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ALTERNATIVE MODELS AND NUMERICAL SIMULATIONS OF RAREFIED GAS FLOW IN VACUUM SYSTEMS

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Abstract – An analytical and a numerical studies of rarefied gas effects on the flow through a vacuum pipe and a rectangular microchannel at low operating pressure are performed by the use of both existing continuum and kinetic approaches. The pipe and the channel operates in a high-Knudsen-, low-Reynolds-numbers regime where the viscous effects as well as the rarefied gas effects dominate the flow. Since only the isothermal flow is focused, the slip-flow at the wall is the main anomaly. The paper shows the implementation of both approaches to predict a rarefied gas flow through a leak artefact. The results from various existing models are compared with the experimental results of a flow through leak artefacts, which were performed by recognized national metrology institutes (NMIs). Pros, cons and the limitation of each approach are pointed out.

Keywords: vacuum, slip-flow, leak, rarefied gas

1. INTRODUCTION

The recent advances in the vacuum techniques and the micro-machinery have led to the creation of various systems with a very high vacuum (extremely low operating pressure), which could be in a very small size. Due to these conditions, the gas is rarefied which makes the flow behaviours differ from those near the ambient pressure and/or in a normal size system. At an extremely low operating pressure, the numbers of gas molecules will be dramatically decreased causing the gas to be rarefied. The situation is magnified if the size of the system is reduced. Consequently, due to the small number of gas molecules, the flow behaviours will be different from general gas, where the number of gas molecules is large enough to consider the gas as a continuum medium. The continuum medium assumption is not valid for the aforementioned cases if the flow behaves as slip, transition, or free molecular flow. Therefore, tube characteristic length, L_C and the tube pressure, p, are the two main factors of Knudsen number, Kn that characterise the flow regime through a sonic nozzle. The Knudsen number is defined as:

$$\mathrm{Kn} = \frac{\lambda}{L_C} \tag{1}$$

where the mean free path, λ is a function of the pressure, p, the viscosity, μ and the most probable molecular velocity, $\tilde{v}$. There are various models to describe the molecular mean free path [1]. However, to avoid the confusion, the mean free path is estimated using Maxwellian theory.

As well as the Knudsen number, the rarefaction parameter, δ is another quantity that is also used to describe the flow regime and is defined as [2]:

$$\delta = \frac{\sqrt{\pi}}{2}\frac{L_C}{\lambda} = \frac{\sqrt{\pi}}{2}\frac{1}{\mathrm{Kn}} \ . \tag{2}$$

From Eq.1, the Knudsen number as a function of the pressure of gas flowing through ISO-standard tube, and the imperial size tube, is plotted in Figure 1.

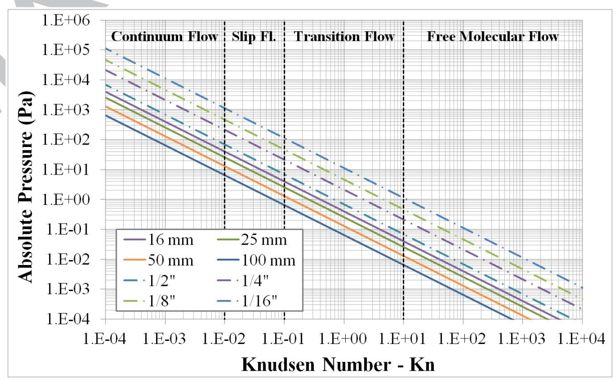

Fig. 1. Pressure versus Kn for usual gas flow through the ISO-standard and the imperial size tubes.

When Kn is very small, there are enough molecules for the gas to be considered as in a continuum regime. The slip-flow starts to appear at values of Kn greater than 0.001 and become dominant at around 0.01, where the slip-flow regime begins. As the gas becomes more and more rarefied, its flow is characterised as being in the transition and free molecular regimes, when Kn reaches 0.1 and 10 respectively.

From Fig. 1, the flows through small imperial size tubes enter the slip-flow state at an early vacuum regime. As the pressure reduces the flow would become more and more rarefied, resulting in a rise in an anomaly due to the rarefied gas effects. The rarefied gas flow behaviours such as the slip-flow, the temperature jump and the thermal transpiration could not be described using normal continuum approaches, which base on Navier-Stoke equations. Larger ISO-standard tubes prolong the continuum flow regime in a lower pressure environment. For the 50 mm tube that uses ISO 50KF or 50CF as a connector, the flow through the tube enters slip-