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Numerical study of thermal creep flow between two ratchet surfaces

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ABSTRACT

Several designs of Knudsen pumps, the principle of which is based on a thermally driven flow generated along a microchannel, have been proposed in the literature. The fabrication of efficient prototypes, however, is generally limited by the difficulty to control the temperature distribution along the walls. An alternative possibility, which only requires isothermal hot or cold walls, is investigated. The pumping element consists of two facing isothermal ratchet surfaces with different temperatures. The asymmetric saw-tooth like surfaces lead to a rectified Knudsen flow along the walls. This flow is numerically simulated in the slip flow regime with Navier–Stokes equations and appropriate first-order velocity slip, including thermal creep and wall curvature effects, as well as temperature jump, boundary conditions. The influence of the geometrical parameters is investigated, among which the ratchet angle and the alignment of the ratchet pattern. The influence of the Knudsen number and of the temperature difference is analyzed as well and guidelines are drawn for designing a prototype.

1. Introduction

In rarefied gases, flows can be generated by a tangential temperature gradient along a wall without any initial pressure gradient. This well-known phenomenon is the so-called thermal creep, or thermal transpiration, effect. It is the basis of the Knudsen pump operation principle, which allows gas pumping without any moving part when the gas is under rarefied conditions. Several different designs of Knudsen pumps have been studied in the past years, following the seminal work of Knudsen itself [1]. The typical Knudsen micropump is based on a cascade system in which a basic unit is composed of a microchannel [2–4] or of a microporous medium [5–8] connecting two mini chambers with different temperatures. An alternative configuration has been proposed and numerically studied, consisting of alternately connected curved and straight microchannels [9] or curved microchannels with different curvature radii [10]. In these designs, however, the main practical difficulty comes from the necessity to accurately control the temperature gradient generated along the walls.

To overcome this issue, a new possible configuration of Knudsen pump consisting of two facing isothermal surfaces with different temperatures, one of which at least being unsymmetrically nanostructured, has recently been proposed in 2011 by Donkov et al. [11] and by Würger [12]. Donkov et al. considered a two-dimensional prototype channel composed of a cold flat wall facing a hot structured wall (Fig. 1(a)). The cold flat wall parallel to the x-direction had a diffusive surface and the hot ratchet-structured wall exhibited a periodic pattern generated by three segments: two diffusive boundary segments in the x- and y-directions linked by one tilted specular segment. Donkov et al. demonstrated that a net flow rate $\dot{m}$ is thermally generated in the x-direction when the gas is rarefied, with a maximum momentum flux in the free-molecular flow regime and a maximum mass flux in the transition flow regime. From an analytical analysis in the free-molecular regime, it was demonstrated that there is no momentum in the x-direction when the entire structured wall has a diffuse surface and that in this regime the asymmetry of the wall topography is not a sufficient condition to generate a flow along the channel. This analysis was confirmed and completed by a numerical simulation based on two Monte Carlo schemes: a time-splitting Monte Carlo method with a hard sphere collision model and a standard DSMC method with a variable hard sphere collision model. It was shown that a maximum flow rate is achieved for a Knudsen number in the order of 10^{-1} and that the maximum value of the velocity is observed around the tips of the ratchet surface.

In the paper of Würger, the initial idea is inspired from the so-called Leidenfrost ratchet effect, by which a surface carved as a ratchet and heated over the Leidenfrost temperature can propel an evaporating droplet in a preferential direction [13,14]. In his paper, Würger pointed out that the thermal creep flow due to a

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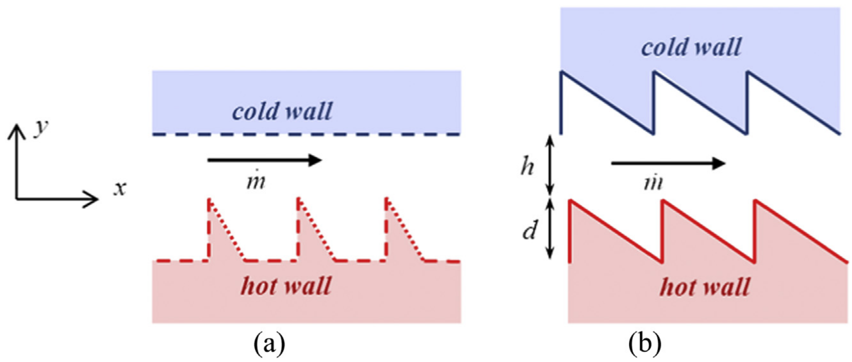

Fig. 1. Two ratchet designs analyzed by (a) Donkov et al. [11] and (b) Würger [12]. In (a), diffusive walls are represented by dashed lines and specular walls by dotted lines.

strong temperature gradient in the cleft between the droplet and the Leidenfrost ratchet surface is the physical mechanism which generates the droplet movement towards the preferential direction. He proposed an analytical model of the vapor flow in the cleft between the droplet (or a piece of dry ice) and the heated ratchet surface which is able to qualitatively predict the velocity of the droplet observed in experiments [13,14]. In contrast to that analysis, Hardt et al. [15] recently concluded from a numerical analysis using a Monte Carlo scheme that the thermal creep flow has an insignificant contribution to the thrust of Leidenfrost solids on ratchet surfaces, and that this thrust is dominated by a pressure-driven flow resulting from the sublimation of the solid. In the absence of any sublimation effect, however, Würger [12] proposed a Knudsen pump design based on the same physical mechanism as the one described in Ref. [11]. It consists of two facing ratchet surfaces with the same topography maintained at a respectively hot and cold uniform temperature (Fig 1(b)). From a simplified analytical model only valid for small ratchet depths (i.e. for $d < h$), it was demonstrated that velocities of several meters per second could be generated and that the phenomenon should also be observed for a high distance between both plates, up to hundred times higher than the mean free path of the molecules. In Würger's analysis, there was no assumption on the accommodation of the gas at the walls, contrary to the hypothesis of Donkov et al. In addition, the thermal creep along the vertical wall segments was neglected in Würger's model, which could partly explain the significant differences with the conclusions of Hardt et al. In the above mentioned papers [11,12,15], the ratchets have acute angles and the strong temperature gradients close to these angles play a significant role in the pumping efficiency.

This so-called “edge flow” effect has been described and analyzed in the literature for other configurations. For example, Sone and Yoshimoto [16] experimentally demonstrated that a flow can be induced around the edge of a uniformly heated plate, using a small windmill and observing a steady state flow as expected from numerical predictions, within the slip flow regime. A thermal edge compressor was further devised by the same authors [17]. This compressor included an array of unheated plates made in ceramic facing an array of heated plates made of a Nichrome ribbon heater. The global performance of the pump was analyzed; the energy supply rate was of the order of 10 W and the measured flow rate of nitrogen was of the order of 10^{-3} m^3/s. The flow velocity was around 1.5 m/s in the pressure range 4–10 Pa, with a temperature difference of 100 K.

The main objective of the present paper is to shed new light on the problem of thermal creep flow generated by a transverse temperature gradient between two ratchet surfaces. The following questions are addressed:

- Is the phenomenon observable in the slip flow regime and can it be analyzed by the Navier–Stokes equations with appropriate boundary conditions?
- Is there a significant generated flow rate, even when the angles of the ratchet have a finite curvature, as expected in a real-case?
- Is there a pumping effect when all surfaces are diffusive and not only when the accommodation coefficient has different values according to the segments of the ratchet?
- What is the influence of the main geometric parameters (ratchet angle, misalignment of the ratchet patterns on the facing walls, gap between the walls) and operating parameters (Knudsen number and temperature difference)?

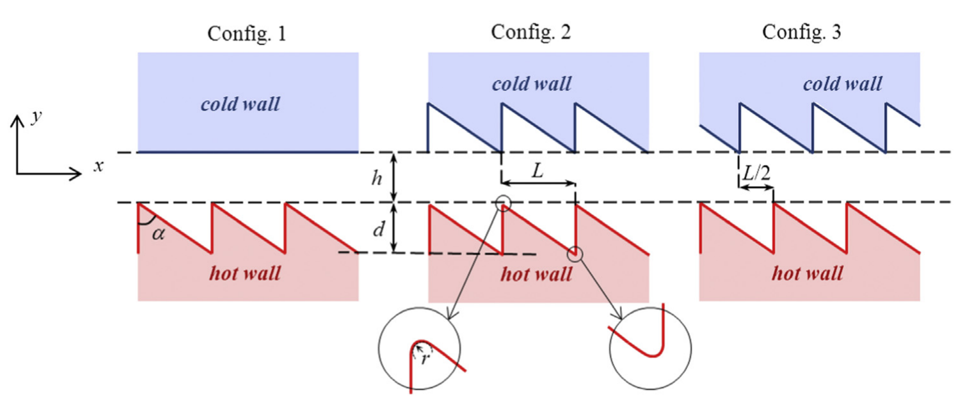

Fig. 2. Three analyzed configurations and geometric parameters.