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Does molecular rotation affect the transition Reynolds number?

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Abstract

We examine recent claims that the molecular rotation, which manifests itself in the form of bulk viscosity, has a measurable effect on the transition Reynolds number in pipe flow. We also conduct new experiments using argon. We conclude that the effects, if they exist at all, are negligibly small for the conditions of the experiment. © 1998 Elsevier Science B.V.

1. Introduction

The success of the continuum hypothesis in describing the dynamics of single phase fluids, in all but extreme thermodynamic conditions, is so remarkable that the molecular structure of the fluid is generally thought to require no explicit consideration. Molecular effects in incompressible flows are thought to be felt only indirectly in so far as they determine the fluid's kinematic viscosity, ν. For a prescribed set of boundary conditions, one then assumes that the flow behavior is governed entirely by the Reynolds number, $\mathrm{Re} \equiv UL/\nu$, where U and L are characteristic velocity and length scales of the flow, respectively, and the initial conditions. The latter play a particularly important role in determining the loss of stability of the laminar state and its subsequent evolution to turbulent state. An especially relevant case is the flow in a straight pipe.

Recent quantum theoretical considerations [1] have suggested that, for gas flows well within the incompressible regime, molecular structure plays a critical role in the laminar–turbulent transition in pipe flows. It has been argued that molecular rotation cannot be neglected, and that it influences the transition characteristics. A naive consideration suggests that molecular effects might become important only if the hydrodynamic background noise and other effects are reduced to low enough levels that differences in molecular characteristics might rise above the background and influence the flow development. Yet, Nerushev and Novopashin [2] claim that such effects become important even when no special efforts are made to suppress the background noise to extremely low levels. In particular, the critical Reynolds number, Re_{cr}, for identical flows of two nearly identical gases, N_2 and CO, were measured to be different. The principal difference between the two gases is that the bulk viscosity of CO is four times as large as that of N_2. Noting that the bulk viscosity is itself a manifestation of molecular rotation, these authors postulated that the difference in Re_{cr} between the two gases (that for CO being 9% higher than for N_2) is owed to the differences in molecular rotation characteristics, an effect that would not be within the hydrodynamic considerations relevant to their flow: the speeds were on the order of 30 m s^{-1}, so the Mach number was at most of the order of 0.1.

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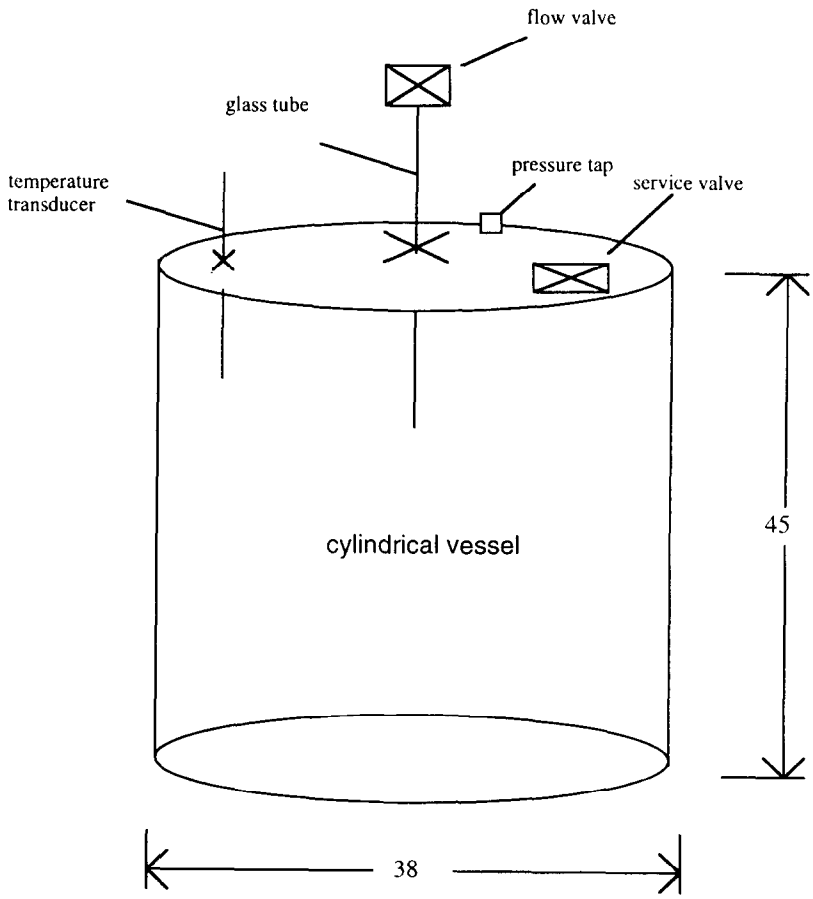

Fig. 1. Schematic of the experimental set-up. Dimensions noted are in centimeters.

This view has been looked upon with skepticism [3]. Partly out of curiosity, we have repeated the experiment of Ref. [2]; we have also made new experiments using argon. The bulk viscosity of argon being exactly zero, we thought that the role of bulk viscosity, if any, could be determined with greater precision: if molecular rotation does contribute to transition as claimed [2], one would expect Re_{cr} for argon to be lower than those of CO and N_2.

It was observed in Ref. [2] that a 9% difference occurs in the friction factor ratio for the two gases. However, both sets of data deviate measurably from the laminar curve, and so an exact determination of Re_{cr} is difficult. Neither this aspect nor the determination of the experimental uncertainties are cited in any detail in Ref. [2].

2. Experiment

The present experimental set-up, shown in Fig. 1, was essentially identical to that used in Ref. [2], but is somewhat smaller. A precision glass tube with bore diameter 1.27 mm and length 303 mm was inserted for approximately half its length into a steel-alloy cylindrical vessel (volume of 58.6 ℓ). A valve located atop the glass tube controlled the flow. A service valve allowed for the vessel to be pressurized or evacuated by proper attachment to a gas cylinder or vacuum pump. Vessel temperature is measured by a temperature transducer, with an accuracy of 0.1 K, inserted well inside the vessel. Gas (gauge) pressure is measured by connecting the pressure tap on the vessel to a Cole–Parmer differential pressure transducer (with

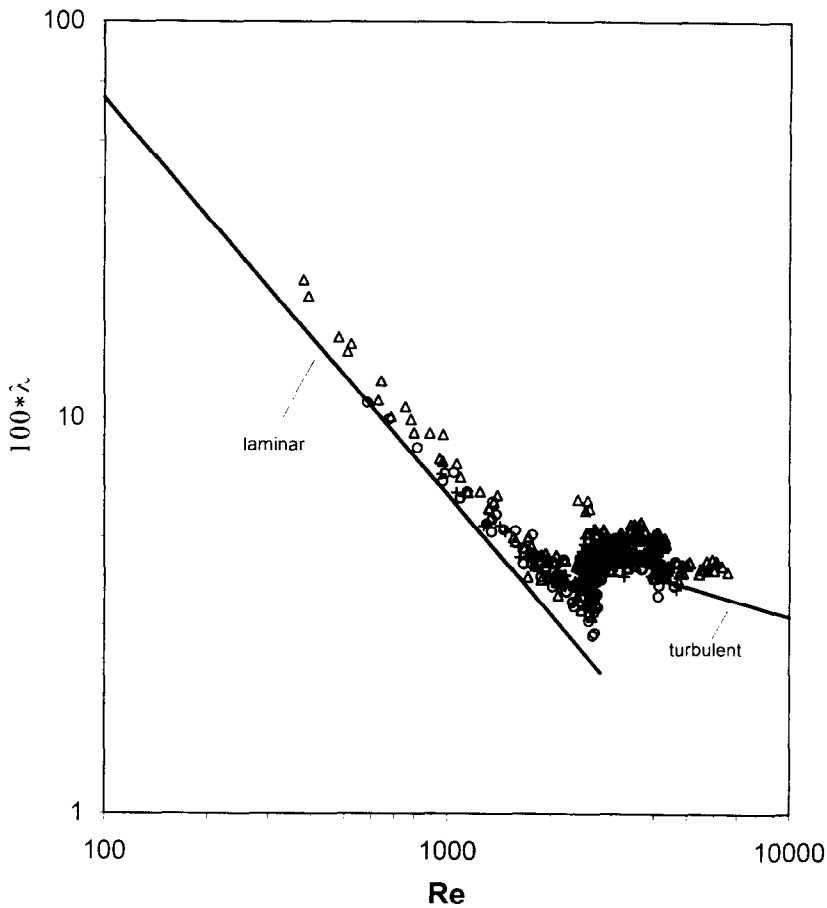

Fig. 2. Friction factor λ as a function of the Reynolds number Re for N_2 (△), CO (○), argon (+). For the laminar flow, $\lambda = 64/\mathrm{Re}$; for the turbulent flow, $\lambda = 0.3164/\mathrm{Re}^{0.25}$, taken from Ref. [4].

a measurement accuracy of 0.25 Torr).

A vacuum pump was used to evacuate the pressure vessel to a pressure of 0.1 Torr. The vessel was then filled with the desired gas to a pressure of 850 Torr, evacuated for a second time and then filled to a pressure of 1000 Torr. The precision glass tube was used to study the flow of the gas from the vessel into the atmosphere. About an hour was allowed for all residual fluid motions to die out and thermal equilibrium to be established. Vessel pressure and temperature were recorded (state 1). The valve was opened for a short time (between 5 and 10 s, longer in the laminar region), then closed; the vessel was allowed to re-establish thermal equilibrium with its surroundings (typically by allowing a duration of 5 min). The pressure and temperature were recorded again (state 2) once the new equilibrium was established. The ideal gas law was used to determine the mass flux from the vessel during the time the valve was open. An average Reynolds number for this duration was obtained. The friction factor was determined from the average pressure difference between vessel and atmosphere at the two equilibrium states. For purposes of comparing with the standard text-book data, the inlet and exit losses were incorporated into the pressure differential used to determine the friction factor. The procedure was repeated until the vessel pressure fell to about 5 Torr (gauge).

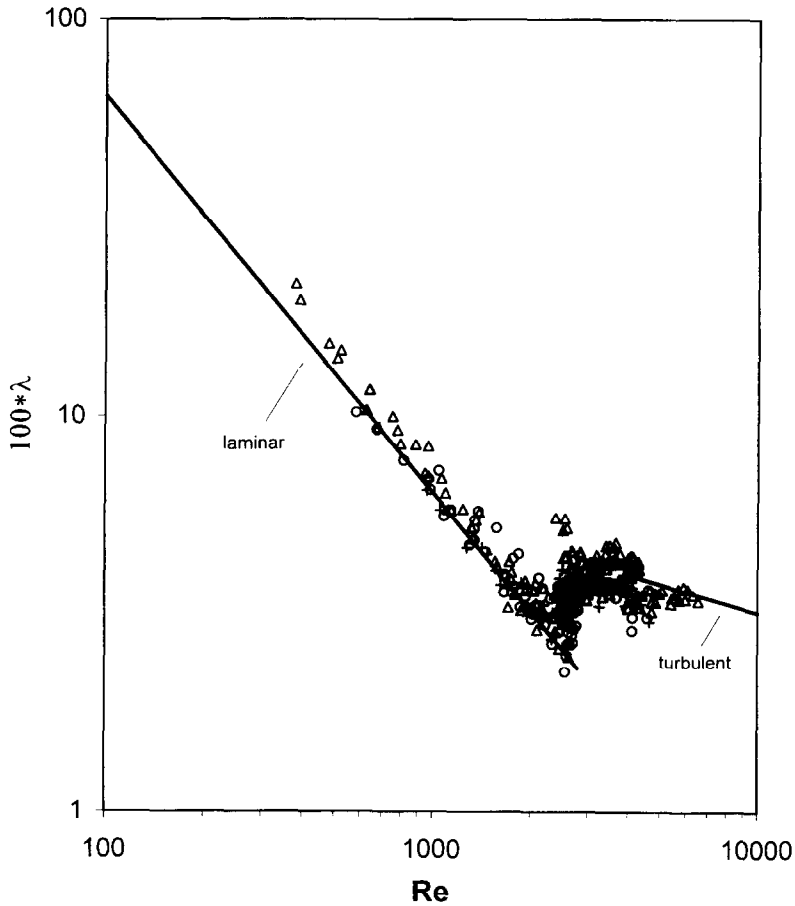

Fig. 3. Same as in Fig. 2, except that the entrance and exit losses have been subtracted from the total pressure loss measured. The secondary losses are computed from standard correlations given in Ref. [4].

3. Results and conclusions

The friction factor,

$$\lambda \equiv \frac{d}{L}\frac{\Delta P}{\rho v^2/2},$$

where d, L, ΔP, ρ, and v are, respectively, the pipe diameter, pipe length, differential pressure, gas density, and gas velocity, is plotted in Fig. 2 as a function of the diameter-based Reynolds number for the three gases considered. Six experimental runs are shown for CO and N_2, and two for argon. Exact determination of Re_{cr} is ambiguous. If one defines it as the Reynolds number corresponding to the minimum of λ, the average over the six runs of CO is higher by about 8% than that for N_2. However, the standard deviation is also comparable. This could not be reduced despite some serious efforts at normalizing the conditions from one experiment to another. Owing to this experimental uncertainty, it appears that profound statements regarding molecular effects on transition cannot be made. However, the fact that the data for argon fall squarely between CO and N_2 data leads to the conclusion that the effects of molecular rotation are negligible in the present experiments.

As already mentioned, one might expect that if the hydrodynamic noise can be lowered sufficiently, molecular effects may indeed play an important role in transition. Such an experiment would require extraordinary care and control. As pointed out to us by

Novopashin, the heat transfer characteristics of these different gas flows – particularly of argon – may be different, and so their quantification also becomes important. On balance, it is not clear that the pipe flow is the best configuration for a detailed study of this important issue. Thus, we opted not to pursue the matter for now.

A noticeable aspect of the data shown in Fig. 2 is the deviation from the theoretical laminar curve. This deviation is largely due to the inlet and exit losses. When these losses are incorporated empirically in the evaluation of the friction factor, the data show a better collapse on to the laminar curve (Fig. 3). The main conclusion does not change because of these corrections.

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