EXPERIMENTAL AND NUMERICAL STUDIES ON GAS FLOW THROUGH ROUGH AND SMOOTH MICROCHANNELS

by

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Dedicated to my

Family and to my Country

icro-electromechanical systems (MEMS);

CERTIFICATE

The thesis entitled **Experimental and Numerical Studies on Gas Flow through Rough and Smooth Microchannels** being submitted by Mr. **Srinivasan K** to the Indian Institute of Technology Delhi for award of the degree of **Doctor of Philosophy** is a record of original bonafide research work carried out by him. He has worked under my guidance and supervision, and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph.D degree of this institute. The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

Gas flow through microchannels has an important application in micro-electromechanical systems (MEMS). The present investigation is focused on validity of continuum approach in those microdevices by modifying the boundary conditions. The present work investigates the extension of Navier-Stokes equations from slip-to-transition regimes with higher order slip boundary condition. Also, the work involves in studying the flow characteristics in microchannels of high aspect ratios ($a = H / W = 0.002$, 0.01 and 0.1) by generating accurate and high resolution experimental data along with the computational validation. Further, a comparative study between the rough and smooth microchannels makes the investigation even more interesting.

The primary objective of the present investigation is to investigate experimentally and computationally the gas flow through microchannels from low to high Knudsen numbers. To achieve this, a slip model based on the second order slip boundary condition was derived. In order to generate a comprehensive database for slip flow regime, microchannels having similar top and bottom surfaces and an experimental set-up which can produce reliable and accurate data at high and low (below atmospheric) pressures were developed.

Unlike conventional macrochannels, analysis of flow regimes in microchannels, requires a combined experimental and simulation method. Two dimensional simulations in planar microchannel geometry were carried out using a commercial CFD tool called FLUENT® in which the derived second order slip model was implemented as a boundary profile. Also, first order and no-slip boundary conditions were implemented for

comparative study. The boundary profile for both top and bottom walls was solved for each pressure ratio by the customized user-defined function and then passed to the FLUENT® solver. The simulation using first order slip model was validated with previous experimental studies for Knudsen numbers up to 0.1. The pressure distribution and velocity distribution along the length of the channel and mass flow predictions were found to be in good agreement with previous studies. Similarly, simulated second order mass flow rate values were validated with previous experimental results for three channel aspect ratios such as 0.01, 0.055 and 0.087 up to a maximum outlet Knudsen number of 0.47. Good agreement was observed even for the closest aspect ratio of 0.087.

Microchannels with inlet and outlet plenum were fabricated in silicon wafers by using silicon etching and surface etching techniques. In the present work, each microchannel system has several identical microchannels of same dimensions in parallel. The increased flow rate reduced uncertainty substantially. To form a complete microchannel system, the processed wafer was bonded with a plane wafer and its interface was viewed by using thermal imaging technique. This interface characterization has not been found in any of the previous microchannel studies.

Experimental facilities developed in the present investigation included basic instrumentation for pressure, temperature and mass flow measurements, fabrication of test section and vacuum assembly unit. Experiments were conducted in microchannels of aspect ratio 0.002 with nitrogen at a constant room temperature of 305.5 K up to an outlet Knudsen number of 0.405. This range was generally considered to belong to slip and transition regimes. The computed mass flow rate using second order slip model was compared with measured values and the average variation was 2.5 %. In the present study, the computed mass flow rate using first order slip model was used to predict the TMAC value, which supplies the value of C_1 and C_2 needed for second order model. The TMAC values were found to be varying from 0.945 and 0.917.

The experimental and numerical comparison of mass flow rates for Knudsen numbers between 0.071 and 1.012 with nitrogen for a channel aspect ratio of 0.01 was performed. Experimental results are in good agreement with computed mass flow rates using second order model up to an outlet Knudsen number of 0.896 with an average variation of less than 2.5 %. The TMAC values were found to be varying from 0.944 to 0.874. The value of TMAC obtained using second order models was monotonically decreasing with increasing Knudsen numbers.

The experimental and numerical comparison of mass flow rates for Knudsen numbers between 0.033 and 0.251 with nitrogen for a channel aspect ratio of 0.1 was performed. The TMAC values were found to varying from 0.955 to 0.923.

Other major contribution of the present research is the determination of flow behavior for the modified microchannel surface. Microchannels were fabricated using surface etching technique, for that modified process flow with additional process steps were adopted. The surface roughness of the modified surface was found to be nearly two orders of magnitude lesser than the rough channels. The TMAC values from numerical and experimental determinations for nitrogen were obtained up to an outlet Knudsen number of 0.851 using second order slip model. The TMAC values were found to be varying from 0.885 to 0.786. The values obtained are appropriate for the real MEMS surfaces which are commonly used in various MEMS applications.

In the present research, a systematic investigation of gas flow through microchannels for various aspect ratios and various surface conditions were performed. The fabricated microchannels in both rough and smooth surfaces of similar materials replicate the real conditions in MEMS applications. All the experiments were conducted under controlled conditions which were validated with simulation results. The simulation methodology and the experimental data obtained can be directly utilized for the microfluidics MEMS industries for various applications.

Keywords: Microchannel system, second order slip model, thermography, rough and smooth surfaces

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