

Application of Knudsen thermal force for detection of inert gases

A. Hassanvand^a, M. Barzegar Gerdroodbary^{b,*}, Rasoul Moradi^c, Younes Amini^d

^a Department of Polymer Engineering, Faculty of Engineering, Lorestan University, Khorramabad, Iran

^b Department of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran

^c Department of Chemical Engineering, School of Engineering & Applied Science, Khazar University, Baku, Azerbaijan

^d Department of Chemical Engineering, Isfahan University of Technology, Isfahan, Iran



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ABSTRACT

Recently, detection and analysis of gas mixtures have become significant for purifications and separation of the natural gas mixture. In the present work, Direct Simulation Monte Carlo (DSMC) method is applied to evaluate the performance of a new micro gas sensor (MIKRA) for mass analysis of three inert gases (Helium, Neon and Argon). This sensor applied the Knudsen force induced by temperature difference at the low-pressure condition to diagnose the main components of the mixture. Since this sensor works in low-pressure condition, Boltzmann equation is used to attain accurate outcomes. To solve these equations, Direct Simulation Monte Carlo (DSMC) approach is used as a robust method for the non-equilibrium flow field. This study performed comprehensive studies to disclose the primary process of force production and applied this for the analysis of the gas mixture. Hence, effects of the main parameter such as temperature gradient and the gap of arms are expansively examined in different ambient pressures. Furthermore, the influence of various mixtures of the (Helium, Neon and Argon) on force generation is also investigated. Our findings show that value of generating Knudsen force significantly varies when the component of the mixture is changed. According to obtained results, the Knudsen force declines as the molecular weight of the gas decreases. In addition, the induced force is highly proportional to the molecular weight rather than other characteristics. Therefore, the Knudsen force is a reliable method for the mass analysis of the mixtures.

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Introduction

In recent years, the application of sensors for detection of gas has become significant due to their importance in industrial devices. Since the first step for the separation of the mixture is detection, the development of this sensor could highly enhance the separation techniques such as membranes, cryogenic column and gas centrifuges [1–3]. In addition, several researchers have tried to develop new simple devices for the detection of the dangerous gas such as NH_3 , CO and H_2S . Due to the significance of inert gas, detection of these gases is important for scientists.

Since the current sensor for the analyzing and sensing of the gas is spacious and expensive, scholars have focused on the new methods and device which are small and simple. The development of the micro-electromechanical system (MEMS) have enabled researchers to decrease the size of the device in micro-scale. Consequently, micro sensors are highly developed due to their

applications in the different device such as medical instruments. Recently, scientists have found that the Knudsen force which is highly sensitive to the properties of the gas could be used as gas sensor. Indeed, the non-homogeneity of the temperature in the low-pressure condition produce a force known as Knudsen force. Previous studies [4,5] showed that this type of force is highly sensitive to the pressure of the domain, temperature difference and the type of gas of the domain. This special characteristic motivated the researchers [6] to use this approach for measurement of pressure.

High amount of studies has been devoted to recognize the characteristics of the Knudsen force in rarefied conditions. Ketsdever et al. [7] reviewed more than hundred papers and documents to present a comprehensive literature review on the origin of the Knudsen force and its history. In addition, the physics of the Knudsen force are explained in this paper. Among various studies, some of the recent work tried to apply this force for diverse applications. Since Crookes radiometer [8] was the first device which applied Knudsen force, various researchers performed extensive studies on this device. Passian et al. [9] investigated Thermal transpiration at the microscale by a Crookes cantilever. They [10] also studied

* Corresponding author.

E-mail addresses: mbarzegarg@yahoo.com (M.B. Gerdroodbary), amin.hassanvand@gmail.com (A. Hassanvand).

Knudsen forces on micro-cantilevers and presented theoretical discussions of the magnitude of the Knudsen forces in various conditions. Moreover, they [11,12] focused on the effect of thermal variations on the Knudsen forces in the transitional regime are also studied. Aoki et al. [13,14] performed numerical simulations to observe the main characteristics of the Knudsen force. Bosworth et al. [15] presented a study on the measurement of negative thermophoretic force.

Several works performed to apply a Direct Simulation Monte Carlo (DSMC) for the simulation of the rarefied gas. Several similar works also applied this method for solving engineering problems [16–21]. Strongrich, et al. [22] investigated the value of the Knudsen thermal force on hot beam with thermal gradients.

In 2016, Strongrich et al. [23,24] introduced a new device (Fig. 1a) for sensing the pressure by Knudsen force. They constructed In-plane Knudsen Radiometric Actuator (MIKRA) sensor which operates by the temperature difference between the two arms in low-pressure condition. In this sensor, the hot arm is fixed while the cold arm known as shuttle arm could move and the capacitor is attached to shuttle arm. Since the gap of these two arms is too small, the Knudsen force exerts force on the cold side and this could be measured by the capacitor. Numerical simulations showed that there are two other types of the mechanism which induce force on the cold arm. Fig. 1b schematically presents main mechanisms inside the MIKRA. The description of each type of flows will be comprehensively presented in the next chapters.

Although numerous scholars investigated the radiometric force, high volume of works investigate vane radiometer in which cold

and hot surface are on the two sides of the blade. In fact, the features of Knudsen thermal force are not comprehensively considered as cold and hot sections are existed on two side of surface. In our previous works [25], the effect of Knudsen thermal force on the performance of the low-pressure micro gas sensor is completely investigated. However, the performance of MIKRA was neither experimentally nor numerically investigated for gas mixtures such as inert gases (He/Ne/Ar) with distinct physical properties. In fact, the effects of mass concentration of each component are not revealed. Therefore, the study of the flow feature and main mechanisms of force generation inside the MIKRA in different conditions is essential for the development of the device.

In this study, DSMC approach is used for the simulation of low pressure micro gas sensor (MIKRA) within the mixture of inert gases (Helium/Neon/Argon) in different domain conditions. This study focuses on the flow feature and main mechanism of force generation for inert gas in low pressure condition. In addition, role of geometrical parameters on thermal force generation is studied to improve the ability of this device. In order to simulate the molecular behavior of gas mixture, Boltzmann equation as a governing equation is explained. Then, DSMC approach as a robust method for solving this equation is presented. Then, boundary conditions and working situation of the MIKRA are determined. Extensive investigations on roles of pressure of domain, length and gap of the arms are presented and the important factors of each parameter on the streamline and induced force inside the micro sensor are explained. Also, the effect of gas species (Helium/Neon/Argon) on force generation in the micro actuator due to temperature

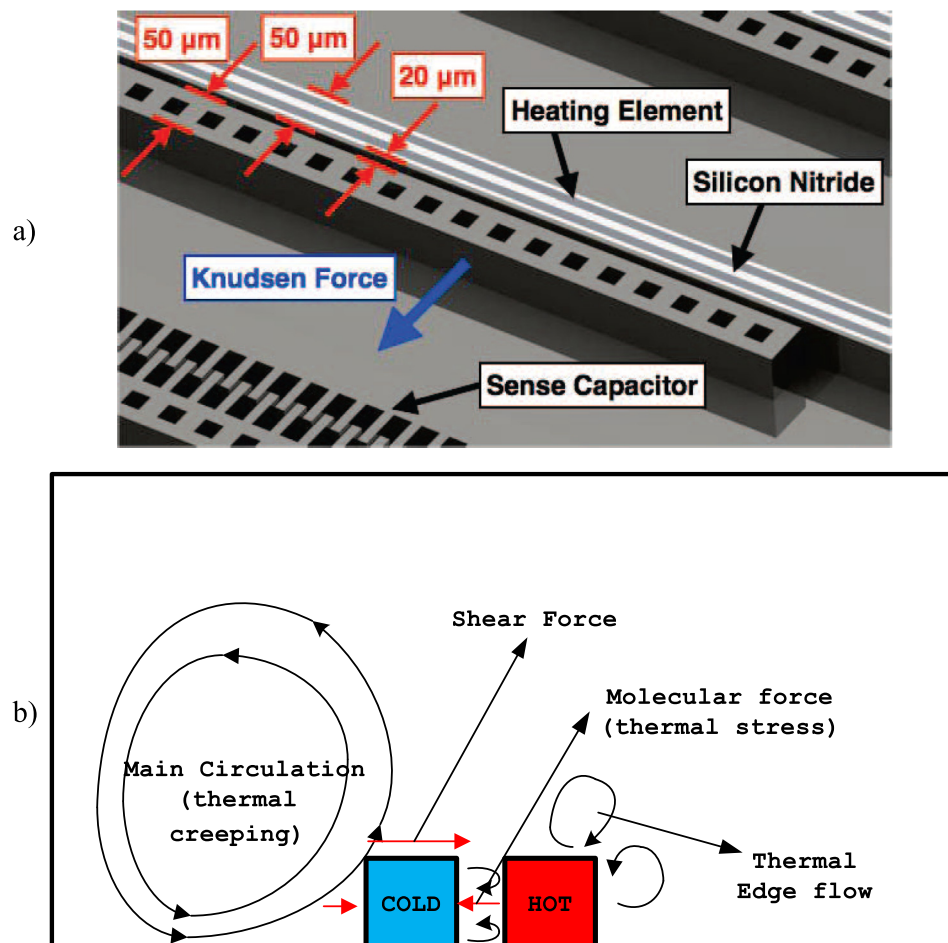


Fig. 1. a) MIKRA device [23] b) Schematic of flow inside the MEMS sensor.

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