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New Results in Cryogenic Helium Flows at Ultra-high Reynolds and Rayleigh Numbers

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Liquid helium I, II and cryogenic helium gas are used to generate and study highly turbulent flows under controlled laboratory conditions. These three working fluids have remarkable versatility, allowing extremely large values and dynamic ranges of the Reynolds (Re) and Rayleigh (Ra) numbers to be reached. In particular, cryogenic helium gas has been used to study turbulent thermal convection in a range $10^6 \le Ra \le 10^{17}$*, by far the largest ever attained in a controlled experiment on turbulence. The upper limit exceeds previous studies by nearly three orders of magnitude.*

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1. INTRODUCTION

Fluid turbulence- characterized by high Reynolds (Re) and Rayleigh (Ra) numbers[1]- is one of the grand-challenge problems of our times: it is profound, difficult, and important in a large variety of applications. A deeper understanding of fluid turbulence and development of a full fledged theory calls for controlled experiments covering a wide scaling range of Re and Ra. In this respect, helium offers considerable flexibility resulting from the temperature and pressure dependence of its fluid properties. Furthermore, the cryogenic gas and two liquid phases of helium possess extremely low values of the kinematic viscosity, enabling the achievement of very high values of Re. Thus, low temperature helium can be used in experiments designed to tackle important fundamental hydrodynamical questions that cannot be addressed otherwise. From a practical perspective, we can envision full Re testing for submarines or surface ships. An equally impressive attribute of helium is

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that it can be used in the laboratory to generate nearly astrophysical levels of thermal turbulence. This is a topic which we address first.

2. HIGH RAYLEIGH NUMBER FLOWS

Turbulent Rayleigh-Benard convection occurs at large values of $Ra = \alpha g \Delta T L^3/\nu\kappa$ where g is the acceleration of gravity, ΔT is the vertical temperature difference across the fluid layer of height L, and α, ν and κ are respectively the thermal expansion coefficient, kinematic viscosity and thermal diffusivity of the fluid. As first demonstrated by Threlfall,[2] the properties of cryogenic helium gas can be varied extensively by changing the temperature and pressure, so that a large scaling range in Ra can be obtained in a single experiment. We use cryogenic helium gas (4.3 K $< T <$ 6 K and 0.1 mbar $< P <$ 3 bar) as the working fluid in a cryogenic apparatus of large height L=1 m. The diameter-to-height aspect ratio was set equal to 1/2 to provide comparison with other recent experiments[3,4].

The cryogenic helium gas is contained in a cylindrical cell between two annealed OFHC copper plates with a surface finish better than 10 μm and hence "dynamically smooth". The top plate of the cell is controlled at a fixed temperature, with an adjustable and uniform thermal link to the helium bath via a "soft vacuum" space, while constant heating is applied to the bottom plate. For both plates we use mylar-encased metal film heaters designed to provide uniform heating over the entire surface. Further details of the apparatus can be found in Ref. 1.

Convective heat transfer is represented by the Nusselt number, Nu, defined as the ratio of total measured heat flux to its conductive component. Of fundamental interest is the scaling behavior of Nu at asymptotically large Ra. In developed turbulent convection Nu is expected[5] to exhibit power law scaling with Ra. Conventional experiments have suffered from a lack of sufficient range and maximum value of Ra in developed turbulence to answer questions about asymptotic scaling with authority. However, the large height of our cell, combined with the favorable properties of cryogenic helium gas, enables not only an extremely wide range of turbulent Ra to be generated- nearly eleven orders of magnitude- but also values of Ra up to 10^{17}. As in other studies, corrections due to an adiabatic gradient- of order 1% of the measured temperature difference across the cell for most Ra- are needed due to the height of the cell.

Our experimental heat transfer data[1] are shown in Fig. 1. To lowest order, the $Nu - Ra$ data can be described by a single power-law function, with an exponent approximately equal to 0.31, over the entire range of Ra.

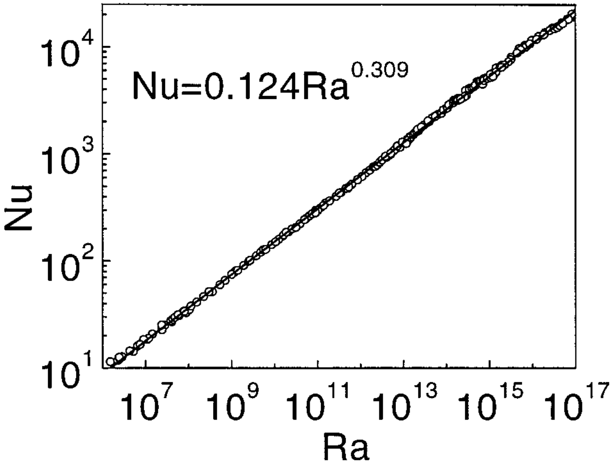

Fig. 1. Log-log plot of the Nusselt number(Nu) versus Rayleigh number (Ra). The line is a least-squares fit over the entire Ra range and represents $Nu = 0.124Ra^{0.309}$

This unprecedented range allows us to rule out the exponent 1/2, characterizing the so-called asymptotic regime predicted[6] to occur at high Ra. This observation is in agreement with other modern investigations[3,8,7] at somewhat lower Ra, but contradicts conclusions recently drawn by Chavanne *et al.*[4], who report an increase in the scaling exponent above $Ra \approx 10^{11}$ toward 1/2.

We have recently made additional observations in an aspect ratio unity cell having half the height of the initial experiment. Although the necessarily smaller height of this cell reduces the maximum Ra, our preliminary measurements of the heat transfer up to $Ra \approx 10^{14}$ display no significant changes in the Nu-Ra scaling. In agreement with previous studies[1] in an aspect ratio 1/2 cell, we find a steady large-scale flow in turbulent convection at relatively low Ra. The situation at higher Ra is somewhat different: a mean, large scale flow persists, but switches direction aperiodically and abruptly, with a switching time much less than the convective turn-over time. The Reynolds number based on the measured circulation speed of the large scale flow and the height of the cell is approximately proportional to $Ra^{1/2}$.

Finally, we have recently added micron-size temperature sensors to the cell interior to measure temperature fluctuations. These sensors will be discussed in more detail below. Temperature fluctuation spectra previously

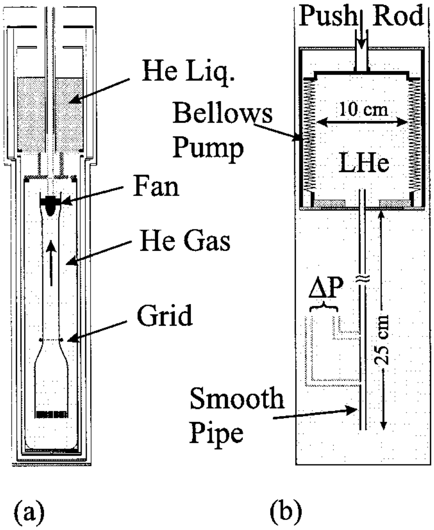

Fig. 2. (a) Schematic diagram of grid flow apparatus. (b) Schematic diagram of the pipe flow apparatus.

obtained using 0.025 cm cubes of neutron-transmutation-doped Ge reveal both Bolgiano- and Kolmogorov-like scaling[1] for certain ranges of Ra. Because the dissipation scale becomes of order of the size of these sensors for $Ra \approx 10^{11}$, it is desirable to utilize the smaller probes.

3. HIGH REYNOLDS NUMBER ISOTHERMAL FLOWS

There are many interesting problems, of both fundamental and applied nature, involving the generation and study of high Re isothermal turbulence. Grid-generated turbulence was an early and fruitful avenue of research for the study of homogeneous turbulence, and there has been recent resurgence of interest in it [9–11]. In conventional studies a sufficiently large dynamic range is often achieved only by combining data from many different experiments; however, apparatus-specific effects limit the applicability of this procedure. The variability of helium's kinematic viscosity with pressure and temperature makes it possible to generate homogeneous turbulence over a wide range of Re in a single apparatus. We have recently constructed and begun operations on a continuous flow tunnel well-suited for this type of study, shown in Fig. 2(a).

The flow tunnel shown in Fig. 2(a) is capable of operating in either liquid or gaseous helium over a range of temperatures from 4 K to 6 K and pressures up to 4 Bar. The experimental section of the tunnel is 6 cm in diameter and 40 cm long and is immersed in a temperature-controlled helium bath. A fan at the top of the tunnel pulls up the working fluid, providing the mean flow shown by the arrow. The flow returns around the outside of the tunnel to reenter the flow conditioning honeycomb and screens at the bottom. The velocity varies from $U = 0.1$ to 1 m/s which results in mesh Reynolds number $Re_M = MU/\nu$ of up to 50,000, where M is the size of the grid mesh.

To study the turbulent flow, we have built micron sized devices that operate as either thermometers or anemometers at cryogenic temperatures. These sensors are designed to measure high-frequency small-scale velocity fluctuations. The need for such small sensors is dictated by the size of the smallest scale in the flow, the Kolmogorov length scale, η, that depends on Re and can be as small as 10 μm in our apparatus. The requirement on frequency is determined by the rate at which small flow structures are advected past the sensor. In our case, the highest frequency is $U/\eta \sim 10^5$ Hz.

The sensitive region of the devices is a 10 μm by 10 μm Au-Ge layer evaporated onto a quartz fiber, with a sensitivity $d \log R / d \log T \approx -1$ from 4 K to 30 K. The resistance of the devices at 4 K is a few tens of kΩ. They have been operated as thermometers using an AC technique and can resolve temperature fluctuations to $\sim$1 mK. Details of the construction of the device and the evaporation of the Au-Ge layer will be published elsewhere. It is noted that room temperature hot wire devices are limited in their frequency response by heat loss to the supports, and the slow response time of the hot wire material. This is largely alleviated in the cryogenic probes because of the low thermal diffusivity of the materials used in their construction.

The apparatus has been recently cooled down and we have begun the task of anenometer calibration. This is currently being done by correlating the signals from a pair of closely spaced sensors operated as thermometers downstream from an oscillating heat source.

Another example of a high-Re experiment is seen in Fig. 2(b), where we schematically illustrate a high-Re pipe flow apparatus. A large compressible bellows is used to generate a high speed flow down the pipe. By controlling the compression rate we are able to accurately set the flow velocity. We can measure the pressure drop in the pipe using two pressure taps located sufficiently far downstream. The pressure gauge is an accurate and highly linear capacitance-type transducer with more than three decades of pressure range[12]. Moreover, its calibration is unaffected by thermal cycling. The gauge operates equally well in liquid helium and in room temperature gas. This enables us to utilize also room temperature helium gas, air, and sulfur hexafluoride, and thus we measure the mean pressure loss in a pipe flow spanning $30 \leq Re \leq 3 \times 10^6$. No other single apparatus we know of has been able to span such a wide range of *Re*. Furthermore, this pipe, with a diameter of only 4.7 mm, allows us to match the *Re* of the two stories tall water facility of Nikuradze[13].

Preliminary data reproduce the standard engineering results over the entire span of Re. We have also used helium II as a test fluid, and it is of some interest that our early results suggest that the pressure drop in turbulent pipe flow is similar for both liquid phases of helium. We note that while the decay of homogeneous and isotropic turbulence in helium II can be described classically to a first approximation, the situation in the presence of significant shear is less well understood.

4. CONCLUSIONS

The described experiments clearly demonstrate the potential of cryogenic helium as a working fluid in the field of fluid turbulence. We believe that pushing the boundaries in generating and studying high *Re* and *Ra* flow, together with unique complementary studies on superfluid turbulence, should stimulate further progress in understanding of the fundamentals of turbulence and lead to important practical applications.

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