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Entrance Configuration Effects on Tube Flow in the Transition Regime

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Nomenclature

C_D = discharge coefficient
D = tube diameter
k = ratio of specific heats
L = total tube length
L/D = tube length-to-diameter
$\dot{m}$ = mass flow rate
P_1 = pressure upstream of the tube entrance
P_2 = pressure downstream of the tube entrance
R = gas constant
Re_D = Reynolds number based on tube diameter
T_1 = upstream temperature
μ_1 = upstream coefficient of viscosity

Introduction

OVER the past seventy years, experimental and theoretical investigations have been conducted on the flow of rarefied gases in tubes and orifices.[1–6] Most theoretical investigations have assumed that the flow entered the tube through an abrupt or square-edged entrance. However, most experimental studies have involved tubes with rounded or bell-mouthed entrances so as to avoid the problem of entrance separation and vena-contracta at higher Reynolds numbers. These experiments have usually specified the tube entrance to be at some point downstream of the rounded entrance in order to compare data with theories assuming fully developed flow at the entrance in the viscous flow range.

In this Note, two recent sets of experimental data[1,4] are compared in order to examine the effect of entrance shape on rarefied flow through tubes and their relation to the theory of Clausing[2] for free molecular tube flow. Clausing's theory depends on the length-to-diameter ratio of the tube, presenting the problem of choosing an effective tube length for a tube with a bell-mouthed entrance.

The recent experimental investigations of Carley and Smetana[1] and Marchman[4] both involved the flow of nitrogen gas through short tubes in the transition regime. Both investigations measured flow rates and upstream and downstream pressures in this range under steady-state conditions and presented data in terms of discharge coefficients,

$$C_D = \dot{m}/[\pi D^2 P_1(k/R)^{1/2}/4(T_1)^{1/2}]([k + 1]/2)^{(k+1)/2(k-1)}$$

and Reynolds number based on tube diameter, $Re_D = 4\dot{m}/\pi D\mu_1$. In both studies flow rates were measured with high accuracy volume displacement flowmeters and pressures with McLeod gages, both of which are calibration standard instruments. All measurements were repeated at least 3 times to insure a high degree of accuracy.

The smooth entrance tube[1] had an entrance-to-exit plane length of 6.22 cm, a constant diameter section downstream

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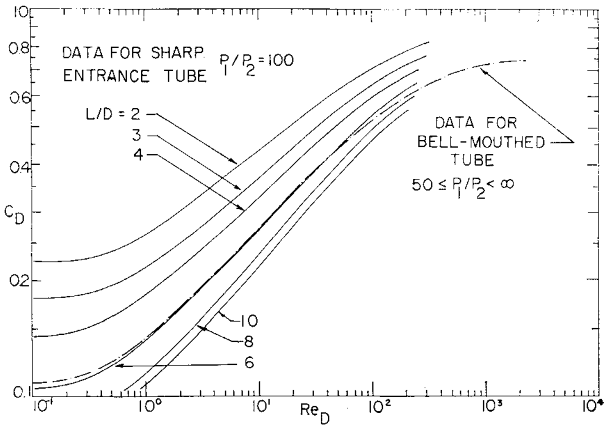

Fig. 1 Comparison of data.

of the entrance of 4.32 cm with a 1.15-cm diam. An effective length-to-diameter ratio of 4.79 was assumed based on an extrapolation of data to the free-molecule limit and comparison with the theory of Clausing. The square-edged entrance tube had a 2.54 cm diam and was tested at L/D values from 2 to 10. The resulting data are presented in Fig. 1. The square-edged tube data are all for pressure ratios of 100 whereas the bell-mouthed tube data are the best curve through the recorded data from pressure ratios of 50 to infinity. A comparison of these curves is valid based on recent studies[1,4,6] which indicate little or no significant increase in discharge coefficient at a given Reynolds number above a pressure ratio of 20. All of the data shown agree with the respective Clausing theory limits for tubes of the given length-to-diameter ratios in the free-molecule limit.

It is noted that at Reynolds numbers from 1 to 30 the bell-mouthed data correspond well with the square-edged data for a length-to-diameter ratio of 6, indicating that the effective length-to-diameter ratio should be nearer to the maximum for this tube (5.42) rather than the value of 4.79 assumed. Below this range of Reynolds number, the rounded entrance tube discharge coefficients exceed those for the square-edge entrance tube, indicating a lower effective L/D. Above this range, the smooth entrance data fall below that for the abrupt entrance indicating a higher effective L/D. While the closeness of the 2 sets of data demands a cautious comparison, a simple analysis of these results would indicate that as the flow approaches free-molecular conditions, the assumption that the rounded entrance can be neglected in computing an effective length becomes more valid. This is indicated by the manner in which the data of Ref. 1 fall remarkably close to those of Ref. 4 for an L/D of 6, while near the free-molecular limit, these data rise above those for the square-edged tube to indicate that the effective L/D of the smooth entrance tube has decreased. At the limit, there is diminishing influence on the flow from molecules reflecting from the wall and hence less retardation of the flow due to the presence of the converging channel. The major influence on the flow is the throat or final tube diameter itself and not the diameter reduction at the entrance. The entrance will always exert some influence on the flow, but as inter-molecular collisions reduce in importance this effect becomes smaller.

In the region above a Reynolds number of 30 the data for the rounded entrance tube again departs from that of the square-edged tube. The indications are that the flow sees an effective tube length even greater than the actual straight tube length. In this range of Reynolds numbers, the viscous forces in the fluid are becoming significant. These viscous effects tend to retard the flow rate in both tubes as is indicated by a decrease in curve slope. However, in the bell-mouth entrance, there is a longer effective wall entrance length actually seen by the flow. This length would be more

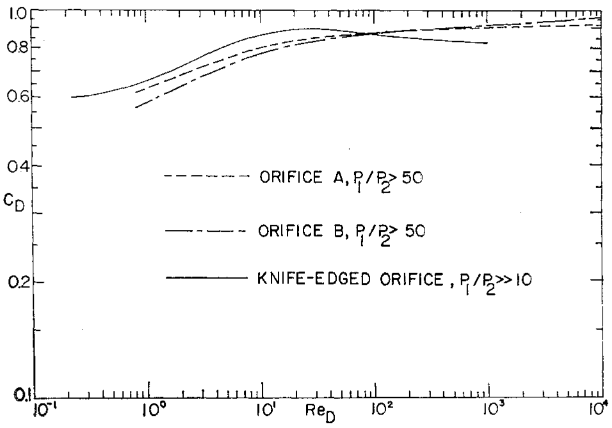

Fig. 2 Orifice results.

closely approximated by using the arc length of the entrance rather than the straight length from the entrance plane. In the case of Carley and Smetana's experiment this would give a total effective length of 7.32 cm and an L/D of 6.37. This effective length should probably be even greater due to the larger surface area seen by the flow in the smooth entrance, which is not fully accounted for by using the arc length alone. Hence, in this region, it is also not accurate to attempt comparison with a theory accounting for only the tube length downstream of the entrance even though this does make the assumption of fully developed flow at the effective entrance more valid.

One of the main reasons, the rounded entrance is used in experiments is to prevent entrance flow separation at larger Reynolds numbers and thus allow more favorable comparison with theories which do not account for separation. It is noted, however, in Fig. 1 that at the highest Reynolds numbers at which data were taken for the square-edged tube there is no indication of entrance separation. One would expect such separation to reduce the discharge coefficient significantly, causing a lower flow rate in the tube with the abrupt entrance than for the smooth entrance case. The opposite is indicated in the figure. However, this trend should change as the Reynolds number continues to increase and inertial effects assume increasing importance. Increased inertial effects should cause entrance separation and the vena-contracta effect reducing the discharge coefficient in the tube with the square-edged entrance. It appears that if the data were extended to higher values of Reynolds number a maximum would be reached for the discharge coefficient through the square-edged tube beyond which there would be a decrease and a crossing of the two curves.

This analysis is supported by the earlier orifice data of Smetana, Sherrill, and Schort[5] as shown in Fig. 2. Orifice *A* had an entry radius of 0.317 cm with a 1.15-cm diam opening. Orifice *B* had the same opening diameter with a 0.579 cm entry radius. The comparison with a thin knife edge orifice exhibits the maximum in discharge coefficient which preceeds a decrease to a limit somewhat below that for the other 2 orifices.

Conclusions and Recommendations

The bell-mouth entry which is used by most experimentors in tube flow study may give deceptive results for flows at low Reynolds numbers. At free molecule conditions, the effective length of the tube is shorter than the actual tube length but not as short as it would be if the entrance length is neglected. In the upper transition or slip-flow regime, the effective tube length is longer than the distance between the entrance and exit planes and results in deceptively low discharge coefficients. It is only above the Reynolds number for entrance separation that the smooth entrance tube provides a better comparison with tube flow theory.

Unfortunately, it is not yet possible to predict the occurrence of entrance separation accurately for tubes of varying lengths. It has long been suggested that the onset of separation is a function of L/D and $L/(DRe_D)$. However, neither theory nor experiment has yet determined this relationship. Hence, the experimentor should carefully choose his entrance shape when working with low Reynolds number flows, choosing the square-edged entrance in the transition to free-molecule range and the smooth entrance in the slip to continuum region. Proper entry choice should result in more meaningful comparison between experiment and existing theory.

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A Study of High-Velocity (4.0–6.5 cm/μ sec) Jet Propagation through Expansion Chambers

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Introduction

In recent years, considerable effort has been expended in studying the propagation of high-energy gas jets. One aspect of this work has been the development of experimental[1–3] techniques for investigating the radiation precursor associated with the propagation of high-velocity gas jets under low-pressure conditions. These experiments have encouraged qualitative discussions[4–6] and theoretical models[3,7] for interpreting and understanding the precursor phenomenon.

The present report describes two Voitenko[8] compressor experiments which were conducted to study the radiation precursor and the effects of divergence and expansion chambers on the propagation of plasma gas jets. In the first experiment, the compressor was connected to a steel outlet pipe, as shown in Fig. 1. In the second experiment, a constant 2.7 cm diam was maintained across the two expansion sections. By direct comparison of the experimental TOA (time-of-arrival) results, the relative effect of chambers on high-velocity gas

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