen durchbohrte ebene Wand wird erforscht. Die Gasströmung nahe einer Wandoberfläche wird mit den Methoden der kinetischen Gastheorie untersucht. Die Verteilungsfunktion der Molekülgeschwindigkeit wird aus der Boltzmann-Gleichung bestimmt, wobei zur Lösung dieser Gleichung die Momentenmethode verwendet wird. Es wird angenommen, daß keine zwischenmolekularen Kollisionen in den Kanälen stattfinden. Moleküle kollidieren in der Knudsenschicht nahe der perforierten Wand. Dies führt zur Bildung einer gleichmäßigen Strömung in weiter Entfernung von der Wand.

ИССЛЕДОВАНИЕ МЕТОДОМ МОМЕНТОВ КИНЕТИЧЕСКОГО СЛОЯ В ЗАДАЧЕ О ТЕЧЕНИИ РАЗРЕЖЕННОГО ГАЗА ЧЕРЕЗ ПЕРФОРИРОВАННУЮ СТЕНКУ

Аннотация—Исследуется течение газа из одной камеры в другую через плоскую перегородку, имеющую цилиндрические каналы. Поток газа вблизи поверхности перегородки исследуется методами кинетической теории газов. Функцию распределения молекул по скоростям находим из уравнения Больцмана, решая его методом моментов. Предполагается, что внутри каналов межмолекулярные столкновения отсутствуют. Молекулы сталкиваются в кнудсеновском слое около перфорированной стенки. Это приводит к образованию вдали от перегородки однородного потока.