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Detection of ammonia gas by Knudsen thermal force in micro gas actuator

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ABSTRACT

Direct Simulation Monte Carlo (DSMC) method is applied to evaluate the performance of a new micro gas sensor (MIKRA) for mass analysis of ammonia in the rarefied gas. In order to simulate a rarefied gas inside the micro gas detector, Boltzmann equation is applied to obtain high precision results. This study performed comprehensive studies to reveal the main mechanism of force generation and applied this for the analysis of the gas mixture. Our findings show that value of generated Knudsen force significantly varies when the percentage of the NH3 varies in the mixture. According to obtained results, the maximum Knudsen force increases when the fraction of the ammonia decreases. Our findings reveal that the effect of gap size varies with the pressure of the domain. In addition, the increase of temperature gradient from 40 K to 100 K rises the maximum Knudsen force more than 400% on the shuttle arm.

1. Introduction

In recent decades, the application of ammonia has been highly increased due its importance and application in industrial plants. Since ammonia is dangerous and toxic, its leakage could lead to dangerous environmental and human loss. Hence, the scholars have tried to find and introduce new devices for detection of this gas. There are various sensors for the detection of gas. However, most of them are spacious and expensive. Hence, several researchers have tried to develop new simple devices for the detection of the dangerous gas such as NH_3, CO and H_2S [1–3].

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) has 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. One of the new methods for the detection of the gas is the application of the Knudsen force which is highly sensitive to the properties of the gas. 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. Findings of the new techniques for develop micro gas sensors are high demanded due to applications of this device. In order to do this, scholars have tried to find a new method which is sensitive to the gas types. Scientist found that the type of molecular force is highly related to the gas pressure and types. Hence, they presented radiometer as the first device which works with effects of the temperature gradient.

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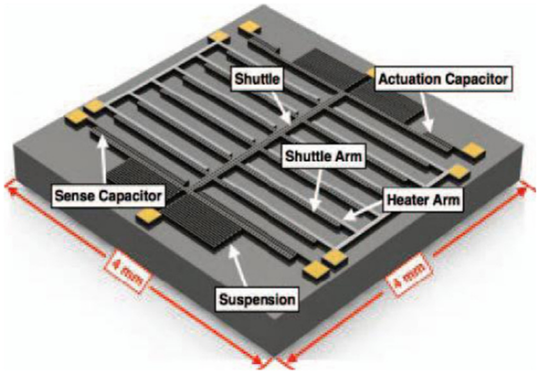
a)



b)

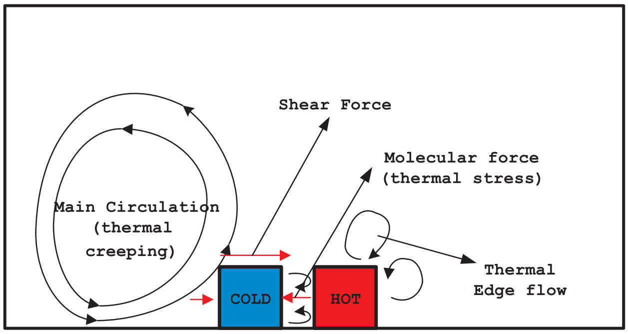


Fig. 1. a) MIKRA device [23] b) Schematic of flow inside the MEMS sensor.

The 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 forces are explained in these papers. Among various studies, some of the recent work tried to apply this force to 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 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. [13–15] performed numerical simulations to observe the main characteristics of the Knudsen force. Bosworth et al. [16] 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. Balaj et al. [17,18] focused on the effects of shear work on non-equilibrium heat transfer characteristics of rarefied gas flows through micro/nanochannels. Poozesh and Mirzaei [19] applied the lattice Boltzmann method for flow simulation around cambered airfoil by using conformal mapping and intermediate domain. Aghakhani et al. [20] studied Heuristic and Eulerian interface capturing approaches for shallow water type flow and application to granular flows. Eskandari and Nourazar [21] focused on the time relaxed Monte Carlo computations for the lid-driven micro cavity flow. Strongrich, et al. [22] performed experimental measurements and numerical simulations of the Knudsen force on a non-uniformly heated beam.

In 2016, Strongrich et al. [23] 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 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 between these two arms is too small, the Knudsen force exerts the 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 a 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, most of the works focused on the study of vane radiometer in which hot and cold sides are on the two sides of the vane. Indeed, the characteristics of Knudsen thermal force are not well studied when hot and cold elements have existed in front of each other. In our previous works [24,25], 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 ammonia and air with distinct chemical properties. In fact, the effects of the 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 the low-pressure micro gas sensor (MIKRA) within the NH3/N2 mixture