Apparatus for laminar-turbulent transition in gases

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(Received 25 February 2005; accepted 9 May 2005)

The field of fluid mechanics has long held that the transition from laminar to turbulent flow can be sufficiently described using the classical, continuum formulation of the Navier–Stokes equation and dimensionless parameters such as the Reynolds number. Recent theoretical and experimental challenges to the continuum description of this transition have led to controversial claims. To help resolve this debate, we have developed apparatus specifically designed to produce repetitive laminar-turbulent transitions so that the details of the transitions with respect to a variety of parameters can be studied. Since the laminar-turbulent transition is by its nature chaotic, it is desirable to have numerous events—each occurring in rapid succession under essentially identical conditions—for a fuller understanding of this phenomenon. The apparatus and method described here produce these repeated transitions spontaneously by exploiting the fact that for gases the conductance in the turbulent regime is higher than that in the laminar regime. It is accomplished with relatively simple, compact, and readily available equipment. Initial operation of the apparatus has produced data which show interesting and characteristic behavior for several gasses. © *2005 American Vacuum Society.* [DOI: 10.1116/1.1946709]

I. INTRODUCTION

There have been some controversial hints by Novopashin and Muriel,[1–3] Nerushev, and Novopashin[4,5] that contrary to scaling arguments from the Navier–Stokes equation (NSE), the critical Reynolds number (at which the laminar-turbulent transition occurs), may not be identical for all gases and liquids. The conventional view is that once the density and viscosity are specified, a redimensioned NSE shows no further atomic or molecular dependence, as explained by Frisch[6] and that the mathematical character of its solution is determined by the dimensionless Reynolds number. Atomic, molecular, and (by implication) quantum physics are irrelevant in the derivation of NSE. As a result, significant and exclusive attention has been devoted to the mathematical search for turbulent, or turbulent-like, solutions of NSE, assuming that they exist, as discussed by Sone.[7] Furthermore, as reviewed by Deissler,[8] massive computational efforts usually begin with this equation, except for some attempts using kinetic theory by Chen *et al.*[9] Analytic results from quantum kinetic theory have also been reported by Muriel *et al.*[10–17] which are in fact the impetus for the body of experiments already published. The fundamental problem of turbulence is so difficult that the Clay Institute of Mathematics has posted a significant prize for any proof that turbulence arises from NSE.

But any claim that there is a molecular signature in the laminar-turbulent transition presupposes doubts on the exclusive universal application of NSE to turbulence. Therefore, one should either dismiss the claims of molecular signatures by appropriate experimental results, thereby nullifying this distraction, returning turbulence research to the NSE mainstream, as attempted by White and Sreenivasan[18] and Swanson *et al.*,[19] or validate the claims of the molecular picture of turbulence to entertain the thought that turbulence belongs to a different regime that demands richer physical models.

Due to the enormous implications of the results and the limited data of the last two experimental groups, the claimed results of earlier experiments have not been universally accepted. But there are now additional data by Novopashin and Muriel[20] that seem to support the earlier experiments. In addition to this supportive development, one needs a radically different approach to go beyond the usual Hagen–Poiseuille apparatus. For this reason, one of us (A.M.) has posed a challenge to members of the American Vacuum Society to use modern technology to resolve the controversy. The result is the apparatus presented here, which provides a convenient, specialized method to produce repeated transitions between laminar and turbulent flow. The repetitive transitions allow for analysis of multiple events occurring within a short period of time under essentially identical conditions.

II. DESCRIPTION OF THE APPARATUS

In the traditional Hagen–Poiseuille apparatus, an inlet to a vessel admits gas at high pressure, and is then closed. A pipe outlet then allows the gas to exit in a controlled manner, allowing quasistatic measurements of pressure in the vessel and flow through the pipe. In the apparatus presented here, there is still a fixed volume, with two openings, the inlet and the outlet, except that the inlet is controlled by a servo valve mechanism which can be implement by one of four processes: (1) increase the pressure by a fixed rate; (2) decrease pressure by a fixed rate; (3) manually increase or decrease the pressure in the vessel; or (4) keep the flow into the vessel

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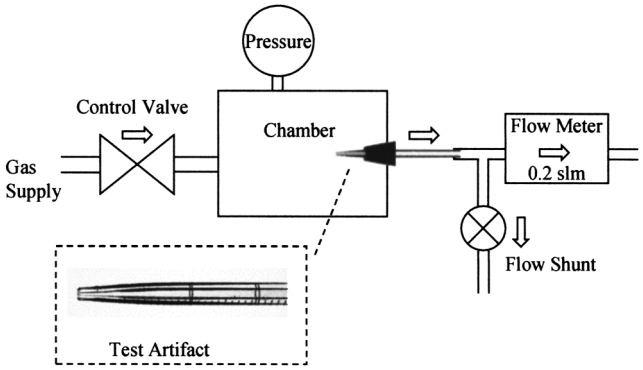

FIG. 1. Schematic diagram of apparatus.

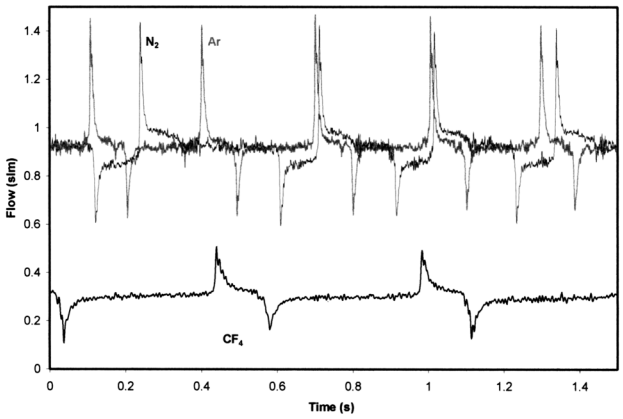

FIG. 2. Flow vacillation for three gases.

constant. This last function allows focus around the critical range of pressure that represents the laminar-turbulent region for the outlet.

In practical terms, we use standard equipment from vacuum technology, but operated within a factor of 2 of atmospheric pressure. Figure 1 shows the apparatus. The entry of gas is controlled by an electromagnetic control valve which allows gas to enter a 0.15 l chamber. To monitor and/or control the absolute pressure inside the chamber, a capacitance manometer measures the pressure. The apparatus also allows for pressure feedback to a controller that may be used to adjust the control valve. The chamber's flow outlet, where the laminar-turbulent transition occurs, can be any one of a number of pipe, nozzle, or orifice artifacts. For the data presented here a small pipette (an off-the-shelf item from biological supply houses) is used as the artifact. The pipette is mostly uniform, except for a few centimeters from one end where the inner diameter varies from 0.8 to 2.5 mm. The pipette is shortened from its manufactured length of 35 to 11.5 cm by scoring and breaking. The narrow end of the pipette is positioned approximately 2 cm inside of and sealed to the chamber wall, while the wide end is connected to a high-speed micromachined flowmeter. For cases where the laminar-turbulent transition flow is above the range of the meter, the flow is divided by a *Y*-shaped tube to proportionally shunt around the flowmeter. In that case, the output signal of the flowmeter with the shunt is linearized and scaled by calibrating with the test gases against a standard thermal mass flow meter (MKS Type 179A); however, for the initial results presented here we regard the flow data as semiquantitative only. The electromagnetic control valve (Type 248A) and the capacitance manometer (Type 750B), as well as the chamber, are manufactured by MKS Instruments. We use the MKS Controller type 250 to adjust the valve for flow or the pressure inside the chamber. The flowmeter used for the initial testing is manufactured by Honeywell Control with part number AWM3100V. We have also successfully used a higher flow range instrument—Model 4121 manufactured by TSI. The physical scale of the equipment is such that the apparatus is at least 1 order of magnitude smaller than conventional pipe flow experiments.

III. OPERATION, RESULTS, AND DISCUSSION

To begin, we monitor the flow rate and pressure as a function of time for a constant rate of increase of pressure in the chamber. The transition from laminar flow to turbulent flow is marked by a spike in the flow rate. The reverse transition from turbulent to laminar flow is observed by gradually decreasing the chamber pressure, with a counter-spike marking the transition. The flow rate preceding the transition from laminar to turbulent is lower than that for turbulent to laminar for each gas species tested—argon, nitrogen, and tetrafluoromethane.

Having located the critical pressure and flow condition at which the transition is observed, we control the flow to the chamber at a value between the highest laminar and lowest turbulent values and observe the downstream flow rate as a function of time. The result is a vacillation in flow as it transitions spontaneously between turbulent and laminar flow.

The mechanism for the meta-stable behavior rests in the fact that, in gases, turbulent flow exhibits higher conductance than laminar flow. To describe the series of events that occur during a vacillation cycle, begin with the downstream flow in the laminar state. Since the upstream flow is controlled at a higher rate, the pressure increases in the chamber. This causes the downstream flow to increase until it suddenly transitions to turbulent flow. Once in turbulent flow, the downstream flow is higher than the upstream flow, so the chamber pressure decreases, which in turn causes the downstream flow to decrease to the point where it suddenly transitions to laminar flow again. For a given gas type the frequency of these vacillation cycles depends primarily on the chamber volume and the difference between the highest laminar flow rate and lowest turbulent flow rate. This general behavior is observed for each of the gas types tested. Three separate runs are plotted in Fig. 2 with flow rate in standard liters per minute (slm).

The following general observations can be made: (1) the flow vacillation is almost periodic, with different periods for the three gases; (2) the structures of the spikes and counter-spikes for each of the gases show similarities but are quantitatively different; and (3) the flow "noise" present in both

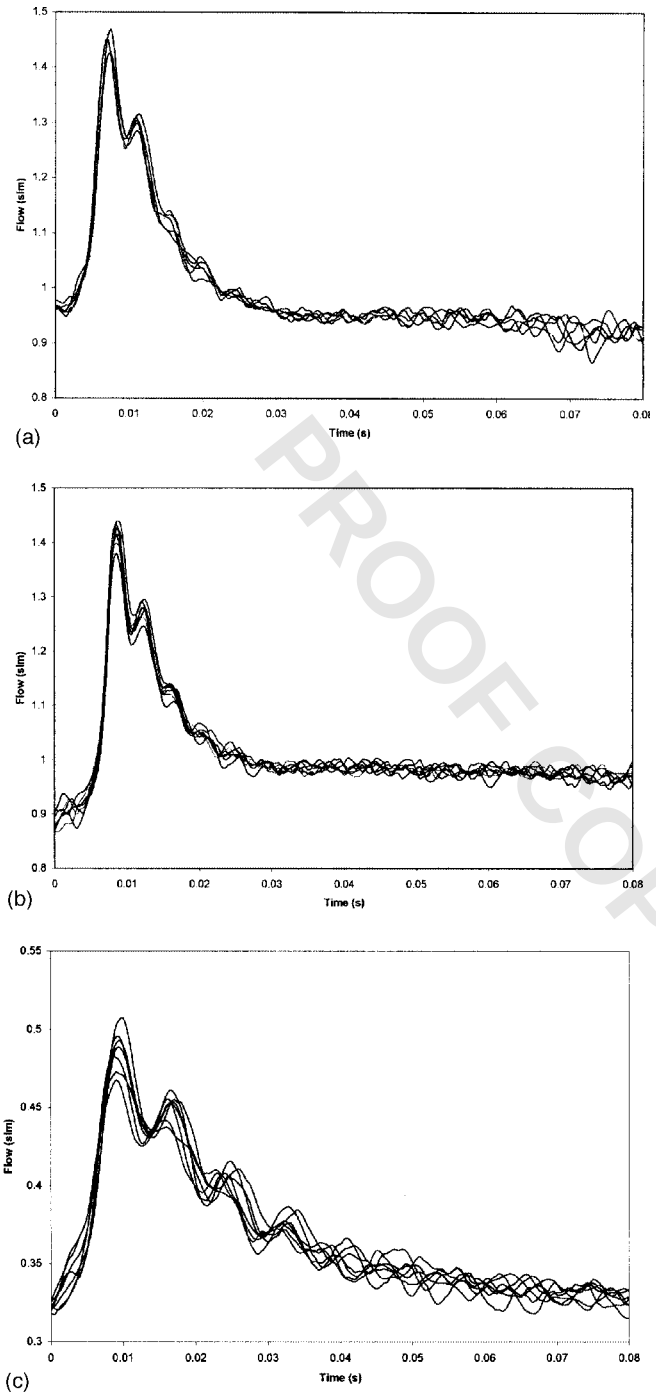

FIG. 3. (a) Flow vs time at the turbulent transition for argon; (b) flow vs time at the turbulent transition for nitrogen; and (c) flow vs time at the turbulent transition for tetrafluoromethane.

laminar and turbulent conditions, has a predominant oscillation frequency which is dependent on the gas type.

We begin to analyze the observations by superimposing six adjacent laminar-to-turbulent transitions for each gas as shown in Fig. 3. For each gas, the largest spike is where the time derivative of the flow rate changes most dramatically, which we interpret as the onset of turbulence. In harmony with the theoretical discussion of Ruelle,[21] our more specific requirement is that turbulence begins when the time derivative of the flow rate becomes infinite. In fact a more stringent requirement, that which we adopt is that the time derivative of the flow rate changes sign from positive to negative immediately after the derivative becomes infinite. In these data, the characterization of the spike is limited by the time response of the flow sensor, specified as 1 ms typical, and to a lesser degree the pneumatic time constant of the connecting tubing between the pipette and the flowmeter. The reverse spike is interesting, tending to be less pronounced under these conditions.

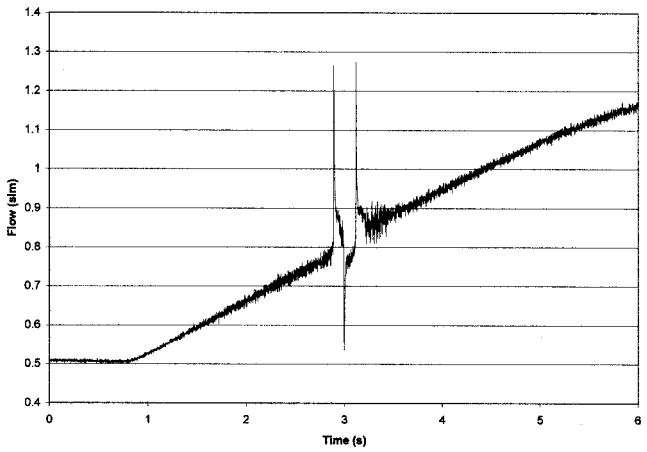

FIG. 4. Chamber pressure is gradually increased resulting in increased flow and flow oscillation (seen as peak-to-peak noise)

The oscillations of flow immediately after the transition to turbulence are phase- correlated with the spike for several periods as shown for each gas in Fig. 3. The frequencies of these oscillations are 210 Hz for argon, 240 Hz for nitrogen, and 120 Hz for CF_4. These frequencies were obtained by fast Fourier transform analysis, but may also be estimated from the plots in Fig. 3. The relationship to molecular mass (inverse square root) is the same as that for the speed of sound. Consideration of resonant structures in the apparatus has motivated controlled tests of the various lengths and volumes of the components; however the frequencies are consistent and apparently not the result of any vessel resonance.

The cause-and-effect relationship between the transition to turbulence and the flow oscillations is worth consideration. One may ask, do the oscillations trigger the timing of the transition or does the transition initiate a series of oscillations? While either functional relationship is plausible, it becomes clear upon examination of several superimposed transitions that the coherence of the oscillations is only present after the transition spike, not before. Therefore it appears that the transition to turbulence "plucks" the flow oscillations; the flow oscillations do not trigger the transition.

For nitrogen, as seen in Fig. 4, when the pressure in the chamber is increased slowly, the flow oscillation (seen as the peak-to-peak "noise") gradually increases in amplitude as the flow is increased to the critical flow. The oscillations continue throughout the transition to turbulent flow (three spontaneous transitions in these data; to turbulent flow, then to laminar and back to turbulent). However, once the flow has

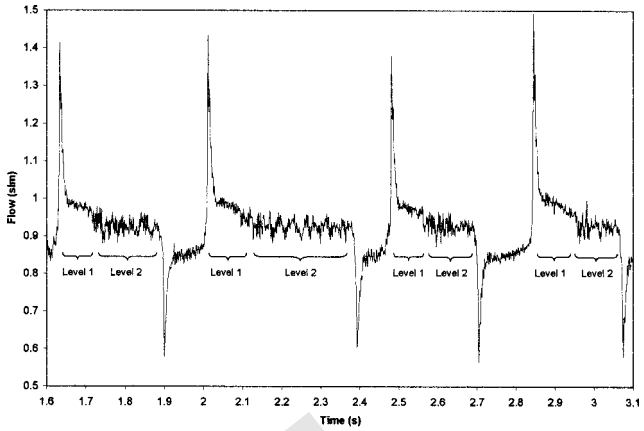

FIG. 5. Structure of the turbulent transition in nitrogen, showing at least two possible levels of turbulence.

moved above the critical region, the oscillation amplitude is no longer dependent on the flow rate. This qualitative behavior is observed in each of the gases tested.

For nitrogen, shown in Fig. 5, there are at least two observed levels of turbulence. The quantization of turbulent flow for pipettes used in the experiment is reproducible with various pipes, with some pipes better than others. From our experience uniform pipes do not show the phenomenon clearly.

The main point of this article is to demonstrate an apparatus that provides details of flow behavior for different gases at the laminar-turbulent transition. We intend to use these data as an indication of molecular nature, but it is still possible to interpret at least some aspects of the data for these experiments in the conventional way using the continuum (NSE) model. The critical Reynolds number is given by $\mathrm{Re}_c = \rho v d/\eta$, where ρ, v, d, η are, respectively, density, velocity, diameter of the pipe, and dynamic viscosity. Since the flow data for these tests are measured as standard volumetric flow, the velocity is replaced by the (temperature adjusted) flow divided by the cross-sectional area at the pipette entrance. For comparison, we calculate ratios of the critical Reynolds numbers for two gases, so the value of the area itself is eliminated. The ratio of critical Reynolds numbers for Gas 1 to Gas 2 is given by

$$\frac{\mathrm{Re}_c(1)}{\mathrm{Re}_c(2)} = \frac{\rho_1 \eta_2 Q_1}{\rho_2 \eta_1 Q_2},$$

where Q is the flow rate at the transition, determined from data such as in Fig. 2. Using the density, viscosity, and the observed average flow rates, we find $\mathrm{Re}_c(\mathrm{N}_2)/\mathrm{Re}_c(\mathrm{Ar}) = 1.01$ and $\mathrm{Re}_c(\mathrm{N}_2)/\mathrm{Re}_c(\mathrm{CF}_4) = 1.03$ which, when considering the measurement uncertainties, are both in agreement with unity—the expected ratio using the continuum model. Previous measurements for argon and nitrogen indicate almost the same critical Reynolds numbers within the expected uncertainties of those experiments. But with the repetition of transitions and instrumentation advantages of the present apparatus, other details of the transitions such as maximum flow at the transition to turbulence and minimum flow at the transition to laminar can be analyzed as a function of gas species, temperature, and absolute pressure. These data may enable a quantitative distinction between the descriptive capability of a continuum approach (NSE) which addresses time-averaged flow, and a molecular picture of flow where attention to the smaller scale cyclic transition from laminar to turbulent flow is considered. The enhanced analysis that this apparatus enables may also help explain the disparity of the experimental results thus far reported.

IV. CONCLUSION

An apparatus of standard flow, pressure, and control instrumentation has been developed to produce detailed data of repeated, spontaneous transitions between laminar and turbulent flow. The initial results using this apparatus have provided a variety of interesting behavior. This apparatus can be used to help settle the debate regarding the ability of the traditional NSE approach to describe the flow behavior at the transition point. We anticipate that data from this apparatus may raise questions regarding the correct theoretical paradigm needed to study turbulence. Furthermore, many different areas of experimental turbulence research are required in pursuit of the quest for observing more phenomena of a molecular signature.

Finally, we need to point out other areas of work which are currently being performed and/or analyzed:

(1) More focused pressure and flow measurements exhibit interesting hysteresis phenomena in the transitions, as displayed on a differential pressure versus flow plot.
(2) Further study of the levels of turbulence will possibly demonstrate a relation to quantized turbulent flow.
(3) The nominal gas pressure, while not affecting the average critical flow transition point, does dramatically affect the detailed behavior of the transitions.
(4) There is some preliminary evidence that at the turbulent regime, the traditional critical Reynolds number is dependent on the magnitude of initial pressure, an expression of the dependence of turbulence on initial conditions, a most interesting problem in nonequilibrium statistical mechanics discussed by Ruelle.[21]

ACKNOWLEDGMENTS

One of the authors (A.M.) acknowledges several discussions with S. Novopashin of the Siberian Academy of Science and J. Dadap of Columbia University. They gratefully acknowledge the use of MKS Instruments' laboratory facilities in Methuen Massachusetts. This research was supported in part by the ICSC World Laboratory.

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