Role of Cryogenic Helium in Classical Fluid Dynamics: Basic Research and Model Testing

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I. Introduction

A. Advantages of Cryogenic Helium as a Test Fluid

Only dimensionless similarity parameters such as Reynolds and Rayleigh numbers matter for the scaling properties of incompressible fluid flows. Natural phenomena in geophysical and astrophysical flows occur at very high ("ultra-high") values of these parameters. Ultra-high Reynolds numbers also occur in navy and aerospace applications. A fundamental understanding of turbulence, often described as the most important unsolved problem of classical physics, requires the study of high-Reynolds-number fluid flows. The generation of such flows in laboratory-scale devices is facilitated by the use of fluids with small kinematic viscosity and thermal conductivity. The smallest kinematic viscosity of any substance belongs to liquid and gaseous helium. For instance, liquid helium at 2.2 K has a kinematic viscosity coefficient of about $1.8 \times 10^{-4}\,\mathrm{cm^2\,s^{-1}}$, so that a Reynolds number of 100 million can be generated with a modest flow velocity of $4\,\mathrm{m\,s^{-1}}$ and a wing chord of 50 cm. For the same speed of water, the corresponding facility would have to be about 55 times larger. The size for air at atmospheric pressure would be about 830 times as large. Thus, using helium, one can create even in modest-scale facilities ultra-high Reynolds numbers suitable for fundamental work and model testing. Similarly, astronomically relevant Rayleigh numbers of the order of 10^{20} can be reached in an apparatus that is of the order of 10 m in height.

Helium has additional advantages as well. The physical properties of its gaseous state near the critical point vary rather sensitively with pressure, so that one can attain a vast *range* of Reynolds and (especially) Rayleigh numbers in an apparatus of *fixed* size and design. By mixing helium II with its lighter isotope, namely, helium 3, it is possible to vary the Prandtl number between about 0.01 and 1. Helium lends itself very well for combined heat transfer and fluid dynamical studies in which both Reynolds and Rayleigh numbers play an essential role, and large ranges of parameters are required. The use of helium allows dynamic similarity to be attained simultaneously in more than one parameter, for example in Reynolds and Froude numbers. In general, this would not be possible with familiar fluids such as water. An array of instrumentation based on superconducting technology is available at cryogenic temperatures. In recent years, high-energy particle accelerators with superconducting magnets have demanded reliable and large refrigerators. As a consequence, a technology for large-scale helium refrigeration is readily available for pushing the limits in the space of similarity parameters. Finally, safety of operation is not a critical issue with helium.

B. Questions about Helium

These attractive attributes of helium have been exploited in a few instances (for a summary, see Donnelly, 1991a, and Donnelly and Sreenivasan, 1998). Yet, much remains to be done before the benefits of helium in classical fluid dynamics can be realized in full. Even though the low viscosity of helium is a familiar fact, some genuine questions continue to be asked about the fluid in the context of classical hydrodynamics. To what degree do helium flows in navy and aerodynamic testing correspond truthfully to air and water flows? Is is possible to make all the crucial fluid dynamical measurements? In particular, can one acquire turbulence data with adequate spatial and temporal resolution? Is the case for helium compelling enough to override the inflexibility of *large* cryogenic operations? These questions need some discussion. Finally, not every fluid phenomenon of practical interest can be replicated in helium—for example, compressibility effects characteristic of high-speed flight (because they depend on the ratio of specific heats of the fluid medium).

There are alternative methods for attaining ultra-high Reynolds numbers. For example, Smits and Zagarola (1997) have argued that air can be pressurized enough to lower the kinematic viscosity to approach that of helium. Ashkenazi and Steinberg (1999) have made convection measurements at very high Rayleigh numbers using SF_6 gas near its critical point. The relative advantages and disadvantages of these schemes need to be assessed in any given context. Helium is not the answer in every situation.

C. Scope and Organization of the Article

Thus, on the one hand, there are frontier opportunities to explore with respect to cryogenic helium; on the other hand, there are questions to be answered regarding the suitability of helium as a hydrodynamic test fluid. In this article, we discuss both opportunities and challenges, and argue on balance that the former considerations outweigh the latter. While in some instances the difficulty of working at cryogenic temperatures is not worth the trouble, there are several others for which it may be the only option—for instance, if dynamical similarity in Reynolds and Froude numbers is simultaneously desired. These views are neither new nor revolutionary. They have surfaced with different emphases at different times, starting perhaps with Smelt (1945) who articulated the advantages of helium. New at present is the confluence of interests in nonlinear physics, turbulence, model testing, instrumentation, and the technology of large-scale refrigeration, as summarized in the books edited by Donnelly (1991a) and Donnelly and Sreenivasan (1998). Over time, experience has been gained in small helium facilities typical of a laboratory-scale situation. The realization is now at hand that, if the use of helium can be pushed to the next level in size and versatility, a broad class of fluid dynamics problems can be addressed far more adequately that before. It is to the articulation of this theme that this article is devoted.

The rest of the article is organized as follows. Section II is a brief primer on the properties of helium. Section III contains examples of ultra-high Rayleigh and Reynolds numbers found in nature and technology, and Section IV makes the case that there are basic and applied problems that could benefit immeasurably by creating and studying flows at such ultra-high parameter values. In Section V, we remark briefly on a few specific examples for which helium offers unique opportunities. Some remarks will be made on the refrigeration opportunities available. Those refrigeration units have been developed at Brookhaven National Laboratory (BNL) and other such institutions for purposes of cooling superconducting magnets. The discussion in these sections is concerned largely with helium as a desirable fluid for hydrodynamic testing. In reality, this desirability is intertwined with promises that helium offers for fundamental new physics as well. The two aspects cannot be separated easily, and we shall specifically consider in Section VI an example of the latter by discussing the use of helium II. A summary of available instrumentation is given in Section VII. In Section VIII, some limitations of helium vis-à-vis our stated purposes will be discussed. We conclude the article with a brief summary in Section IX.

II. Brief Note on Helium

Cryogenic helium is one of the well-studied fluids, probably next in detail only to water and air. It offers essentially three fluids of dynamical interest, each with its own special and attractive properties. It is convenient to discuss these fluids with respect to the phase diagram of helium (Figure 1). The different states of the fluid are marked on it.

To the right of the λ line and above the liquid–vapor coexistence line is liquid helium I. This liquid obeys Navier–Stokes equations and satisfies

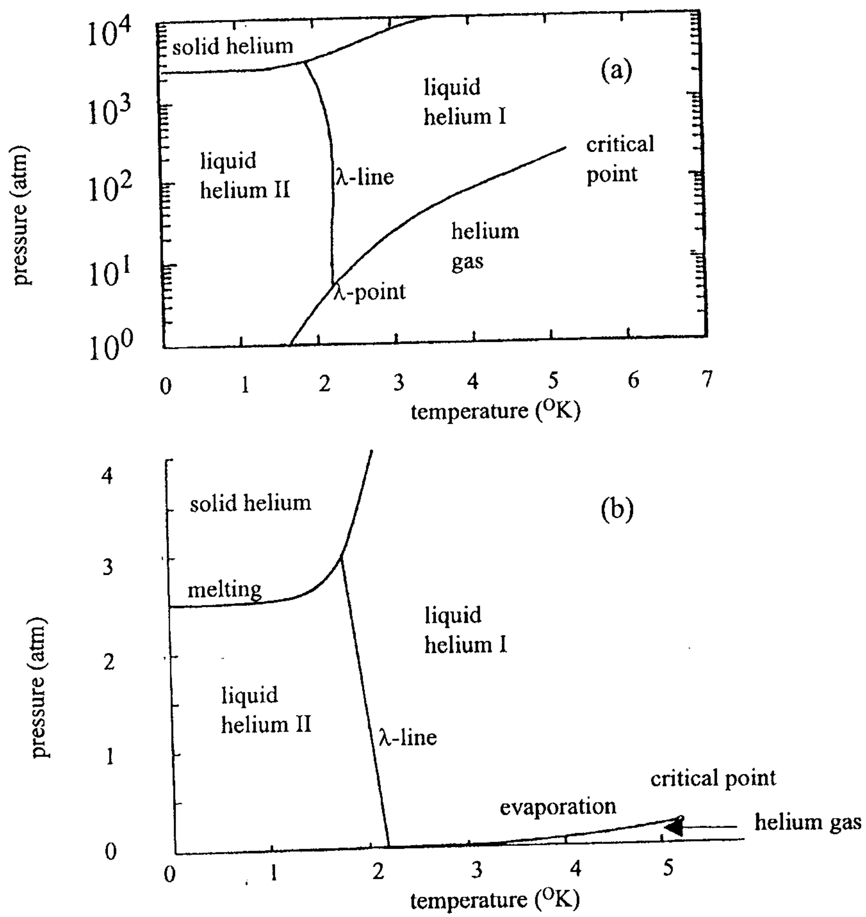

Fig. 1. The phase diagram of helium in the pressure–temperature plane. Pressure is given in the logarithmic scale in (a) and in linear scale in (b).

viscous boundary conditions. The viscosity of helium I is small but finite. If we reduce the pressure, helium I boils like any other liquid and enters the vapor state. The normal boiling point of liquid helium is 4.2 K. Gaseous helium is also a Navier–Stokes fluid. The critical temperature and pressure of helium are 5.2 K and 2.26 bar, respectively. In the vicinity of the critical point* the viscosity and thermal conductivity of gaseous helium depend sensitively on the temperature and, especially, on the pressure (see Figure 2). This latter dependence is not unlike the inverse power law for air, say, except that, even at 1 or 2 atm of pressure, very low viscosities can be attained. Thermal conductivity changes similarly, so one can easily attain a vast *range* of Rayleigh numbers (see Section III).

The point of intersection of the λ line with the coexistence line is the so-called "λ point." The corresponding temperature is about 2.17 K. The liquid state to the left of the λ line is helium II. Helium II exists as a liquid down to absolute zero and does not solidify except at pressures of the order of 25 atm. Roughly speaking, helium II is a mixture of a superfluid component and a normal component. The former has no viscosity or

*We consider conditions far enough away from the critical point for the effects of finite correlation length to matter.

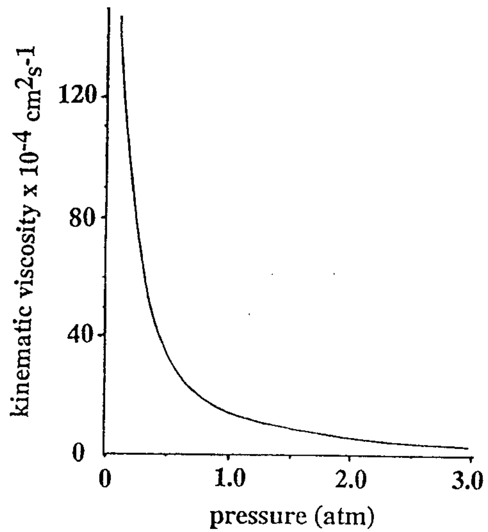

FIG. 2. The variation with pressure of the kinematic viscosity of the critical gas at 5.4 K. Similar curves exist for other temperatures.

TABLE 1

FLUID DYNAMICAL PROPERTIES OF HELIUM COMPARED WITH AIR AND WATER

Fluid	T (Pressure)	ν (cm²/sec)	ρ (gm/cm³)	α (K⁻¹)	κ (cm²/sec)	$\alpha/\nu\kappa$
Air	20°C	0.150	1.21×10^{-3}	3.67×10^{-3}	0.200	0.122
Water	20°C	1.004×10^{-2}	0.998	2.07×10^{-4}	1.43×10^{-3}	14.4
Helium I	2.2 K (SVP)	1.78×10^{-4}	0.146	1.03×10^{-2}	2.49×10^{-4}	2.32×10^{5}
Helium II	1.8 K (SVP)	8.94×10^{-5}	0.145	X[a]	X	X
Helium gas	5.5 K (2.8 Bar)	3.21×10^{-4}	0.0685	2.86	6.31×10^{-5}	1.41×10^{8}

[a] Properties are not defined because the superfluid component has infinite thermal conductivity.

entropy, while the latter, in addition to having a small viscosity, carries the entire heat content of the fluid. The two fluids are, of course, not separable because all helium atoms are identical. The hydrodynamics of the two fluids can be described at very low velocities by the Tisza–Landau two-fluid equations (see, for example, Roberts and Donnelly, 1974). We argue in Section VI that the interaction between normal and superfluid components of helium II can be used to advantage for hydrodynamic studies. A special feature of helium II is that variations in temperature do not propagate according to the Fourier law of heat conduction, but as a true wave motion. This longitudinal wave in temperature (or entropy) is called the *second sound*. Its speed depends on the temperature but a typical value is on the order of 20 ms^{-1}. We shall see in Section VII that second sound is an important tool for studies of turbulence in helium II.

Finally, the lighter isotope of helium, namely, helium 3, also serves useful fluid dynamical purposes (e.g., Metcalfe and Behringer, 1990). The Prandtl number of a mixture of helium II and helium 3 can be tuned by varying the mean temperature of the mixture. A major distinction between helium II and helium 3 is that the latter is not a superfluid. We shall not concern ourselves with helium 3 any further.

Table 1 lists a few representative properties of helium compared to those of water and air.

III. Some Examples of Flows at Very High Rayleigh and Reynolds Numbers

Recall that the Reynolds number, Re, and the Rayleigh number, Ra, are defined as $Re = UL/\nu$ and $Ra = \alpha g \Delta T L^3/\nu\kappa$, where U and L are characteristic velocity and length scales of the flow; ΔT is a characteristic temperature difference; ν, κ and α are, respectively, the kinematic viscosity, thermal conductivity, and isobaric thermal expansion coefficient of the fluid; and g is the gravitational acceleration. How high are the Reynolds and Rayleigh numbers in physical situations of interest? We consider some specific examples next.

A. Geophysical Flows

On the average, earth's atmosphere and oceans are stably stratified, so that the motion is generally a combination of three-dimensional turbulence and waves. Under special conditions, however, parts of these systems do become unstable. The large-scale overturns of water masses in Mediterranean and Polar seas are two examples. For water, the combination $\alpha g/\nu\kappa \sim 1.5 \times 10^4$ in CGS units. For a length scale of a little over a kilometer and for temperature differences of the order of 1 K, one obtains a Rayleigh number of the order 10^{19}. For the atmosphere, unstable conditions obtain if the lapse rate is greater than the adiabatic value of about $10°\mathrm{C\,km^{-1}}$. The most unstable conditions are observed off the coasts of Africa and Brazil in the Atlantic, and off California and Honolulu in the Pacific (Krishnamurti, 1975). Rayleigh numbers of the order of 10^7 are typical, and are smaller than those encountered in the ocean. Furthermore, because the wind shear is relatively pronounced, a more useful indicator of unstable conditions in the atmosphere is the Richardson number (see, for example, Monin and Yaglom, 1971).

Hurricanes, tornadoes, and other large-scale geophysical disturbances are sources of high-Reynolds-number phenomena in geophysical flows.

B. Solar Convection

The computation of Rayleigh and Reynolds numbers for the sun is nontrivial. We are content with rough estimates appropriate to the convection zone (the outer 30% of the solar radius except toward the surface where the fractional ionization is very low). From the knowledge of the temperature in that region and hence of the mean free path (Gray, 1988), one estimates the kinematic viscosity and computes the Reynolds number to be of the order of 10^{13}, and the Rayleigh numbers in the rough vicinity of 10^{22}.

Table 2
Some Examples of High Rayleigh and Reynolds Numbers

Example	Ra	Re
Sun	10^{22}	10^{13}
Ocean	10^{19}	10^{9}
Atmosphere	10^{7}	10^{9}
Naval applications	—	10^{9}
Aerospace applications	—	5×10^{8}

C. Aerospace and Navy Applications

The Rayleigh number is irrelevant in these instances. For reasonable operating conditions, the Reynolds number on the fuselage of a Boeing 747 could be of the order of 5×10^8. A modern torpedo (MK48) operates at a Reynolds number (based on length) of about 1.6×10^8. For an attack submarine (SSN688), the length-based Reynolds number could be as high as 10^9. An aircraft carrier (CVN68) produces a Reynolds number that is about five times higher; other ships on sea have comparably high Reynolds numbers.

Table 2 lists some of these numbers. Needless to say, they should be interpreted generously in a rough order-of-magnitude sense.

IV. Need for Studies at Conditions Approaching Ultra-High Parameter Values

Granted that there exist flow phenomena at these ultra-high Reynolds or Rayleigh numbers, it is not obvious that one should necessarily make tests under such extreme conditions. What reasons could compel such studies? Why is a straightforward extrapolation from a lower parameter range not adequate? In a brief attempt to address these questions, we shall consider both applications and basic research, although there are qualitative differences between the two instances. Basic research usually requires a "one of a kind" experiment, made with important questions in mind; this uniqueness renders irrelevant, or at least less pressing, the many considerations—such as the ease of repeated operation, minimum operating and turnaround times, and low operating costs—that are paramount in applications.

A. Model Testing and Difficulties with Extrapolation

Even in these days of supercomputers and advanced methods of computational fluid dynamics, there is still a place for a good experimental flow facility. Recent instances in which wind tunnel testing has played an essential role are for transonic wing and gas turbine development. An immense variety of problems could similarly benefit from model testing, but we shall consider instances where large gaps exist between the test and operating conditions. This gap often leads to "almost unmanageable risks" (Bushnell, 1998), a situation one would wish to avoid.

As an example, consider a submarine moving at some angle to its longitudinal axis. The vortices shed from the frontal fin will interact with the rear fin and the propeller, which in turn affects the latter's performance tremendously. The sound generated from these regions of intense interaction radiates outward and can be detected in the far field. Thus, one would not only like to understand the development of the boundary layer on the submarine body, but also the entire flow field including far-field acoustics and cavitation on the propeller blade. What makes navy and aerodynamic testing at ultra-high Reynolds numbers especially important is that the complexity of flow fields and the multiplicity of interactions among their various elements render uncertain the extrapolation to higher Reynolds numbers. Needless to say, new designs and development cannot occur without the ability to make rapid tests under realistic conditions.

Figure 3 shows some of the water facilities available in the world and the maximum Reynolds numbers attainable in them. The Reynolds numbers are based on the length of the largest model that can be tested in the facility. (Given the length-to-diameter ratio of the model, the maximum allowable blockage determines the maximum testable length.) For submarine-like bodies, Reynolds numbers of the order of 10^8 can be attained in these facilities, and it is sensible to ask why the knowledge acquired at these (or even lower) Reynolds numbers cannot be extrapolated adequately. Two superficial arguments might suggest that an extrapolation is possible. First, no surprising and qualitatively new physical phenomena may occur once a "sufficiently high" Reynolds number is reached. If so, the returns for working at these ultra-high Reynolds numbers are meager in relation to the costs. Second, such quantitative changes as might occur beyond this "sufficiently high" Reynolds number are slow, and so extrapolations for a decade or two in Reynolds number should be reasonably adequate. A plausible strategy for understanding the flow at Reynolds numbers of 10^9 would then be to

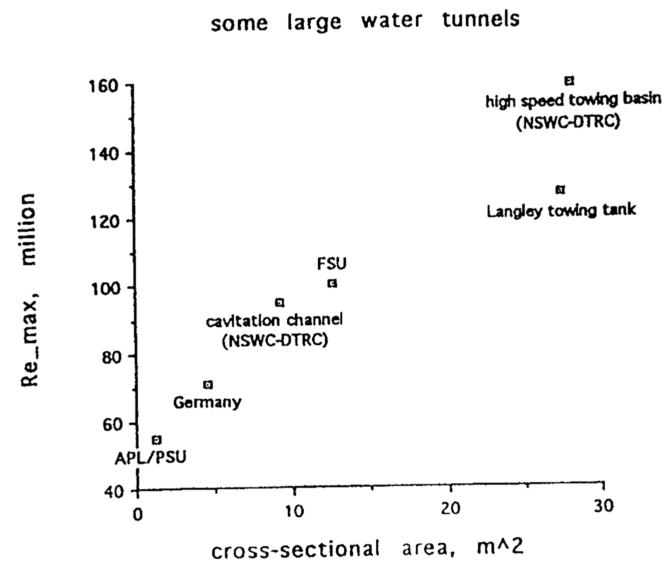

Fig. 3. A representation of some large-scale water tunnels in existence.

acquire solid information for Reynolds numbers up to, say, 10^7 and extrapolate it.

Unfortunately this is not always possible. While certain types of changes are indeed slow with respect to Reynolds number (Section IV.C.2), some are not—especially when several types of interactions occur. As an example, one does not know how to extrapolate the interaction of the intense vorticity field with the propeller by a scale factor of 10, let alone 100. One does not know how to calculate the far-field pressure reliably from the knowledge at low Reynolds numbers. The practice in the U.S. Navy is to build quarter-scale models and operate them in lakes with radio control. Even these enormously expensive and roughly realistic tests do not yield results that can be satisfactorily extrapolated for full-scale submarines. Here is a case where almost nothing but a full-scale test can produce satisfactory answers.

Similar circumstances exist for aerodynamic testing. In Figure 4, we show on the left ordinate the chord Reynolds numbers estimated for various aircraft, while on the right we show Reynolds numbers attainable in a few available test facilities. By convention, chord length is taken as a tenth of the square root of the cross-sectional area. Again, the gap in the Reynolds

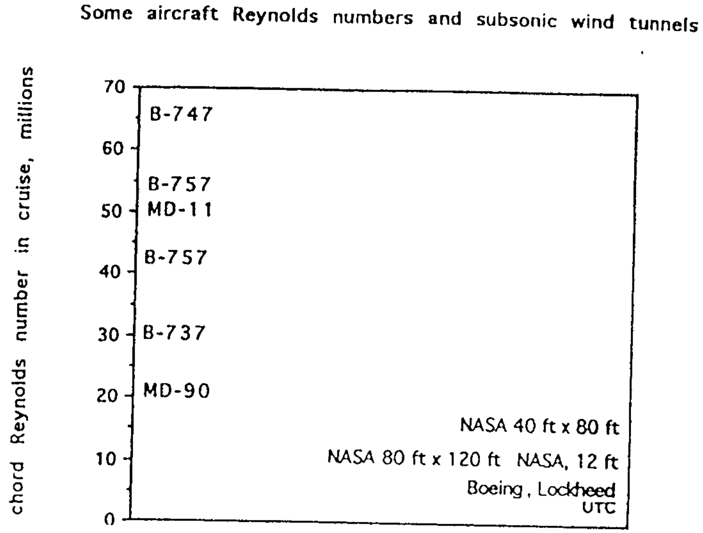

FIG. 4. Some aircraft Reynolds numbers and existing subsonic wind tunnels.

number between flight conditions and wind tunnel tests is an order of magnitude or larger. More thorough accounts of the wind tunnel situation can be found in various NASA documents of limited availability and AIAA information papers, but our purpose here is to point out that full-scale testing cannot be done in any existing facilities.

The one important exception to this statement is the National Transonic Facility (NTF) at NASA Langley (e.g., Kilgore, 1991, 1998); as is well known, NTF operates at cryogenic conditions of liquid nitrogen. The value of cryogenic testing has long been appreciated and used to advantage in NASA. The use of helium is the natural next step.

B. Other Applied Issues

A few Reynolds-number-dependent issues of interest to the navy and air force are the dynamic response to nonlinear maneuvers, transition to turbulence, effects of tripping the boundary layers (which could be significantly different between low and high Reynolds numbers), scaling of submarine propellers, and so forth. Bushnell and Greene (1991) cite other practical instances of low-speed aerodynamics where research at ultra-high Reynolds numbers is critical. Their first example is the hazard to lighter

aircraft encountering strong wing-tip vortices left behind larger aircraft. The distance needed for the natural dissipation of these vortices is unacceptably large (probably proportional to their Reynolds number) in a modern airport. A useful strategy would be to "control" the vortices so as to ameliorate their effects. Wind tunnel tests made for the purpose have been at Reynolds numbers that are smaller by about two orders of magnitude. This mismatch in Reynolds numbers is thought to be responsible for the observed discrepancy between the flight and laboratory data. A second example is the enhancement of the maneuverability of jet fighters by particular use of vortex generation techniques. Here again, Reynolds number effects are known to be critical. The third example is the development and evaluation of high-lift devices where, for instance, one cannot predict the position of separation. In general, the interaction between vortices and solid body can be understood only by controlled studies at very high Reynolds numbers. Helium flows offer tremendous opportunities here.

C. Basic Problems in High-Reynolds-Number Turbulence

Turbulence is intrinsically a high-Reynolds-number phenomenon. Much is known about it (e.g., Monin and Yaglom, 1971, 1975, and the hundreds of papers that occupy journal pages year after year) and yet, only a small part of that knowledge is impeccable. The theory is very hard for good reasons, and is still a long way from being satisfactory (e.g., L'vov and Procaccia, 1996). The so-called "universal aspects" of turbulence can be found (if at all) only at very high Reynolds numbers. One does study high-Reynolds-number turbulence in atmospheric and oceanic flows, but they are not well controlled.

What, specifically, are the types of questions that one supposes will be answered by studying turbulence at "high enough" Reynolds numbers? How high is "high enough"? Finally, at the risk of inviting ridicule, we might as well ask: What constitutes a solution of the turbulence problem, and how does one recognize it when it appears on the horizon? These questions are considered below.

1. *Large-Scale Phenomena*

Historically, one has always learned something valuable and unexpected when the Reynolds number boundary has been pushed behind by one or two orders of magnitude. The drag crisis for the sphere (see Schlichting, 1956), Roshko's (1961) work on the drag coefficient for the circular cylinder, Kistler and Vrebalovich's (1966) data in grid turbulence, spectral measurements of Grant *et al.* (1962) in the ocean, and Saddoughi and Veeravalli's (1994) experiments in the NASA AMES wind tunnel are a few examples worth citing. The Nusselt number measurements of Castaing *et al.* (1989), Chevanne *et al.* (1997), and Niemela *et al.* (2000a) have revealed unexpected features. The mean velocity measurements in pipe flow at very high Reynolds numbers (Zagarola and Smits, 1997) possess unsuspected elements. In all of these instances, new global aspects have come to surface; even if some findings confirmed what was previously expected, the value of these high-Reynolds-number studies cannot be exaggerated.

It may be worth emphasizing that one does not yet know for certain basic quantities such as the asymptotic value of the drag coefficient of a smooth sphere. One does not yet know at what Rayleigh numbers, if any, the Nusselt number begins to vary as the half power of the Rayleigh number (Kraichnan, 1962; Howard, 1972). What is the effect of the aspect ratio of the apparatus on the observed power law, and what is its form for large aspect ratio? What is the effect of surface roughness on convective heat transport, and how does one conveniently parameterize it? Do thermal "plumes" survive at ultra-high Rayleigh numbers? More generally, how much of the coherent structure observed at low and moderate Reynolds numbers survives at ultra-high Reynolds numbers? What is the effect of the large-scale motion on various power law exponents? How much does the large-scale motion itself depend on initial conditions? Beyond what Rayleigh numbers does the average value of the energy dissipation rate follow the Kolmogorov form? An empirical observation of Niemela *et al.* (2000a,b) is that the variation of the Nusselt number with the Rayleigh number has a *functional form* that is very close—over 11 orders of magnitude in Ra—to the prediction of a weakly nonlinear theory. Whether this is a happenstance or has a profound theoretical basis of some generality remains to be understood.

Instead of listing more questions, we emphasize that a sound theory of turbulence will not be possible without putting such basic issues on firm footing: One well-executed experiment at very high Reynolds numbers may be superior to a host of repeats at low to modest Reynolds numbers.

2. *Small-Scale Turbulence*

Let us now turn our attention to the scaling properties of turbulence in inertial and dissipative ranges. This is an area of active research, propelled

not the least by the extraordinary success that has occurred in critical phenomena during the recent two or so decades (e.g., Goldenfeld, 1992); that success is in no small measure due to simultaneous progress in theoretical and experimental work. A reasonable goal of research in small-scale turbulence is to reach a comparable state of certainty with respect to scaling. Some typical problems are mentioned below.

As has been well known now for almost 60 years, Kolmogorov's (1941) ideas have ruled the horizons of research in turbulence physics (see, e.g., Hunt *et al.*, 1991). Experiments have revealed deviations from Kolmogorov's theory (e.g., Frish, 1995), and these deviations are attributed to the intermittency of small scales. The role of intermittency is not fully understood. Its importance for certain aspects of turbulence such as energy spectral density may be small, but could be rather large for turbulent combustion, breakage of liquid droplets, particulate aggregation, and the like. The finiteness of the Reynolds numbers renders the observed effects of intermittency to varied interpretations (e.g., Nelkin, 1994; Sreenivasan and Antonia, 1997). The kinematic and dynamic effects of the sweep of small scales by the large scale are not fully understood (Tennekes and Lumley, 1972). The much simpler problem of passive scalars mixed by turbulence contains partially understood aspects: Some examples are the fractal character of isotherms (Constantin *et al.*, 1991) and the effect of shear on it, the asymptotic shape of the probability density functions of temperature increments and derivatives (e.g., Sinai and Yakhot, 1989; Shraiman and Siggia, 1995), and the limitations of cascade-type ideas for describing the interscale transfer of scalar variance. Looming large are potential limitations of the very notion of universality of small scales—a supposition that has been at the core of the subject.

To improve the state of these long-standing uncertainties, first and foremost, one needs solid experimental data. However, for experiments to be compelling in this respect, one needs to have a large scaling range (say, three decades) and the information extracted from them should not be subject to dubious artifacts of data processing. (The situation becomes less stringent if a plausible theory emerges.) An important fact about turbulence is that the scaling range increases only logarithmically with Reynolds number. So do the number of steps in the spectral cascade (Onsager, 1949); the number of effectively independent layers in wall-bounded flows (Tennekes and Lumley, 1972); plausible corrections for finite Reynolds number effects (Barenblatt and Chorin, 1996); the Reynolds number dependence of the volume occupied by the dissipation field and of the fine-scale vortex structures (Sreenivasan and Meneveau, 1988), and so forth. If we ignore flows that are very close to solid boundaries, and those driven by extremely large shear, the number of decades of inertial scaling varies with the Reynolds number roughly as

$$\text{number of decades} = \log_{10} R_\lambda - 1.75 \text{ for } R_\lambda > 200,$$

where R_λ is the microscale Reynolds number based on the root-mean-square velocity fluctuation and the Taylor microscale (see, e.g., Batchelor, 1953). This suggests that one needs an R_λ of the order of 50,000 to obtain three decades of scaling. Translating R_λ to the bulk Reynolds number, Re, is not precise but the equivalent Re is roughly on the order 3×10^8. (It must be said, however, that the scaling range shrinks if the forcing is very strong or spectrally broad.) Theory will then have a stronger foothold.

3. *The "Turbulence Problem"*

The so-called "turbulence problem" has been with us for substantially longer than a century. Given the multifaceted complexity of turbulent flows, a minimal set of conditions that ought to be satisfied before we can declare that the problem is "solved" is worth some consideration. This issue is not central to our thesis about helium here, but is marginally relevant because we are advocating very high Reynolds number studies as a means to this end. One possible scenario is that every flow of interest can be computed away fast enough to be useful in practice. Though computing is not "understanding," the problem will then assume less urgency. Given the large Reynolds numbers in some cases of interest, this scenario does not seem realistic despite rapid advances that continue to occur in computing power. There is thus a need to "model" turbulence. Modeling involves many issues; among them are functional relationships between different quantities as the Reynolds number is varied, and the numerical coefficients involved in these relationships. Scaling studies mentioned earlier focus on the interrelationships. Detailed numbers and coefficients have to come from measurements, theory, or simulations. A program of basic research in turbulence would thus involve the experimental determination of scaling relationships over the entire range of Reynolds number of interest, theoretical advances that understand such relationships, and a detailed exploration through simulations as well as experiment at a few Reynolds numbers. Helium offers an excellent opportunity in terms of the experiment.

V. Some Considerations about Large-Scale Helium Flows

We have so far argued that there is a need for ultra-high Reynolds number experiments from both practical and fundamental perspectives. Some at least of these needs cannot be met by existing wind and water facilities. Even those that can be met in principle by existing facilities cannot always be explored in them because of their meager availability and large operating expenses. In particular, it is nearly impossible to procure for fundamental research in turbulence the services of NTF at NASA Langley. As for high-Rayleigh-number research, no large-scale facilities are in existence. Alternatives are clearly needed.

A. Examples of Large-Scale Facilities

After making a careful study of these factors, Donnelly *et al.* (1994) recommended the following three large-scale helium facilities to be built:

1. A 10-m-high convection cell to generate a Rayleigh number as high as 10^{20} using cryogenic helium gas. This Rayleigh number is of direct interest in geophysical and astrophysical problems (Table 2).

2. A helium tunnel with a cross section of side 125 cm. A submarine model of 25 cm in diameter and 250 cm in length can be operated at a Reynolds number of the order 10^9, comparable to that of a full-scale submarine in operation.

3. A liquid helium tow tank, about 8 m wide and 40 m long, that could match both Reynolds and Froude numbers at the same time. The run time would be of the order of 10 s.

It is useful to keep these concrete examples in mind as we proceed with the following discussion.

B. Refrigeration

In building helium flow facilities that exceed a modest scale, one concern is the availability of refrigeration. Helium volume of more than a few thousand liters is difficult to manage in a university research laboratory. None of the facilities mentioned above could be operated in this mode, and so require special considerations. Fortunately, demands placed on the cooling of superconducting magnets used for high-energy particle accelerators have perfected techniques of large-scale refrigeration. For instance, the refrigeration available at BNL, as part of its Relativistic Heavy Ion Collider (RHIC) project, is about 25 kW (Sondericker, 1998). An inventive suggestion made in Donnelly (1994) was that such refrigeration facilities could be used off-line for the special helium facilities of the sort just discussed. For instance, the 10-m convection cell would require about 60,000 liters of helium and about a kW of refrigeration. The helium tunnel with the 125-cm test section would require about a million liters of helium and about 1 kW of cooling power at 1.6 K. The towing tank would also use about a million liters of helium and need comparable cooling power. All of them are, in principle, well within the BNL capacity (and those of Fermilab, Livermore, and CEBAF in the United States, and a few places such as at CERN in Europe; see Quack, 1998).

This granted, one may still question whether helium offers the right choice; we have already noted highly compressed air and SF_6 near the critical point as possible alternatives. There is less experience with SF_6, and so we will consider a brief comparison between helium and compressed air. Helium I at 2.5 K and 1 atm, helium gas at a temperature of 5.4 K and 2.9 atm, and compressed air at room temperature and about 200 atm all possess roughly the same kinematic viscosities. Thus, to obtain the same model Reynolds numbers, the same flow velocity is required in all three cases. To test an ellipsoid of aspect ratio 12 at a length-based Reynolds number of 10^9, assuming that the blockage permitted is of the order of 3%, one requires a test section of about 1-m diameter and a flow velocity of about 50 ms^{-1}. Thus, issues such as allowable surface roughness of the model and the resolution required of the instrumentation will be of equal import in all three cases. What would render one of the fluids more, or less, desirable are issues such as the dynamic pressure (which directly determines the forces on the model), the flexibility of use, possibilities for research and further development, sophistication of available instrumentation, and so forth. Some of these issues are discussed below. For comparisons to be useful in practice, reliable cost estimates and power requirements should be made to the same degree of detail in all the cases. We have not made such detailed studies (nor has anymore else). Without the benefit of such studies, we have to be content with discussing some general considerations with respect to helium.

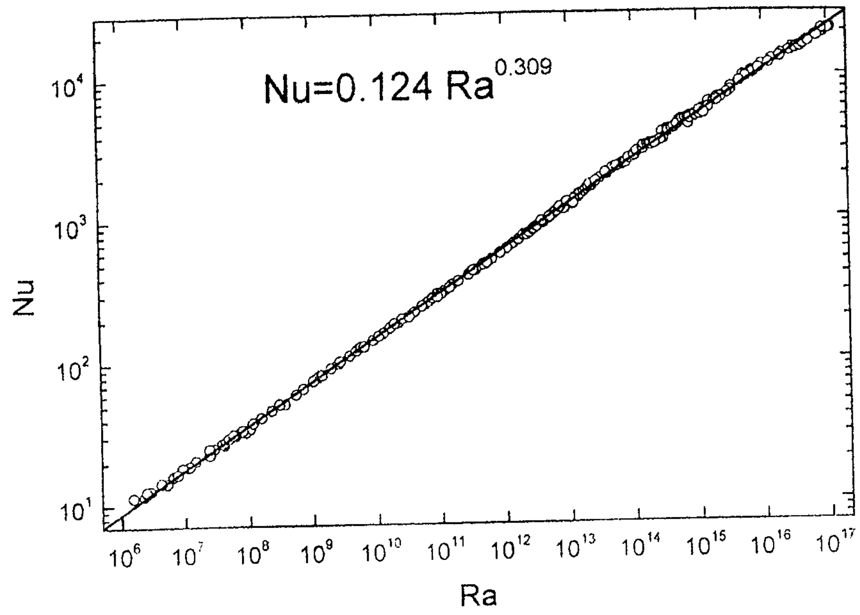

FIG. 5. A plot of the Nusselt number, Nu, versus Rayleigh number in the 1-m convection apparatus at the University of Oregon. (Nusselt number is the ratio of the convective heat transport to the conductive transport for the same temperature difference between bottom and top plates.) The Rayleigh number covers about 11 orders of magnitude. Over this range, the power law has an exponent of about 0.3. (From Niemela *et al.*, 2000a.)

C. Thermal Convection Experiment

The suitability of helium for the convection studies has been recognized for more than 25 years now, and studies exploiting its special features have been made in various laboratories around the world (e.g., Threlfall, 1975; Castaing *et al.*, 1989; Chevanne *et al.*, 1997; Niemela *et al.*, 2000a,b). Presently, the largest cell in operation is at the University of Oregon; it is 1 m high and 0.5 m in diameter and produces Rayleigh numbers between 10^6 and 10^{17}. At the upper end of its use, it uses 60 liters of helium and requires 10 W of refrigeration.

The uniqueness of this cell is demonstrated by Figure 5, which plots the Nusselt number data over 11 orders of magnitude of Rayleigh number—all acquired in the same apparatus by controlling the gas pressure and the temperature difference between top and bottom plates. Rayleigh number is roughly proportional to the square of the Reynolds number, so one has in the same facility 5 or more orders of magnitude variation in Reynolds number, or about 2.5 orders of magnitude in the Taylor microscale Reynolds number. It is extremely rare that one can obtain such a range in one apparatus. One can also observe an extensive scale range, transition from Bolgiano scaling (1962) to Kolmogorov scaling (1941), and so forth. More details can be found in Niemela *et al.* (2000a,b).

The Oregon apparatus is nearly at the limit of what is possible in a university laboratory. The large convection cell proposed in the previous subsection cannot be built and operated in this same way. It is also expensive. Keeping this latter in mind, Donnelly (1994) designed the same cryogenic cell to house other flows such as turbulence behind a towed grid, Taylor–Couette flow, a medium-sized helium tunnel, and basic drag experiments of falling bodies. These other purposes to which the convection call can be put are illustrated in Figure 6. Perhaps the most basic of them is the towed grid experiment. (A small-scale version of this flow is in operation at Yale University.)

D. Helium Flow Tunnel

The operation of a helium tunnel is no different in principle from that of a water tunnel, but the advantage of a helium I tunnel is the small size. Although the smallness could also be true of highly compressed air — as has been noted already — some features make helium additionally desirable. First, the forces on the model are smaller. We show in Figure 7 the ratios of the dynamic head of compressed air at 300 K, as functions of the air pressure, to that of liquid helium at two temperatures, keeping the Reynolds number fixed. This ratio is appreciably larger than unity even for air pressures of a few hundred atmospheres. Second, an array of instrumentation is available at low temperature, as we shall see briefly in Section VII. A superconducting magnetic suspension could be used to support the model in the test section (Goodyer, 1991; Lawing, 1991; Britcher, 1991, 1998).

The limiting parameter in the design and operation of a helium tunnel is the refrigeration available. In circumstances where refrigeration is limited, transient operation is a plausible alternative. This is discussed in Donnelly (1991a). As a precursor to the 125-cm tunnel, a 6-cm tunnel has been built at the University of Oregon.

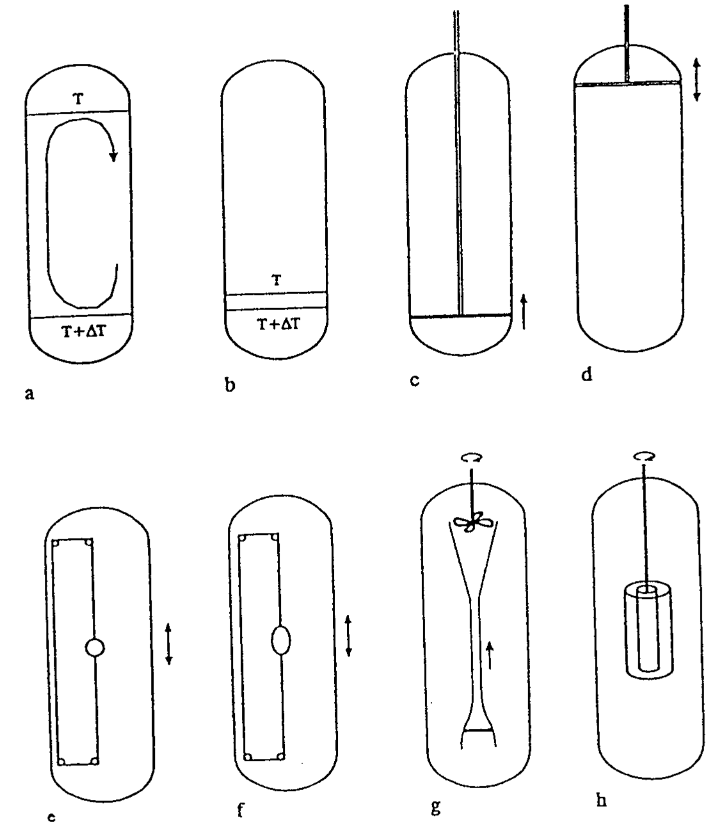

FIG. 6. A schematic of the proposed large cryostat and its potential uses: (a) ultra-high-Rayleigh number convection, (b) convection with variable aspect ratio, (c) towed grid, (d) oscillating grid, (e) towed sphere, (f) towed ellipsoid, (g) a tunnel insert, and (h) a Taylor–Couette insert. (From Donnelly, 1994.)

E. Tow Tanks Using Liquid Helium

The properties of liquid helium, especially helium II, vary rapidly with temperature. These variations can be used to advantage in modeling the motion of ships or waves on a free surface. In these instances, we need to simulate the Froude number $\mathrm{Fr} = U/(gL)^{1/2}$, where L is the length of the vessel. The difficulty in model studies is that the matching of the Froude number leads to a drastic mismatch of the Reynolds numbers.

As an illustration, consider the motion of a surface ship 100 m long, 10 m in lateral size, moving at 30 knots ($\sim 16\,\mathrm{m\,s^{-1}}$). For water temperature of

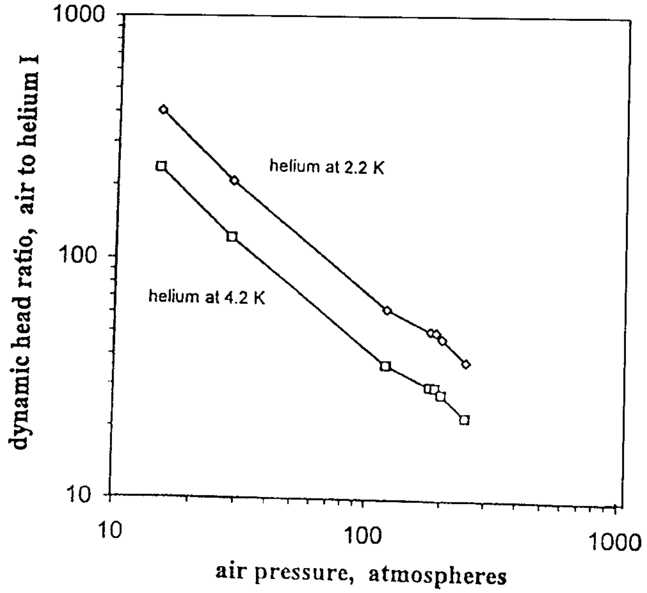

FIG. 7. The ratio of the dynamic head in compressed air flow at 300 K to that in helium I at 2.2 and 4.2 K, as a function of the air pressure in atmospheres.

15°C and a scale ratio of 25, a 4-m-long model in a water tow tank will match the Froude number of 0.52 if towed at 3.3 ms^{-1}. However, under these conditions the Reynolds number of the model is 1.3×10^7 compared to the full-scale Reynolds number of 1.7×10^9, smaller by a factor of about 130.

Operating in helium gives greater flexibility for matching similarity parameters. For instance, using helium I at 2.2 K, a scale ratio of 25 can match the Froude number exactly and the Reynolds numbers to within a factor of 2. Donnelly (1994) has provided additional details of design for an 8-m × 40-m facility (see Figure 8). Helium II offers even greater flexibility but needs a separate discussion because of its superfluid part. This is the subject of the next section.

VI. Superfluid Helium and the Hypothesis of Vortex-Coupled Superfluidity

We remarked in Section I that helium offers flexibility for exploring uncharted territories in hydrodynamics. Here we advance one such possibility with respect to helium II.

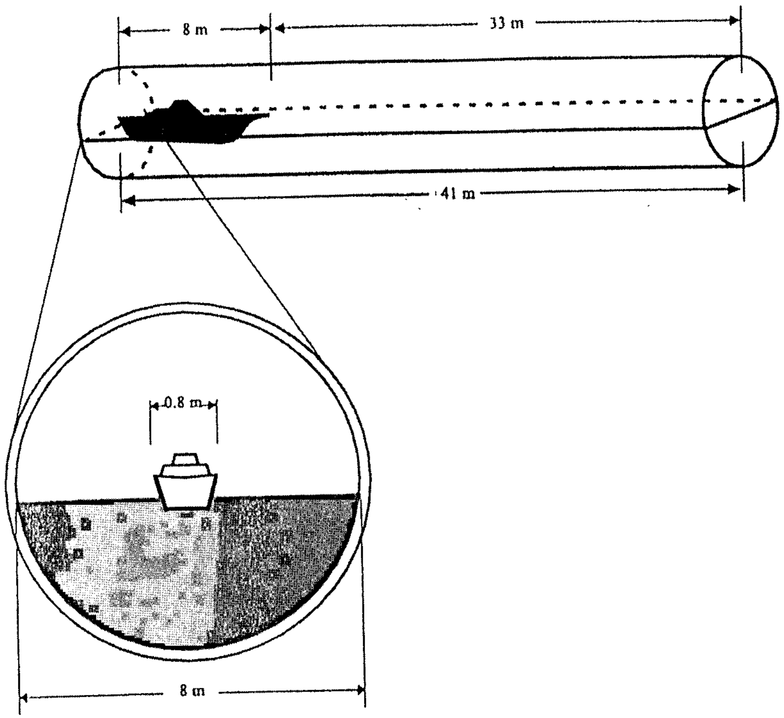

FIG. 8. A schematic of a liquid helium tow tank, which is capable of matching Reynolds and Froude numbers at the same time.

Helium II has several attractive attributes. One of them is the saving of refrigeration. The kinematic viscosity of liquid helium at 4.2 K is $2.6 \times 10^{-4}\,cm^2\,s^{-1}$; it falls steadily with temperature, reaching $9 \times 10^{-5}\,cm^2\,s^{-1}$ at 1.75 K, below which it begins to rise again. Since the pressure drop in a pipe flow, for example, depends on the cube of the kinematic viscosity, operation at 1.75 K instead of 4.2 K needs a mere 4% of the refrigeration. Another advantage is the ease of stable temperature control, with microdegree stability being routine in small cryostats. Additionally, the high heat conductivity of helium II suppresses cavitation that frequently plagues normal saturated liquid testing: the small heat of vaporization and surface tension of helium I forces one to operate under pressure to minimize the possibility of two-phase flow conditions.

However, there is a price to pay: helium II contains not only a normal fluid component but also a superfluid component with no viscosity, and one has to understand the interaction between the two fluids before helium II can be considered a hydrodynamic test fluid. We limit ourselves here to a few elementary comments. The relative fraction of the two fluids varies with temperature, from being entirely normal at the lambda point and entirely superfluid at absolute zero. The two fluids independently obey the hydrodynamic equations (Euler equations in the case of superfluid) until quantized vortex lines appear, as they do beyond a critical flow speed. Quantized vortex lines are similar to classical vortex lines except that their core radius is of the order of an Ångstrom, and the circulation κ around them is fixed by quantum mechanical considerations as $h/m \approx 9.97 \times 10^{-4}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, where h is the Planck's constant and m is the mass of the helium atom. In the presence of quantized vortices, the interaction between the normal and superfluid components is described through a mutual friction coefficient. These facets of helium II have been known for about 60 years (see Vinen, 1961, and Donnelly, 1991b, for a historical account).

This interaction between the two fluids after the appearance of quantized vortices is simple in certain circumstances and complex in others. In the case of a rotating bucket containing helium II, quantized vortex lines run parallel to the axis of rotation, and the density of these vortex lines is such as to match the vorticity of a fluid in solid body rotation. Except in such simple situations, the quantized vortices occur in random orientations ("tangled mass") with respect to the main flow, and the interaction becomes more complex. It is relatively easy to do a kinematic simulation of the evolution of this tangled mass. From such calculations (e.g., Schwartz, 1985, 1988; Aarts and DeWaele, 1994), a great deal has been learned regarding the generation of quantized vortices at the boundary, their reconnection, their density, and the mutual friction. Barenghi and Samuels (1999) have incorporated in a simple example the back reaction of the superfluid vortex tangle on the normal fluid. More generally, experimental observations beginning with Donnelly and Hollis Hallett (1958) have suggested that the interaction between the classical vorticity and superfluid vorticity is strong beyond a Reynolds number (for the normal fluid) of the order of 100.

The question of present interest is the interaction of the superfluid tangle ("superfluid turbulence") with the classical turbulence generated by the flow of normal fluid: One supposes that classical turbulence can be generated when the Reynolds number of the normal component exceeds an appropriately large value. It is plausible that the two random fields of vorticity are coupled in some strong way. The coupling has been designated (Donnelly, 1991a) *vortex-coupled superfluidity* (VCS). VCS has been invoked in the interpretation of the turbulence experiments of Smith (1993) and Stalp *et al.* (1999) behind towed grids in helium II. Vinen (2000) has recently examined this issue theoretically. He has shown that the coupling is strong for classical turbulent eddies of size larger than the Kolmogorov scale. The differences that may arise in the two types of turbulent motion are thought to disappear in a timescale that is set by mutual friction, this being typically smaller than the characteristic small-scale eddy time of classical turbulence.

Even though our understanding of these interactions is tentative, it is helpful to state the VCS hypothesis explicitly as follows.

> When forced sufficiently strongly, superfluid helium behaves as a Navier–Stokes fluid with respect to measurements made on a length scale large compared to the characteristic spacing between quantized vortices, and small compared to the length scale associated with the forcing. For those conditions, the quantum vortex lines track the high-vorticity filaments in the normal fluid. The inter-vortex spacing of the quantized vortices is of the order of the Kolmogorov scale.

Qualitatively, the hypothesis imagines that a turbulent flow will be threaded with a complex tangle of superfluid vortices. In a completely random tangle of quantized vortices, no large-scale superfluid vorticity can be present, because it will average out to zero. Therefore, superfluid vorticity field attains a macroscopic value only when superfluid vortex lines come together in the form of a tight bundle near the core of the normal fluid vorticity, and on scales that are small compared to that of external forcing.

The VCS hypothesis derives support not only from the numerical work of Barenghi *et al.* (1997) and Barenghi and Samuels (1999), but also from the sphere-drag experiments of Laing and Rorschach (1961) and Smith *et al.* (1999). See also Van Sciver (1991). Experiments, to the extent they are available, support the notion that helium I and helium II flows are very similar. The pipe friction data of Walstrom *et al.* (1988) also suggest that there is no perceptible difference between helium I and helium II data. Given the experimental difficulties, the absolute quality of results in all these cases is not as good as one desires, so there is a need to reaffirm the conclusions taking due account of features such as tunnel blockage and entry length. Finally, Maurer and Tabeling (1998) have shown that the spectral density of turbulence, measured at different temperatures — on the one end dominated by the superfluid component and on the other end by the normal component — display the same power-law scaling.

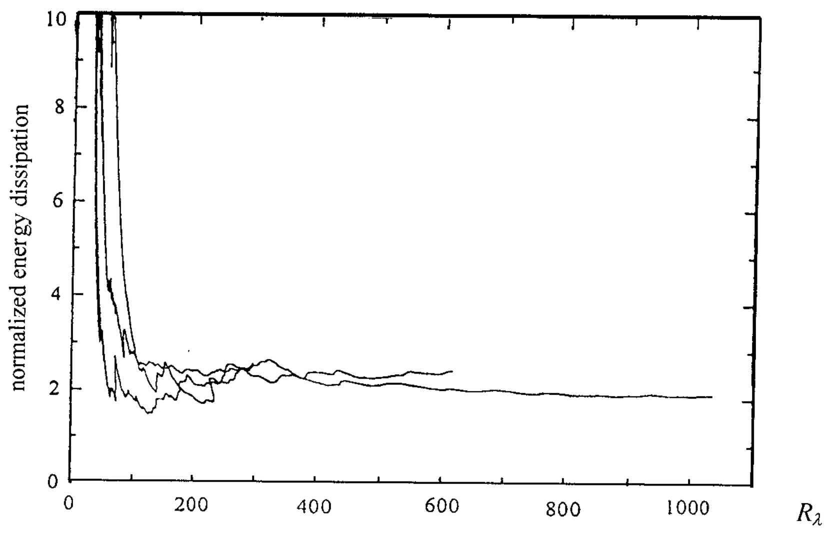

FIG. 9. The energy dissipation rate, measured by the VCS hypothesis behind a towed grid in helium II contained in a channel of a square centimeter cross section. The three curves correspond to the three different grid speeds of 10, 50, and 100 cm s^{-1}. The energy dissipation is normalized by the velocity and length scales characteristic of large-scale motion. The Taylor microscale Reynolds numbers, against which the normalized energy dissipation is plotted, are larger than those obtained in one of the largest wind tunnels (Kistler and Vrebalovich, 1966).

If the VCS hypothesis holds up under more intense scrutiny, it provides an important tool for studying classical problems using this nonclassical fluid (whose advantages have been mentioned earlier). In particular, the second sound attenuation in helium II is a sensitive tool for measuring the line density (line length per unit volume) of quantized vortex lines. When all the vortices are perpendicular to the second sound wave, as in the case of a rotating bucket, the attenuation is proportional to the vorticity (in addition to the speed of the second sound wave and the so-called mutual friction coefficient). No attenuation occurs along the axis of the quantized vortex lines. This fact can be used to estimate the attenuation of second sound in an isotropic and homogeneous distribution of quantized vortices. Under plausible assumptions, which need closer scrutiny, this attenuation can be related to the root-mean-square superfluid vorticity. Root-mean-square values as small as 10^{-2} Hz have been measured behind a towed grid (Smith, 1993; Stalp, 1998). By relating the second sound attenuation to classical vorticity, and thence to the turbulent energy dissipation rate, Stalp (1998) deduced the scaling of the latter as a function of Reynolds numbers. One of Stalp's graphs, reproduced here as Figure 9, shows that at high enough Reynolds numbers, the energy dissipation scales on the large-scale velocity and length scales, just as in classical turbulence (Sreenivasan, 1984). The difference is that much higher Reynolds numbers have been achieved in a channel of square-centimeter cross section than in the largest wind tunnels. The observed decay laws are essentially identical to those of classical turbulence behind grids (Skrbek and Stalp, 1999), as are the inertial-range energy spectra. Though there are gaps in the arguments leading to the interpretation of the data, these results suggest that the VCS hypothesis is likely to be correct essentially as stated above. These are exciting possibilities worthy of further exploration.

VII. Summary of Instrumentation Development for Helium Turbulence

Creating ultra-high Reynolds number flows is merely a part of the challenge, the measurement of dynamically interesting quantities being the other. A summary of the present state of instrumentation is therefore worthwhile. Our focus here is on helium flows, but the problems of resolving small scales of turbulence at high Reynolds numbers is not peculiar to them by any means.

A. Average Quantities

1. *Mean Flow Velocity*

Several methods are available for the measurement of average velocity in cryogenic engineering. They have been reviewed by Van Sciver *et al.* (1991), and include turbine flow meters, venturis, fluidic flow meters based on vortex shedding, acoustic transit time flow meters, and flow meters based on the propagation of temperature or pressure pulses. These methods are applicable to experiments where there is a mean velocity, and not to counterflow experiments (where the classical and superfluid components of helium II move in opposite directions). Two examples of acoustic flow meters are given in Swanson and Donnelly (1998).

2. *Mean Temperature and Its Gradient*

Instrumentation for measuring absolute temperature and temperature gradient has been developed to an exquisite state for liquid helium studies. High-resolution thermometers now reach nanokelvin resolution (e.g., Lipa, 1998). Germanium resistance thermometers are stable and highly sensitive (10^{-4}–10^{-6} K). Their response times are of the order of 10 ms. More rapid responses of the order of a microsecond at 4.2 K belong to silicon diodes in unencapsulated form. Thus, mean characteristics such as the Nusselt number, requiring only average temperature measurements, are feasible even for the most demanding circumstances considered so far, and the available instrumentation has been used successfully (e.g., Wu, 1991; Chevanne *et al.*, 1997; Niemela *et al.*, 2000a,b).

3. *Differential Pressure*

Measurement of absolute pressure and pressure gradients has also been developed to a high degree of sensitivity, principally by using capacitance manometers consisting of light diaphragms near a fixed electrode. This sensitivity has been made extremely high by means of bridges or resonance circuits, and can easily detect Angstrom-range movements of the diaphragm. Typical resolution is 1 part in 10^8 of the capacitance under study. These devices maintain their calibration after multiple cycles to room temperature. Swanson *et al.* (1998) report details of a recent capacitance manometer.

4. *Aerodynamic Forces*

NASA has for a long time promoted the development of magnetic suspension and balance systems. Several authors in Donnelly (1991a) and Donnelly and Sreenivasan (1998) discuss various important details. Superconducting magnets can replace conventional ones at helium temperatures. These systems can measure lift and drag on a suspended body (Goodyer, 1991; Kilgore, 1991), and also execute sophisticated maneuvers. These devices are most useful when there is a substantial mean flow. Britcher (1998) summarizes the current status of this topic.

5. *Wall Stress Gauges*

Wall stress gauges were first developed for fluid mechanics by Lambert *et al.* (1965). They consist of a very sensitive bolometer that is heated above the environmental temperature so as to give information about the shear at the location of the bolometer. In Taylor–Couette flow, the wall stress gauge gives information equivalent to torque measurements.

Wall stress measurement in Taylor–Couette flow of helium I have been reported by Perrin (1982). Perrin used an aquadag painted layer

TABLE 3
ROUGH ORDERS OF MAGNITUDE OF SCALES AND FREQUENCIES IN A FEW PROPOSED EXPERIMENTS

Flow	R_λ	η (μm)	f_η(Hz)
Convection (Ra = 10^{19})	30,000	3	10^7
(Ra = 10^{16})	3,000	100	10^6
Towed grid	4,000	5–20	10^5–5×10^5
	600	85–350	6,000–30,000

Here, η is the Kolmogorov length scale and f_η is the corresponding frequency. The larger R_λ numbers are for the convection facility considered in Section V.A., and the towed grid experiment for which it can be used. The smaller R_λ numbers are for their counterparts presently in operation.

~1 × 5 mm carrying a dc power of typically 10^{-5} W. However, these devices are unlikely to be successful for experiments in helium II.

B. TURBULENCE MEASUREMENTS

Turbulence measurements with needed resolution are hard to make. Very small scales that also oscillate rapidly are generated at very high Reynolds numbers. If the apparatus is large, the problem is alleviated to some degree because all length and timescales increase correspondingly. The problem is serious in helium because, by design, the apparatus for a given Reynolds number tends to be smaller than for water or air. (This same observation applies also to compressed air flows at very high pressures.) These circumstances demand substantial upgrading of instrumentation capability. The resolution requirements for the few instances considered in Section V are illustrated in Table 3.

1. *Flow Visualization*

An important aspect of research in fluid dynamics is the ability to visualize flows. This is a nontrivial matter in helium because of its low density and the relatively low speeds of the fluid involved. Investigators working on very high resolution Brillouin scattering experiments in liquid helium find that, unless prefiltering at helium temperatures is successful, liquid helium consists of microscopic particles (probably dissolved solid air) that remain suspended for hours. Various tracer particles have also been introduced in a controlled manner with reasonable success. For instance, when a mixture of helium and deuterium is injected into a test section containing helium, the mixture solidifies on contact with helium. These particles can be arranged to have matched density with sizes of the order of microns (Murakami *et al.*, 1991; Ichikawa and Murakami, 1991). Hollow glass spheres and monodisperse silicon dioxide particles have also been used to visualize thermal counterflow jets of helium II (Murakami *et al.*, 1998), small-scale and large-scale vortex rings (Murakami *et al.*, 1987; Stamm *et al.*, 1994), and turbulent Taylor–Couette flow (Bielert and Stamm, 1993). Although these techniques appear highly promising, significant development work will be needed in terms of the uniformity of size distribution of the particles, avoidance of adhesion, etc.

Conventional optical techniques such as shadowgraphs are usually not attempted in helium because the refractive index is close to unity ($n \approx 1.02$). However, Woodcraft *et al.* (1998) point out that, under properly engineered circumstances, thermal convection in helium is only an order of magnitude more difficult to visualize than in water. They substantiated the claim by calculating the so-called "visualizability" parameter, and obtained working shadowgraphs of dilute mixtures of helium 3 in superfluid helium.

2. *Temperature Fluctuations*

Single-point and multipoint temperature measurements have already been made by fine bolometers (e.g., Wu, 1991; Niemela *et al.*, 2000a). Their response has to improve significantly before the smallest scales in the large convection cell of Section V.C can be resolved. For an example of the limitations imposed by poor probe response, see Grossmann and Lohse (1993). Continuing efforts suggest that an improvement by an order of magnitude is well within reach.

3. *Velocity Fluctuations*

Taking advantage of a "mean wind" present in his convection apparatus, Wu (1991) was able to use two arsenic-doped silicon bolometers, mounted closely together, to measure a mean flow velocity by means of delayed correlation of temperature fluctuations. This technique, used also by Niemela *et al.* (2000a,b), is crude at best and beset with many limitations. Hot wire methods work well at low temperatures, provided there is a substantial mean velocity. Castaing *et al.* (1992, 1994) have developed micron-sized hot wires working near 4 K, and using both resistive and superconducting thin films. Single-component velocity measurements with

superconducting hotwire probes have also been made by Tabeling *et al.* (1996) in a helium apparatus with counter-rotating disks. No one has yet attempted cross-wire measurements. Even for single-wire probes, there are some difficult issues relating to temporal response (Emsellem *et al.*, 1997) but, on the whole, single-point single-component velocity measurements in helium flows have been successfully carried out. Whether the dissipative scales can be resolved in flows listed in Table 3 is still an open question, but further development ideas do exist (Wybourne and Smith, 1998).

If it is possible to seed helium gas or liquid helium for flow visualization studies, one can in principle use laser doppler velocimetry (LDV) and particle image velocimetry (PIV) methods. The development work necessary to obtain controlled seeding is currently under way.

Success in PIV depends on being able to seed the flow with particles that faithfully follow the fluid motion. The cross-correlation methods currently in use in water and air require a minimum of about five or ten particle pairs in the interrogation area. To resolve the finest scales, we need to have the interrogation volume no bigger than the Kolmogorov scale. The two requirements put serious constraints on the particle loading. Too high a particle loading (say, more than about 10^{-5} in volume fraction) will alter flow properties. Furthermore, the ability to image the particles depends on the laser power available and the index of refraction of the particles chosen. There are also issues related to the spatial resolution demands set by flow scales and constraints imposed by optics (such as fringe spacing).

It is thus clear that the ability to obtain a reliable PIV image depends on a combination of many specific issues. One will have to tailor a special PIV system for a given helium apparatus. Measurements (including the use of the so-called super-resolution PIV) are in progress at this time at Yale, where the first-generation measurements have already been made.

4. *Measurement of Vorticity*

Direct measurement of vorticity is still a challenging problem in classical turbulence. Even a qualitative method of visualizing the turbulent vorticity field would be of immense value. In helium II, ion measurements have been used for marking quantized vortices. Since ions are trapped on the cores of quantized vortices in helium II, they could, in principle, be used to obtain quantitative features such as root-mean-square vorticity. Complications arise because the ions can move along the cores of the vortices. At the present state of development, ions can locate vorticity spatially in a turbulent flow, but cannot easily determine the magnitude.

We have mentioned in Section VI a possible connection between second sound attenuation and root-mean-square vorticity. Studies at Oregon (Smith, 1993; Stalp, 1998) behind towed grids in a 1-cm^2 tube have shown the versatility of these measurements.

VIII. Limitations of Helium as a Hydrodynamic Test Fluid

We have cited a conceptual flow facility of 125 cm in diameter that can generate Reynolds numbers of the order 10^9. In Donnelly (1991a), several alternatives have also been considered to show that full-scale operation Reynolds numbers can be attained with helium. Although this satisfies the high Reynolds number requirement, it does not guarantee that satisfactory answers about *all* aspects of the overall field can be obtained. For instance, one does not know the nature of interaction between vorticity and the acoustic field reflected off the tunnel boundary, or the cavitation properties of helium in a turbulent environment. Some worries have also been expressed that turbulent motion at such high Reynolds numbers may not be the same in every respect as that for water flows. For example, local heating due to focused energy dissipation may affect the constitutive properties of helium (especially because of the extreme sensitivity of these properties to temperature changes); these local sources of heat may act as randomly distributed pressure sources. The smallness of velocity scales in ultra-high Reynolds number helium flows may render Navier–Stokes equations irrelevant to aspects of helium turbulence. These questions are often phrased, somewhat awkardly but succinctly, as "Is helium a Navier–Stokes fluid?" The worry is not that some unknown stress-strain behavior is needed to describe flows of helium I; it is that faithful similarities between water and helium I flows may break down when the *total* environment, such as the interaction between sound and vorticity, sound propagation through the medium, its far-field properties, reflection from boundaries due to differences in acoustic impedance, cavitation effects, and so forth, are all considered. Some of these questions are relevant only to model testing, but others to basic research in turbulence. We have not pursued these questions to great depth but examined them via back-of-the-envelope calculations. These calculations suggest that no "show-stoppers" of principle exist, but more detailed calculations are called for.

Turning now to aerodynamics, usually ultra-high Reynolds numbers occur simultaneously with sizable compressibility effects, and there may

even be regions of the flow where shocks are formed. Given that the ratio of specific heats for air ($\gamma = 1.4$) is different from that of helium gas ($\gamma = 1.67$), the shock structure will be undoubtedly different. The position of shocks depends to some degree on γ, as does the nature of shock boundary layer interaction. Thus, one has to be concerned about the degree to which the flow field observed in helium corresponds to that in air. In particular, this makes a transonic tunnel using helium gas less practical for aerodynamic testing.

Finally, one should be mindful of the fact that both the cool-down and warm-up phases of operation of any sizable helium facility would be significant.

IX. Concluding Remarks

This article has tried to provide a perspective on the use of helium as a test fluid for research and applications in classical fluid dynamics. Helium offers tremendous opportunities and advantages. At the moment, there is a convergence of interests from diverse fields such as turbulence, physics of helium, wind tunnel and water tunnel testing, instrumentation, and the technology of large-scale refrigeration plants. One should not lose sight of the uniqueness of this opportunity. The uniqueness of data that can be acquired by this means would amply justify the effort—on both fundamental and applied fronts.

Even well-known technologies, when applied to a different domain, pose unforeseen problems; this is not different with helium. However, the advantages of helium should not be buried under the cloud of uncertainties. Instead, some of the remaining questions should be given careful attention. Our discussion in this article—admittedly cursory on most fronts—shows that helium is an excellent option for some purposes. A large-scale experimental facility housed at BNL, say, can go a long way toward addressing some important problems of classical fluid dynamics. Already, some interim experiments in smaller scale facilities are under way. Their objectives are as follows:

1. To make turbulence measurements in helium flows with meaningful accuracy and resolution (using hot-wires, PIV and LDV), and make satisfactory comparisons with equivalent water or air flows;

2. To gain experience about vortex-coupled superfluidity, and the transmission of pressure waves generated by an oscillating body in still helium; and

3. To obtain aerodynamic data such as the drag coefficient on a cylinder or a sphere as a function of the Reynolds number through the "drag crisis" value.

The combined experience, which is now developing fast, will no doubt facilitate further decisions on the larger facilities. The outlook at the present is quite optimistic.

Acknowledgments

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