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Velocity measurement in low Reynolds and low Mach number slip flow through a tube

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ABSTRACT

This paper presents an experimental procedure and results of velocity measurement in the slip flow regime. The measurements are for nitrogen gas flowing at low pressure (flow Reynolds number: 4–198, Mach number: 0.05–0.12) in a conventional tube of 16 mm internal diameter. The static pressure is measured at the wall of the tube and the stagnation pressure is measured through a Pitot tube, for different mass flow rates. The velocity is estimated by applying stagnation pressure correction proposed by earlier researchers, as the Bernoulli equation cannot be applied in gas flow for $Re_p < 30$. In the slip regime, the stagnation pressure correction is found to be a function of Reynolds number and a weak function of rarefaction. A new correlation for stagnation pressure correction is also proposed. Using this correction, velocity within ±8% with reference to the analytical solution is obtained. These results are not previously available and should help in velocity measurement ability of low Reynolds number slip flows.
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1. Introduction

In 1732, Pitot demonstrated that a bent tube facing the oncoming flow stream brings the fluid to rest and thereby the total pressure of the flow stream can be measured. Since then, this simple instrument named as Pitot tube, remains the most widely used device for the measurement of total or impact pressure, even in the slip flow regime [1]. Its usefulness for the measurement of fluid velocity has been extended by the development of electronic pressure transducers. These transducers facilitate the accurate measurement of small pressure differences registered by the Pitot tube. It is assumed that the flow is brought to rest at the Pitot tube tip and the pressure measured by the Pitot tube is the stagnation pressure. Thus the flow velocity through a tube can be estimated using the Bernoulli equation. However, in the case of rarefied gas flow with low Reynolds number, the magnitude of viscous force is comparable with inertia force; which alters the flow pattern around the Pitot tube. Further, the assumption of zero velocity at the Pitot tube tip is no longer correct because of slip at the walls. Hence the Bernoulli formula needs correction owing to these viscous and rarefaction effects. The present work focuses on velocity measurement of internal rarefied gas flow with low Reynolds and low Mach number using a Pitot tube.

The deviation of stagnation pressure from Bernoulli pressure was first experimentally demonstrated by Barker [2] for $7 < Re_p < 100$ (Re_p = Reynolds number on the basis of Pitot tube diameter; see Eq. (4)); which is known as Barker effect. Homann [3] theoretically and experimentally estimated the total pressure on cylinder and sphere in viscous flow for $3.2 < Re_p < 120$, and presented an expression for stagnation pressure correction coefficient (Cp). Hurd et al. [4] proposed a correlation for Cp applicable to a blunt nosed Pitot tube, based on experiments over $1.7 < Re_p < 100$. Similar experimental studies were later performed by MacMillan [5] and Schowalter and Blaker [6]. An experimental correlation for Cp was also suggested by Mikhailova and Repik [7]. Chebbi and Tavoularis [8] investigated very low Reynolds number range ($Re_p < 1$) for circular Pitot tube and proposed an expression for Cp. Lester [9] performed numerical simulations for circular Pitot tube with $1 < Re_p < 10$ and also suggested a correction coefficient. Boetcher and Sparrow [10] performed numerical simulations and reported that the breakdown of the Bernoulli interpretation occurs at $Re_p < 45$ for hemispherical nosed Pitot tube and at $Re_p < 65$ for blunt nosed Pitot tube. All of these studies are aimed at studying the effect of viscous forces on the stagnation pressure correction for low Reynolds number continuum flow.

In the case of rarefied gas flow, researchers [11–18] studied the effect for low Reynolds number and supersonic flow. The correction for rarefaction is considerable when the flow Mach number is more

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than 0.4 and Knudsen number (Kn; defined later through Eq. (2)) ≈ 1. Limited studies are available for low Reynolds and low Mach number in the slip flow regime. Lin and Schaaf [19] noted that the effect of slip on viscous flow ($1 < Re_p < 400$, $0.1 < Ma < 0.8$) around Pitot tube (hemispherical end) increases the viscous correction to stagnation pressure. The experimental study by Sherman [12] and Enkenhus [20] showed that the stagnation pressure correction coefficient is independent of Mach number for $Re_p > 10$. Sreekanth [21] proposed a correction coefficient as a function of Re (based on internal diameter of Pitot tube) for the Re range of 0.1–1, and Kn (based on internal diameter of Pitot tube) range of 1–20. The slip velocity correction coefficient for plane and tubular flows as a function of Knudsen number was proposed by Fichman and Hetsroni [22]. Soundalgekar and Divekar [23] reported in a numerical analysis that the pressure gradient increases and skin friction decreases with increasing rarefaction.

This work presents an experimental study on the velocity measurement of the internal rarefied gas flow through a tube in the slip flow regime with nitrogen as the working fluid. The long term objective of our work is to improve fundamental understanding of gas flow in a microchannel. The approach of Sreekanth [1], Demsis et al. [24,25] and Varade et al. [26] is adopted here; in that a scaled-up facility, which facilities measurement of local quantities, is employed for velocity measurements. The objectives of this work are to establish suitable correction for the viscous effect and to estimate the uncertainty in obtaining the streamwise velocity using a Pitot tube in the slip flow regime.

2. Experimental arrangement

The experimental setup consists of a vacuum system, inlet reservoir, outlet reservoir, and a mass flow controller, as shown in Fig. 1a. The vacuum system consists of a diffusion pump with a maximum volume flow rate capacity of 700 lpm and a rotary pump with a volume flow rate capacity of 350 lpm. The minimum pressure that can be achieved by the vacuum system is 10^{-6} mbar. An air filter is used for blocking particles of size larger than 25 μm in the incoming gas stream. Two different mass flow controllers (from M/s MKS Instruments) with ranges of 0–200 sccm ($0–3.73 \times 10^{-6}$ kg/s) and 0–5000 sccm ($0–9.33 \times 10^{-5}$ kg/s) are used to achieve different Reynolds and Knudsen numbers in the experiments. The absolute pressure in the test section is measured by an absolute pressure transducer (M/s MKS Instruments) of range either 0–100 Pa or 0–10,000 Pa. The uncertainties in the measurement of the flow rate and the pressure (along with other measured and derived parameters) are tabulated in Table 1.

Table 1
Maximum uncertainty in various measured and derived parameters.

Parameter	Maximum uncertainty
Mass flow rate	±2% of full scale
Absolute pressure	±0.15% of the reading
Diameter	±0.1%
Reynolds number	±2%
Knudsen number	±0.5%

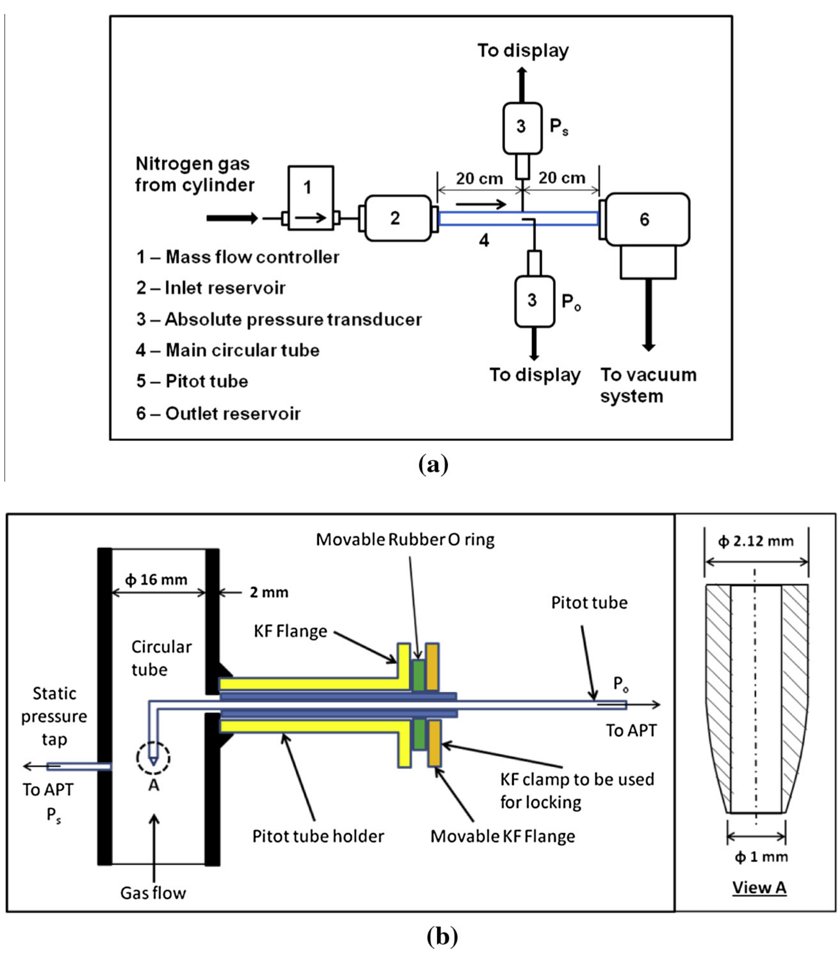

Fig. 1. Schematic diagram of (a) experimental set up and (b) Pitot tube arrangement (P_s = static pressure, Pa; P_o = stagnation/total/impact pressure, Pa; APT = absolute pressure transducer.

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