EXPERIMENTS ON THE INFLUENCE OF A MAGNETIC FIELD ON THE DUFOUR-EFFECT IN POLYATOMIC GASES: CONFIRMATION OF AN ONSAGER RELATION

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Experimental data are reported on the influence of a magnetic field on the Dufour-effect, the reciprocal phenomenon of thermal diffusion, in an equimolar N_2–Ar mixture at room temperature. An Onsager relation in the presence of a magnetic field is confirmed.

In the absence of a magnetic field the Onsager relation between the Dufour and the thermal diffusion coefficient has been experimentally confirmed by Waldmann thirty years ago [1]. For transport phenomena occurring in polyatomic gases under the influence of an external field (Senftleben–Beenakker effects) [2], such a relation has not been verified to date. Recently [3], experiments were performed on the influence of a magnetic field on thermal diffusion: transverse thermal diffusion was measured and preliminary results for the system N_2–Ar were reported. In the present paper experiments will be described on the reciprocal effect, viz. the transverse heat flux which occurs in a diffusing N_2–Ar mixture under the influence of a magnetic field.

The apparatus is essentially the same as the apparatus used by Eggermont for measuring the viscomagnetic heat-flux [4]. It consists of a rectangular channel, length 80 mm, width 10 mm, thickness 1 mm, made of low thermal conductance polyester "mylar" of thickness 75 μm (fig. 1a). A concentration gradient across the length of the channel is set up by connecting each end of the channel to a 20 l bulb filled with a pure component. This concentration gradient decays with a relaxation time of approximately five hours at 1 mm Hg (10^2 Pa).

It is monitored by measuring the difference in thermal conductivity between the gas mixtures directly at the ends of the channel. Under the influence of a magnetic field a heat flow $\boldsymbol{q}^{tr}$ perpendicular to both $\boldsymbol{B}$ and ∇x is produced. This gives rise to a transverse temperature difference δT ($\delta T_{max} \approx 2 \times 10^{-4}$ K) across the width of the channel. This is detected by means of two thermistors, glued onto the narrow walls of the channel. It was verified that δT is linear in ∇x and odd in the field, the sign of the effect being such that in the setup of fig. 1a, with the highest concentration of N_2 at the top, the highest temperature was found at the right. For calibration of the observed temperature difference in terms of a heat flux, the field induced heat flux q^{tr} was simulated by electrically heating one side of the channel. To this end the opposite side of the channel was connected to a heat sink, which unambiguously fixes the path of the heat flow (for details see ref. [4]). Results for the transverse heat flux q^{tr} are given in fig. 2, after correction for small Knudsen effects.

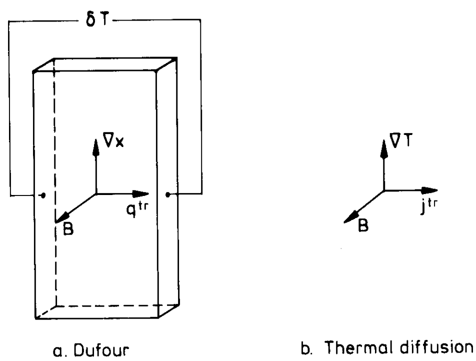

Fig. 1. (a) Schematic diagram of the apparatus. The directions of the applied N_2 concentration gradient and of the observed heat flux are indicated. (b) Direction of the observed N_2 flux in the thermal diffusion experiment (ref. [6]).

In a magnetic field the phenomenological equation for a heat flux is given by

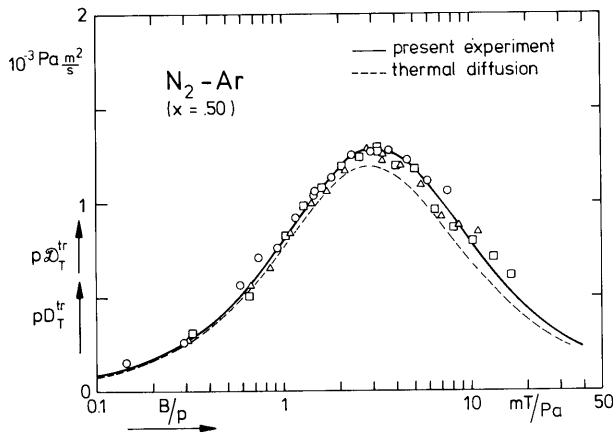

Fig. 2. Measured values of $p\mathcal{D}_T^{\mathrm{tr}} = x(1-x)q^{\mathrm{tr}}/\nabla x$ as a function of field to pressure ratio. ○ p = 258 Pa; △ p = 196 Pa; □ p = 112 Pa. The dashed curve represents pD_T^{tr} obtained from transverse thermal diffusion measurements (refs. [3], [6]). Note that 1mT/Pa corresponds to 1333 Oe/torr.

$$\boldsymbol{q} = -\boldsymbol{\lambda}\cdot\nabla T - (nkT/x_1x_2)\,\boldsymbol{\mathcal{D}}_T\cdot\nabla x_1\,, \tag{1}$$

where $x_i = n_i/n$ are mole fractions. In the present setup, where a concentration gradient ∇x ($\equiv \nabla x_1$) is applied, one finds for the magnitude of the observed transverse heat flux q^{tr}:

$$x(1-x)q^{\mathrm{tr}}/\nabla x = p\mathcal{D}_T^{\mathrm{tr}} \times [1 - (D^{\mathrm{tr}}/\mathcal{D}_T^{\mathrm{tr}})(\mathcal{D}_T/D)]\,, \tag{2}$$

where $\mathcal{D}_T^{\mathrm{tr}}$ and D^{tr} are the off-diagonal elements of the Dufour tensor $\boldsymbol{\mathcal{D}}_T$ and the diffusion tensor D, respectively. The correction term in the right-hand side of eq. (2) is of the order 10^{-3} (see below) and can be neglected.

For comparison with thermal diffusion we write down the phenomenological equation for a diffusion flux:

$$\boldsymbol{j}_1 = -nT^{-1}\mathsf{D}_T\cdot\nabla T - n\mathsf{D}\cdot\nabla x_1\,. \tag{3}$$

In the experimental setup for the measurements of the field effect on thermal diffusion, where a temperature gradient ∇T is applied, one finds for the transverse diffusion flux j_1^{tr}:

$$kTj_1^{\mathrm{tr}}/\nabla \ln T = pD_T^{\mathrm{tr}}[1 - (D^{\mathrm{tr}}/D_T^{\mathrm{tr}})(D_T/D)]\,, \tag{4}$$

where D_T^{tr} is the off-diagonal element of the thermal diffusion tensor D_T. The correction term in the right-hand side is of the order 10^{-3}, since the thermal diffusion ratio D_T/D is of the order 10^{-2} and since theoretically one estimates $D^{\mathrm{tr}} \approx \frac{1}{4}D_T^{\mathrm{tr}}$ [5].

Onsager relations for systems in the presence of a magnetic field $\boldsymbol{B}$ (z-direction) require that $(D_T)_{yx}(B) = (\mathcal{D}_T)_{xy}(-B)$, which can be written with the use of spatial symmetry considerations as $(D_T)_{yx}(B) = -(\mathcal{D}_T)_{yx}(-B) = (\mathcal{D}_T)_{yx}(B)$, or

$$D_T^{\mathrm{tr}}(B) = \mathcal{D}_T^{\mathrm{tr}}(B)\,. \tag{5}$$

This relation is confirmed experimentally (see fig. 2) by comparing the quantity $p\mathcal{D}_T^{\mathrm{tr}}$ from the present experiment with pD_T^{tr} obtained from transverse thermal diffusion [3, 6]. For all field values the two coefficients are found to be equal within the joint experimental error. Also the signs of $\mathcal{D}_T^{\mathrm{tr}}$ and D_T^{tr} are found to agree, as can be seen by comparing the phenomenological eqs. (1) and (3) with fig. 1.

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