University of Victoria | Graduate Studies

Notice of the Final Oral Examination for the Degree of Doctor of Philosophy

of

ALIREZA MOHAMMADZADEH

MSc (Ferdowsi University of Mashhad, 2012)
BSc (University of Tehran, 2009)

"Moment Method in Rarefied Gas Dynamics: Applications to Heat Transfer in Solids and Gas-Surface Interactions"

Department of Mechanical Engineering

Thursday, October 20, 2016
1:00 P.M.
Engineering Computer Science Building
Room 468

<u>Supervisory Committee:</u>
Dr. Henning Struchtrup, Department of Mechanical Engineering, University of Victoria (Supervisor)
Dr. Peter Oshkai, Department of Mechanical Engineering, UVic (Member)
Dr. Reuven Gordon, Department of Electrical and Computer Engineering, UVic (Outside Member)

<u>External Examiner:</u>
Dr. Nicolas Hadjiconstantinou, Department of Mechanical Engineering, Massachusetts Institute of Technology

<u>Chair of Oral Examination:</u>
Dr. Slim Ibrahim, Department of Mathematics and Statistics, UVic

Dr. David Capson, Dean, Faculty of Graduate Studies

Abstract

It is well established that rarefied flows cannot be properly described by traditional hydrodynamics, namely the Navier-Stokes equations for gas flows, and the Fourier's law for heat transfer. Considering the significant advancement in miniaturization of electronic devices, where dimensions become comparable with the mean free path of the flow, the study of rarefied flows is extremely important. This dissertation includes two main parts.

First, we look into the heat transport in solids when the mean free path for phonons are comparable with the length scale of the flow. A set of macroscopic moment equations for heat transport in solids are derived to extend the validity of Fourier's law beyond the hydrodynamics regime. These equations are derived such that they remain valid at room temperature, where the MEMS devices usually work. The system of moment equations for heat transport is then employed to model the thermal grating experiment, recently conducted on a silicon wafer. It turns out that at room temperature, where the experiment was conducted, phonons with high mean free path significantly contribute to the heat transport. These low frequency phonons are not considered in the classical theory, which leads to failure of the Fourier's law in describing the thermal grating experiment. In contrast, the system of moment equations successfully predict the deviation from the classical theory in the experiment, and suggest the importance of considering both low and high frequency phonons at room temperature to capture the experimental results.

In the second part of this study, we look into the gas-surface interactions for conventional gas dynamics when the gas flow is rarefied. An extension to the well-known Maxwell boundary conditions for gas-surface interactions are obtained by considering velocity dependency in the reflection kernel from the surface. This extension improves the Maxwell boundary conditions by providing an extra free parameter that can be fitted to the experimental data for thermal transpiration effect in non-equilibrium flows. The velocity dependent Maxwell boundary conditions are derived for the Direct Simulation Monte Carlo (DSMC) method and the regularized 13-moment (R13) equations for conventional gas dynamics. Then, a thermal cavity is considered to test and study the effect of these boundary conditions on the flow formation in the slip and early transition regime. It turns out that using velocity dependent boundary conditions allows us to change the size and direction of the thermal transpiration force, which leads to marked changes in the balance of transpiration forces and thermal stresses in the flow.