Effect of a magnetic field on heat transport in tenuous molecular gases

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Results are reported of an experimental study of the heat flux Q in H_2, N_2, SF_6, and CO_2 as a function of the magnetic field H for Knudsen numbers in the range between 0.1 and 20. It is shown that when the Knudsen number is large the heat flux through all these gases is reduced when the magnetic field is introduced. For a fixed geometry of the experiment and under conditions approaching the free-molecular state, the change in the heat flux ΔQ is a monotonic function of the magnetic field H and tends to a limiting value ΔQ_{sat} which is a linear function of the pressure. It is found that ΔQ_{sat} is a function of the angle between the field and the temperature gradient. This anisotropy is different from the well-known anisotropy in the thermal conductivity in the Senftleben effect.

1. INTRODUCTION

In a previous paper[1] we predicted a change in the heat flux through a molecular gas when an external magnetic field is applied, provided the mean free path λ of the molecules is much greater than the characteristic linear size L of the container (this defines a Knudsen gas). It was assumed in[1] that the reason for the change in the heat flux in the presence of the field is that the probabilities of condensation and evaporation of molecules from a solid surface depends on the orientation of the molecules. In this type of interaction between the molecules and the wall, the distribution function for the Knudsen gas between two plane parallel surfaces at different temperatures depends not only on the velocity vector but also on the angular momentum vector which characterizes the orientation of the molecules. The interaction between the magnetic moments of the molecules and the magnetic field H leads to the precession of the molecules and, therefore, the orientation of the molecules varies during their flight between the two walls. It follows that the angular momentum distribution functions and, consequently, the corresponding heat fluxes, will be different for H = 0 and $H \neq 0$. This phenomenon was discussed in detail in[2].

It was shown in[1,2] that the change ΔQ in the heat flux in a magnetic field H exhibits the following properties:

1) ΔQ depends on the product of the magnetic field H and the distance L between the surfaces: $\Delta Q = \Delta Q(HL)$;

2) the function $\Delta Q(HL)$ should have a damped oscillatory character (such oscillations in the heat flux have been detected in N_2, CO, and NF_3[3]);

3) ΔQ is proportional to the gas pressure, other things being equal;

4) as $HL \to \infty$, the quantity ΔQ tends to the limiting value $\Delta Q(\infty) = \Delta Q_{sat}$ (saturation).

5) ΔQ_{sat} depends on the angle between the magnetic field and the normal to the surface (this is the anisotropy of the effect).

In this paper we report the results of experimental studies of the effect of the magnetic field on the heat flux in H_2, N_2, SF_6, and CO_2 under nearly free-molecular conditions, when the Knudsen number is ~10. The data obtained are compared with the assumptions and predictions of the theory of this phenomenon given in[2] and with the results of studies of the Senftleben effect[4]. In particular, it is demonstrated that the change in the heat flux in the magnetic field exhibits an anisotropy which differs from the anisotropy in the thermal conductivity as observed in the Senftleben effect[4,5].

2. EXPERIMENTAL METHOD

The change in the heat flux in a magnetic field was measured with two identical elements filled with the gas under investigation. The two elements contained temperature-sensitive resistors which formed the adjacent arms of a dc bridge. One of the elements was placed in the gap of an electromagnet and the other was used to balance the thermal drift. The off-balance signal in the bridge due to the change in the heat flux, ΔQ, when the field was switched on was measured with a F-116/1 microvoltmeter.

The experimental procedure was similar to that used previously in studies of the Senftleben effect (see, for example,[4,6,7]). Each of the elements was in the form of a cylindrical glass ampule which contained two copper plates with dimensions of 35 × 60 × 8 mm held at a fixed distance from one another (5 mm). A special holder containing a quartz frame with a mica plate mounted upon it (16×45 mm^2, 5×10^{-3} mm thick) was placed between the plates. The distance between the mica plate and the two copper plates was 2.5 mm. Π-shaped strips of gold were deposited on both sides of the mica. The strips were connected in series and were used as the temperature-sensitive elements$^{1)}$.

In all the experiments, the temperature of the gold strip deposited on the mica surface and heated by an electric current was held at 100°C. The copper plates were kept at 20°C. They were cooled with water flowing through tubes sealed to them. The tubes were taken out of the ampule through a conical ground-glass joint whose axis lay along the axis of symmetry of the element and was perpendicular to the magnetic field. The ground-glass joint could be used to rotate the entire system without affecting the gas pressure and thus vary the angle between the field and the temperature gradient. In addition to the cooling tubes, provision was made for leads through which the element could be connected to the measuring bridge.

The elements could be evacuated and gas could be leaked into them through tubes at the ends of each ampule. Prior to measurements, the system was pumped down to $\sim 10^{-5}$ Torr.

The experiments were performed in magnetic fields between 0 and 8 kOe at pressures in the range between 0.3 and 0.008 Torr. For the chosen geometry of the experiment (L = 0.25 cm), the Knudsen number for the gases under investigation lay between 0.1 and 20.

3. RESULTS AND DISCUSSION

Typical experimental results showing the change in the heat flux due to the magnetic field for two directions of the field relative to the temperature gradient are shown in Fig. 1 in the case of carbon dioxide. It is clear from the figure that the heat flux is reduced by the magnetic field and, in high fields, the quantity $|\Delta Q|$ tends to a limiting value which is different for different angles between the field and the temperature gradient.

Our experiments have shown that, in the above pressure range, the quantity ΔQ_{sat} is a function of p. This is illustrated in Fig. 2. It is clear that, as the pressure decreases, the absolute magnitude of ΔQ_{sat} also decreases. For pressures $p < 0.006$ Torr ($Kn \approx 3$), the function $\Delta Q_{sat}(p)$ is nearly linear. This is in agreement with the theoretical predictions[2] for a Knudsen molecular gas. The linear function $\Delta Q_{sat}(p)$ and also the linear dependence of the total heat flux Q through the gas on pressure (see Fig. 3) suggest that the heat transfer conditions in the carbon dioxide for $p < 0.006$ Torr are nearly free-molecular. Similar results were obtained for the other gases (H_2, N_2, and SF_6).

Figure 4 shows the experimental results for the ratio $\Delta Q/\Delta Q_{sat}$ as a function of the magnetic field for different pressures of carbon dioxide and $H \perp \nabla T$. The change in the heat flux at high pressures, when $Kn < 1$ (for $p = 0.040$ Torr, $Kn \approx 0.3$), is connected with the change in the thermal conductivity in a magnetic field (Senftleben effect, see, for example, [4-8]). This effect is known to be due to the nonspherical character of the interaction between the molecules and their precession in the magnetic field.

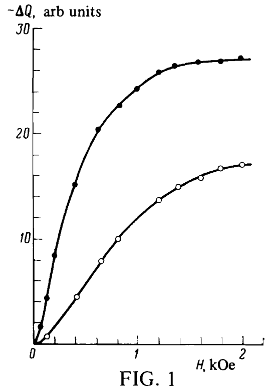

FIG. 1

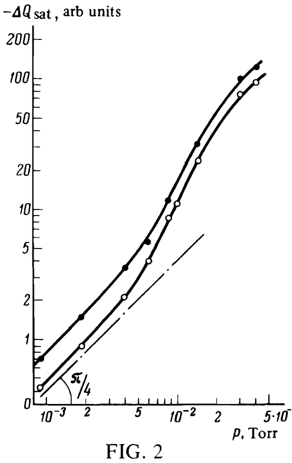

FIG. 2

FIG. 1. Dependence of the change in the heat flux through carbon dioxide on the magnetic field when the field is perpendicular to the temperature gradient (full points) and when it is parallel to the temperature gradient (open circles). The pressure is p = 0.002 Torr.

FIG. 2. Dependence of ΔQ_{sat} on the pressure of carbon dioxide when the magnetic field is perpendicular to the temperature gradient (full points) and when it is parallel to the temperature gradient (open circles).

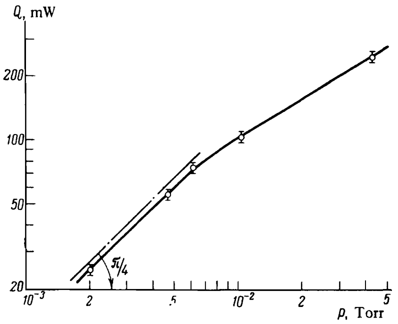

FIG. 3. Total heat flux through carbon dioxide as a function of pressure ($Q = Q_{tot} - Q_{loss}$).

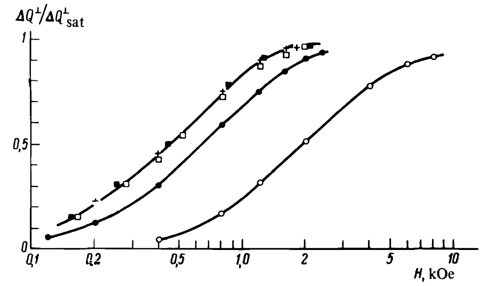

FIG. 4. The relative change in the heat flux as a function of the magnetic field $H \perp \nabla T$ for the following pressures: ○–p = 0.02, ●–p = 0.012, □–p = 0.006, ■–p = 0.004, +–p = 0.002 Torr.

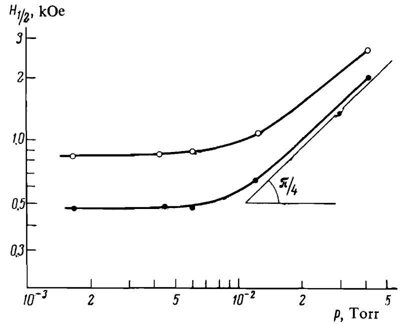

FIG. 5. The quantity $H_{1/2}$ as a function of pressure for a magnetic field parallel to the temperature gradient (open circles) and perpendicular to the temperature gradient (full points).

It is also clear from the figures that, as the pressure is reduced, the $\Delta Q/\Delta Q_{sat}$ curves shift toward lower fields, and there is a limiting curve which, to within experimental error, describes all the experimental results (independently of pressure) for $p \leq 0.006$ Torr. For $H \parallel \nabla T$ the curves behave in a similar fashion. It thus transpires that, under conditions approaching the free-molecular state, the relative change in the heat flux $\Delta Q/\Delta Q_{sat}$ depends only on the field and is independent of pressure. This experimental result confirms the theoretical prediction[2] that $\Delta Q/\Delta Q_{sat} = \varphi(HL)$ is a universal function for given experimental geometry.

Let us consider in greater detail the shift of the curves in Fig. 4 when the pressure is reduced. Let us define the magnetic field $H_{1/2}$ for which $\Delta Q(H_{1/2}) = \frac{1}{2}\Delta Q_{sat}$. Figure 5 shows $H_{1/2}$ as a function of pressure for $H \parallel \nabla T$ and $H \perp \nabla T$ in the case of carbon dioxide. It is clear that, for $p < 0.006$ Torr, the field $H_{1/2}$ is practically independent of pressure. As the pressure increases, the function tends to become linear. This last effect ($H_{1/2}/p$ = const) is in agreement with the known dependence of the thermal conductivity of a molecular gas on the ratio H/p for $Kn \ll 1$ (Senftleben effect[4-8]).

It is known from the theory of the above phenomenon[2] that the quantity ΔQ is a function of the product of the precession frequency Ω of the molecules in the field and the mean free time τ of the molecules between the two walls: $\Delta Q = \Delta Q(\Omega\tau)$. Since for nonparamagnetic molecules $\Omega = \mu_n gH/\hbar$ (μ_n is the nuclear magneton and g is the gyromagnetic ratio), and $\tau = L/\bar{v}$ where $\bar{v}$ is the mean velocity of the molecules, we have $\Delta Q = \Delta Q(HL)$. The value $\Delta Q = \frac{1}{2}\Delta Q_{sat}$ is reached for $\Omega\tau \sim 1$. Since in our experiments $L = 0.25$ cm, and for carbon dioxide $g = 0.055$[9], $\bar{v} \approx 40\,000$ cm/sec, and for $\mathbf{H} \perp \nabla T$, $H_{1/2} = 400$ Oe, we have $\Omega\tau = 0.9 \sim 1$. These estimates show that the observed change in the heat flux in a magnetic field under free molecular conditions can be described by the theory which takes into account the precession of the molecules in a magnetic field.

It was shown theoretically in[2] that ΔQ_{sat} depends on the angle between the magnetic field and the temperature gradient. This anisotropy of the heat flux is connected with the dependence of the interaction between the molecules and the solid surface on the orientation of the former. The distribution function for the molecules in the problem which we are considering depends on the velocity vector **v** and the angular momentum vector **M**: $f = f(\mathbf{v}, \mathbf{M})$. Precession, which appears when the field is introduced, produces a regular variation in the orientation of the molecules in the plane perpendicular to the direction of the field during their flight from wall to wall. For sufficiently high fields, when the precession period is much less than the time of transit of the molecules from one wall to the other, the averaging of the distribution functions over the directions over the magnetic moment in the above plane will be complete, and the change in the flux ΔQ will reach its saturation value ΔQ_{sat}. It is clear that the change in the function $f(\mathbf{v}, \mathbf{M})$ when the field is switched on will be different for different directions of H relative to the temperature gradient. When $\mathbf{H} \parallel \nabla T$, the distribution function is $f(\mathbf{v}, \mathbf{M}) = f^{\parallel}(\mathbf{v}, \mathbf{M})$ and when $\mathbf{H} \perp \nabla T$ we have $f(\mathbf{v}, \mathbf{M}) = f^{\perp}(\mathbf{v}, \mathbf{M})$. Moreover, $f^{\parallel}(\mathbf{v}, \mathbf{M}) \neq f^{\perp}(\mathbf{v}, \mathbf{M})$ and, consequently, $\Delta Q^{\parallel}_{sat} \neq \Delta Q^{\perp}_{sat}$. The ratio $\Delta Q^{\parallel}_{sat}/\Delta Q^{\perp}_{sat}$ is determined by the particular dependence of the molecule-wall interaction potential on the orientation of the molecules.

The results of the present measurements of the ratio $\Delta Q^{\perp}_{sat}/\Delta Q^{\parallel}_{sat}$ for four gases at different pressures are shown in Fig. 6. It is clear that, at low pressures, this ratio is constant for all the gases which we have examined. As the pressure increases, the ratio is found to decrease, and again tends to a constant value (see the table).

At higher pressures, when $Kn \ll 1$, we have $(\Delta Q^{\perp}/\Delta Q^{\parallel})_{sat} = (\Delta\kappa^{\perp}/\Delta\kappa^{\parallel})_{sat}$ where $\Delta\kappa^{\perp}_{sat}$, $\Delta\kappa^{\parallel}_{sat}$ are the changes in the thermal conductivity in the magnetic field (Senftleben effect). The ratio $(\Delta\kappa^{\perp}/\Delta\kappa^{\parallel})_{sat}$ is determined by the particular form of the dependence of the distribution function of the molecules on the directions of their angular momenta and velocities, and is connected with the form of the nonspherical intermolecular interaction potential. The Table lists the values of $(\Delta\kappa^{\perp}/\Delta\kappa^{\parallel})_{sat}$ for H_2, N_2, and SF_6 given in[5]. It is clear from the Table that, even for pressures $p \sim 0.1$ Torr ($Kn \sim 0.1$), the values of these ratios for the above gases agree to within experimental error with known values for $Kn \ll 1$[5], which suggests that the intermolecular collisions predominate in heat transfer even for $Kn \lesssim 0.1$.

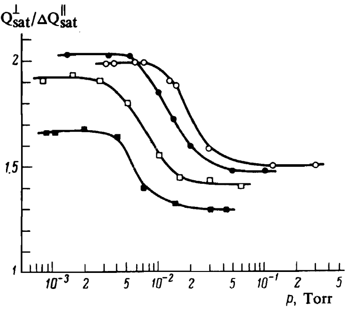

FIG. 6. The ratio $(\Delta Q^{\perp}/\Delta Q^{\parallel})_{sat}$ as a function of the pressure for: ○–H_2, ●–N_2, □–SF_6, ■–CO_2.

Gas	$\Delta Q^{\perp}_{sat}/\Delta Q^{\parallel}_{sat}$		$\Delta\kappa^{\perp}_{sat}/\Delta\kappa^{\parallel}_{sat}$ $Kn \ll 1$ (from [5])
	$Kn \approx 20$	$Kn \approx 0{,}1$	
H_2	2.00±0,05	1.50±0.05	1.5±0.1
N_2	2.00±0.03	1.53±0.03	1.57±0.01
SF_6	1.93±0.04	1.40±0.03	1.45±0.04
CO_2	1.65±0.05	1.30±0.05	—

The ratio $(\Delta Q^{\perp}/\Delta Q^{\parallel})_{sat}$ at low pressures does not agree with the calculations in[2] where the dependence of the diffuse reflection coefficient α on the orientation of the molecules was taken in the form

$$\alpha = \alpha_0(1 + \mu\mathbf{k}[\mathbf{vM}]),$$

where **k** is the normal to the surface, $\mu \ll 1$ is a scalar, and α_0 is the diffuse reflection coefficient which is independent of **k**, **v**, and **M**. Moreover, the interaction model taken in this form leads to an increase in the heat flux when the magnetic field is introduced, whilst the present experiments show that the flux is reduced in all the four gases which we have examined. It follows that, at least for these four gases, the model for the interaction with the wall must be improved.

It is important to note that, under the conditions of our experiments, we found no oscillations in the heat flux of the form established in[3]. This is probably connected with the fact that the cold (glass) walls used in[3] were much smoother than the copper surfaces used in the present research. If we allow for the fact that the interaction of the molecules with the surface depends on the direction of the normal **k** at each point on the surface, then the oscillations in the heat flux connected with different parts of the surface may be suppressed as a result of the averaging of the interaction over the random orientations of **k**.

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[1)] These temperature-sensitive resistors were developed in collaboration with L. L. Gorelik and V. V. Sinitsyn.

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