µFLU-NEGF18-51

KNUDSEN PUMP WITH SPECULAR AND DIFFUSE WALLS

Tobias Baier[*1], Steffen Hardt[1], Vahid Shahabi[2], Ehsan Roohi[2]
[1] Institute for Nano- and Microfluidics, Technische Universität Darmstadt, Germany
baier@nmf.tu-darmstadt.de
[2] High Performance Computing Laboratory, Ferdowsi University of Mashhad, Iran

KEY WORDS

Rarefied gas dynamics, thermally induced gas flow, Knudsen pump, Direct Simulation Monte Carlo (DSMC)

SHORT SUMMARY

Knudsen pumps transport gas by imposing a temperature profile onto a rarefied gas confined within a channel with structured walls. We investigate the influence of specularly reflecting wall segments on the pumping performance of two types of Knudsen pumps, where a temperature gradient is applied perpendicular to the channel direction. One configuration is inspired by a Crookes radiometer with blades, having different reflection properties on both sides, inserted into a channel. A second configuration features a channel with a flat hot wall opposing a cold wall with a saw-tooth structure possessing alternating diffusely and specularly reflecting segments. Both configurations are analyzed numerically using the Direct Simulation Monte Carlo method, and where available the results are compared to analytical solutions.

EXTENDED ABSTRACT

As early as the 1870s, Osbourne Reynolds observed that when creating a temperature gradient across sheets of porous materials such as stucco or meerschaum, a gas flow is induced through the pores, a phenomenon that he called thermal transpiration. We have numerically investigated two configurations, where instead of the temperature gradient along the channel axis, a temperature difference is applied perpendicular to it [1,2]. By a suitable choice of the surface morphology and of the reflection properties of the gas molecules at the walls, a periodically varying temperature profile is induced along the channel, which in turn leads to a net gas flow directed along the channel. In particular, configurations were studied in which predominantly specularly reflecting wall segments are crucial for the development of the temperature profile. This arrangement is numerically analyzed using the Direct Simulation Monte Carlo Method (DSMC) and, where available, compared with analytical results. The DSMC method lends itself for this task, as the optimal working conditions occur in the transition regime between molecular and continuum-mechanical flow, where the mean free path of the gas molecules and the structure length are of the same order of magnitude.

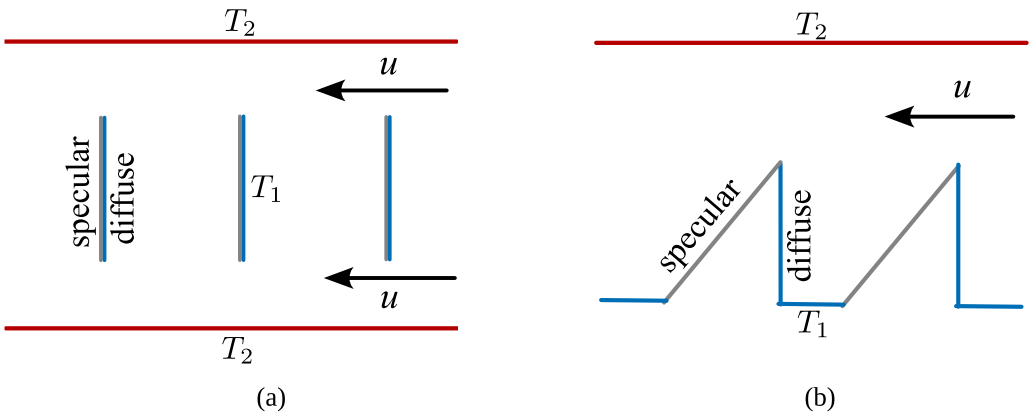

Figure 1: (a) Knudsen pump inspired by Crookes radiometer: vanes with specular/diffuse walls placed in a channel induce a flow when a transverse temperature difference is applied. (b) Knudsen pump containing a saw-tooth surface patterned with sections of specular and diffuse reflection.

The two configurations studied are sketched in figure 1. The first configuration was inspired by the Crookes radiometer which contains an impeller with one-sided blackened blades [1]. When heating the blades, e.g. by irradiation with light, the impeller is set in motion. Accordingly, when the impeller is held stationary, a gas flow is induced within the radiometer chamber. This can be used to pump gas by periodically nesting such blades along a channel bounded by two parallel plates and applying a temperature differential between the channel walls and blades, see Fig. 1(a). Since we are particularly interested in the influence of a wall with a low accommodation coefficient for the reflection of gas molecules, we assume that one of the sides of the plates reflects ideally specularly.

In the second configuration [2], a flat hot wall faces a cold wall structured with a sawtooth pattern, Fig. 1(b), the surface of which again consists of alternately specularly and diffusely reflecting segments in order to augment the temperature profile around the teeth. For both configurations, the influence of the pressure (and thus the mean free path), as well as the geometric parameters on the mass flow, is investigated. As an example, we show in Fig. 2 the average flow velocity at a plane midway between two blades of the pump configuration of Fig. 1(a) with a blade height $2H$, channel half-width $W = 2H$ and blade separation $L = 5H/8$ at a temperature ratio of $T_2/T_1 = 2$ between the sidewalls and the blades. The Knudsen number, $\mathrm{Kn} = \ell/W$, is defined as the ratio between the mean free path ℓ of the gas molecules and the channel half-width. The maximum flow velocity is achieved for $\mathrm{Kn} \approx 0.1$ for all configurations of H/W studied.

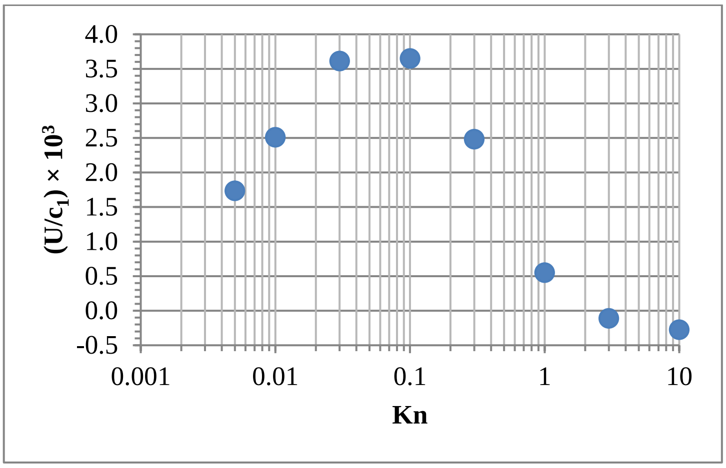

Figure 2: Average axial velocity in a plane midway between two blades of pump configuration (a), scaled by the characteristic molecular velocity, $c_1 = \sqrt{2k_B T_1/m}$. Blade width: $2H$, channel half-width: $2H$, blade separation: $5H/16$, temperature ratio $T_2/T_1 = 2$.

Of particular interest is the mechanism for the generation of the flow across the tip of the blades or teeth in configuration (a) and (b), respectively. It is found that for low Kn numbers, this mechanism is essentially the same as for thermal edge flow on a blade with a temperature dissimilar to its environment or for thermal creep flow along a wall with a tangential temperature gradient. Thus, under these conditions it can be interpreted as a boundary effect, needed to reconcile the continuous phase space distribution in the bulk with its discontinuity at the wall, imposed by the boundary condition.

Our studies were performed with a focus on the ideal case containing a fully specularly refecting wall. This may seem artificial at first, as most surfaces are known to have an accommodation coefficient close to 1. However, already Knudsen [3] explained his experimental results on radiometric forces on a heated plate by assuming different accommodation coefficients on opposite sides. More recently, accommodation coefficients between 0.1 and 0.4 have been reported for certain gas-surface combinations [4-7]. Extending our simulations to finite accommodation coefficients shows that the obtained net mass flow rates scale roughly proportionally the the fraction of specularly reflected molecules [1, 2]. Finally, we note that similar pumps have also been reported for purely diffuse surfaces both for vanes in a channel [8] (with different tempertures on opposite sides of the vanes) as for ratchet walls [9-12] (with different temperatures on opposing isothermal walls). In the latter case, due to the different mechanism for generating the driving temperature profiles and the corresponding flow profiles, the mass flow rates is significantly smaller for purely diffuse surfaces than for the mixed diffuse/specular case [12, 13, 2].

References and Citations

[1] Baier, T., Hardt, S., Shahabi, V., Roohi, E. (2017), *Knudsen pump inspired by Crookes radiometer with a specular wall*, Phys. Rev. Fluids 2(3), 033401.

[2] Shahabi, V., Baier, T., Roohi, E., Hardt, S. (2017). *Thermally induced gas flows in ratchet channels with diffuse and specular boundaries*. Sci. Rep. 7.

[3] Knudsen, M. (1930), *Radiometerdruck und Akkommodationskoeffizient*. Ann. Phys. 398, 129-185.

[4] Honig, C. D., Ducker, W. A. (2010). *Effect of molecularly-thin films on lubrication forces and accommodation coefficients in air*. J. Phys. Chem. C 114, 20114–20119 (2010).

[5] Seo, D., Ducker, W. A. *In situ control of gas flow by modification of gas-solid interactions*. Phys. Rev. Lett. 111, 174502 (2013).

[6] Seo, D. & Ducker, W. A. (2014). *Effect of Gas Species on Gas–Monolayer Interactions: Tangential Momentum Accommodation*. J. Phys. Chem. C 118, 20275–20282.

[7] Lei, W. & McKenzie, D. R. (2015). *Enhanced Water Vapor Flow in Silica Microchannels: The Effect of Adsorbed Water on Tangential Momentum Accommodation*. J. Phy. Chem. C 119, 22072–22079.

[8] Taguchi, S., Aoki, K. (2015). *Motion of an array of plates in a rarefied gas caused by radiometric force*, Phys. Rev. E 91, 063007.

[9] Würger A. (2011). *Leidenfrost gas ratchets driven by thermal creep*. Phys. Rev. Lett. 107 (16) 164502.

[10] Hardt, S., Tiwari, S., Baier, T. (2013). *Thermally driven flows between a Leidenfrost solid and a ratchet surface*. Phys. Rev. E 87, 063015.

[11] Chen, J., Baldas, L., Colin, S. (2014). *Numerical study of thermal creep flow between two ratchet surfaces*. Vacuum 109, 294–301.

[12] Chen, J., Stefanov, S. K., Baldas, L., Colin, S. (2016). *Analysis of flow induced by temperature fields in ratchet-like microchannels by Direct Simulation Monte Carlo*. Int. J. Heat and Mass Transfer 99, 672–680.

[13] Wang, R., Xu, X., Xu, K., Qian, T. (2016). *Onsager's Cross Coupling Effects in Gas Flows Confined to Micro-channels*. Phys. Rev. Fluids 1, 044102.