Helium Flows at Ultra-High Reynolds and Rayleigh Numbers: Opportunities and Challenges

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ABSTRACT
The use of helium as a working fluid enables the generation of flows at ultra-high Reynolds and Rayleigh numbers. Such flows create new opportunities for hydrodynamic testing and turbulence research. On the other hand, there are uncertainties to be overcome before helium can be used with familiarity, ease and confidence. This paper reviews some relevant considerations and discusses opportunities and challenges ahead.

1 Introduction

1.1 Advantages of helium as a working fluid

It has been pointed out (see, e.g., Ref. [1]) that the kinematic viscosity of helium is very low, which makes it a highly desirable fluid for generating very high Reynolds number flows in modest size facilities. For example, liquid helium at 2.2 K has a viscosity coefficient of about $1.8 \times 10^{-4} \mathrm{cm}^2\mathrm{s}^{-1}$, so that a Reynolds number of 100 million can be generated with a flow velocity of 4 ms^{-1} and a wing of 50 cm chord. For the same speed of water, the facility would have to be about 55 times larger. The size for similar air flow would be about 830 times as large (although air flow facilities need not be as large because much higher speeds are commonly used). Thus, with helium, one can envision creating very high Reynolds number flows suitable for navy testing (say), without building monstrously large facilities. Similarly, astronomically relevant Rayleigh numbers (say, 10^{20}) can be obtained in an apparatus that is of the order of 15 m in height. For convenience, Reynolds and Rayleigh numbers in the ranges just mentioned will be designated here as "ultra-high".

A second attractive feature is that the physical properties of helium gas change rather sensitively with pressure near the critical point (as we shall discuss momentarily), so that one may attain a vast range of Reynolds and (especially) Rayleigh numbers in an apparatus of fixed size and design. Helium lends itself nicely for combined heat transfer and fluid mechanics

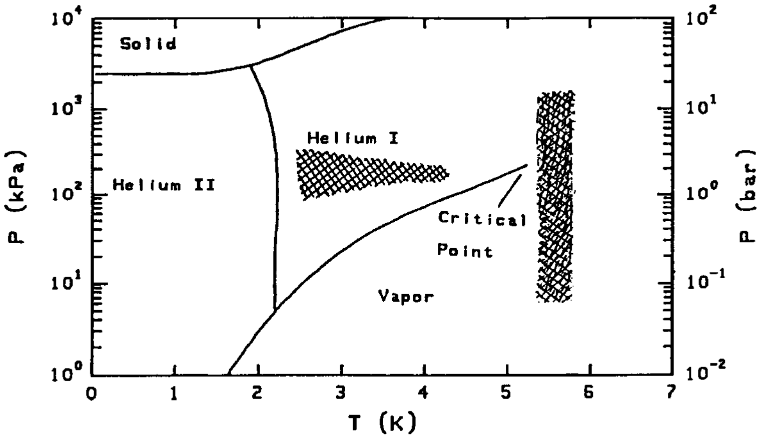

FIGURE 1. The phase diagram of helium.

studies in which both Reynolds and Rayleigh numbers play an essential role and large ranges of these parameters are required. A wide array of instrumentation, based on superconducting technology, is available at cryogenic temperatures. Further, for a given Reynolds number, the dynamic head of helium is low compared to that for water, say, so that struts and other mounts for the model need not be as strong. Finally, safety of operation is not a specially difficult issue with helium.

It must be noted that ultra-high Reynolds numbers can be obtained by using highly compressed air so that its kinematic viscosity is brought down to levels comparable to that of helium, see [2]. A few comparative comments will be made in section 4.

1.2 A brief note on helium

Helium exists in several states (and some have seemingly strange properties), so it is useful to be specific. To this end, let us examine the phase diagram of helium (Fig. 1). We shall operate above about 2.2 K and avoid helium II altogether. Even for the purposes already mentioned, it is conceivable that we will someday take advantage of the interaction between the classical and superfluid components of helium II, but it would require a detailed scientific study that goes far beyond the present scope. Our intention is to use both gaseous and liquid states above about 2.2 K, where helium is known to behave like a classical fluid. We shall also avoid working with helium vapor close to the coexistence curve but consider the gaseous state near (though not at) the critical point; this is the critical helium gas. The critical temperature and pressure are about 5.2 K and 2.3 bar, respectively. It is difficult to operate helium I at pressures very much different from 1 bar, but this restriction does not apply to critical helium gas. One

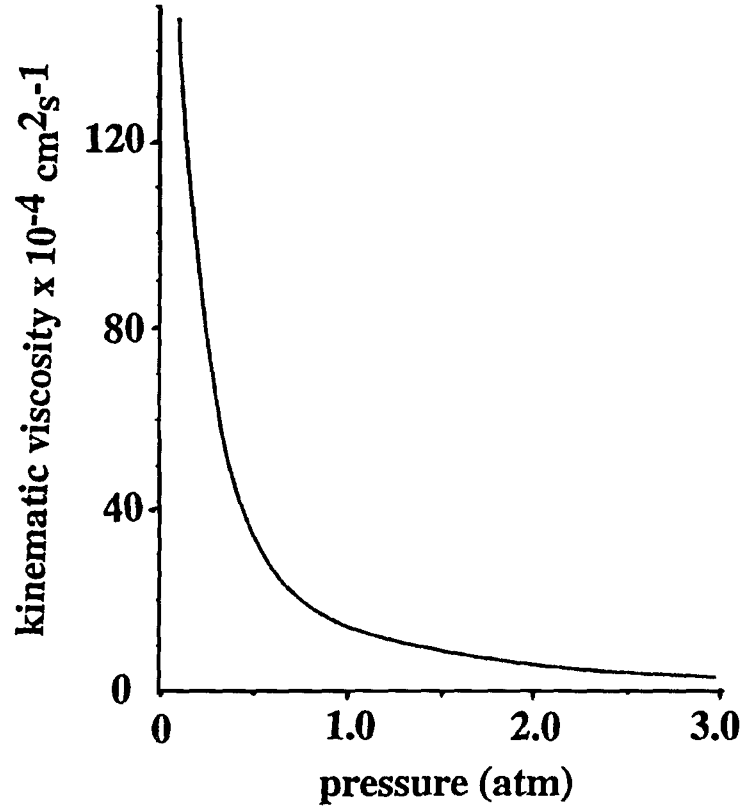

FIGURE 2. The variation with pressure of the kinematic viscosity of the critical gas at 5.4 K. Similar curves exist for other temperatures.

may change the pressure roughly by an order of magnitude on either side of the critical pressure. These considerations essentially define the conditions of interest; they are loosely sketched by hatched regions in the phase diagram. In this paper, when we say helium without specifying further, it could mean helium I or the critical gas.

The properties of helium change with temperature and pressure. The viscosity and surface tension of helium I change roughly by a factor of 2 as one spans the temperature range within the restrictions just mentioned. This is not a large variation. For the critical gas, however, viscosity changes tremendously with change of pressure (see Fig. 2). This is not too different from the inverse power law for air, except that, even at one or two atmospheres of pressure, very low viscosities can be attained. Thermal conductivity changes similarly, so one can easily see how a vast range of Rayleigh numbers can be attained.

1.3 The scope of the article

The attributes of helium just mentioned are compelling and have been exploited in some isolated and noteworthy instances; for some historical remarks, see Donnelly's article in this volume. Yet, much remains to be done before the benefits of helium can be realized in full: creating flows at ultra-high Reynolds and Rayleigh numbers is one thing, quite another it is to take full quantitative advantage of them. If such flows are used for aerodynamic or navy testing, an essential question to be answered is the degree to which the helium flows *in their totality* correspond to water and air flows. If used for turbulence research, the issue is one of acquiring, in helium, spatial and temporal data of the sort now acquired in water and air, with comparable or better precision and ease.

Thus, on the one hand, there are frontier opportunities to explore; on the other hand, there are questions to answer and difficulties to surmount. We shall develop this theme in the rest of the article. On balance, we argue that the opportunities opened up by helium flows cannot and should not be ignored. Time is especially ripe now because of advances that seem to be occurring concurrently on several fronts. In particular, the refrigeration needed for large-scale helium experiments is available (among other places) at the Brookhaven National Laboratory (BNL) which houses the world's largest refrigerator as part of the Relativistic Heavy Ion Collider project.

The rest of the article is organized as follows. Section 2 contains examples of ultra-high Rayleigh and Reynolds numbers found in Nature and technology, and section 3 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 4, we remark briefly on various ways of creating ultra-high Reynolds number flows, and consider the unique opportunities offered by helium. In particular, we discuss the specific case of the cryostat proposed for construction at BNL, and the potential uncertainties facing helium flow technology. A few desirable steps as a prelude to the BNL experiment are listed in section 5, and some concluding remarks are presented in section 6.

2 Some examples of high Rayleigh and Reynolds numbers

It is useful—if only to fix the notation—to recall that the Reynolds and Rayleigh numbers are defined, respectively, as

$$Re = UL/\nu \quad \textit{and} \quad Ra = \alpha g \Delta T L^3/\nu\kappa$$

where U and L are characteristic velocity and length scales of the flow, ΔT is a characteristic temperature difference, ν, κ and α are the kinematic viscosity, thermal conductivity and isobaric thermal expansion coefficient, respectively, and g is the gravitational acceleration.

The question to ask is: how high a Reynolds or Rayleigh number is attained in situations of interest to us? We shall consider some specific examples to illustrate the numbers involved.

2.1 Geophysical flows

For water, the combination $\alpha g/\nu\kappa \sim 10^5$ in c.g.s units. For a length scale of the order of a kilometer and for temperature difference of the order of 1 degC across it, one obtains a Rayleigh number of the order 10^{20}. In Mediterranean and Polar seas, where one has large-scale overturns of water masses, these conditions are quite realistic [3]. Thus, the Rayleigh numbers one encounters in oceanography are typically huge.

For the atmosphere, unstable conditions obtain if the lapse rate is greater than the adiabatic value of about 10 degC 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 [4]. Rayleigh numbers of the order 10^7 are typical. These are far smaller than those encountered in the ocean. Furthermore, because the wind shear is relatively pronounced in the atmosphere, a more useful indicator of unstable conditions in the atmosphere is the Richardson number.

In terrestrial atmosphere and oceans, one obtains Reynolds numbers of the order 10^9. Hurricanes, tornadoes, and other large scale geophysical disturbances are sources of high-Reynolds-number flows.

2.2 Solar convection

The computation of Rayleigh and Reynolds numbers for the Sun is nontrivial. We shall be content to obtain rough estimates valid for the convection zone (outwards of about 70% of the solar radius except towards 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 [5], one estimates the kinematic viscosity and computes the Reynolds number to be in the range of 10^{13}, and Rayleigh numbers in the range of 10^{21}.

2.3 Aerospace and navy applications

Rayleigh number is irrelevant in these instances. For reasonable operating conditions, the Reynolds number on the fuselage of a Boeing 747 could be as high as 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 1 lists some of these numbers. They should be interpreted generously in an order-of-magnitude sense.

example	$Ra \equiv (\alpha g/\nu\kappa)\Delta T L^3$	$Re \equiv UL/\nu$
Sun	$\sim 10^{21}$	$\sim 10^{13}$
ocean	$\sim 10^{20}$	$\sim 10^{9}$
atmosphere	$\sim 10^{7}$	$\sim 10^{9}$
naval applications	—	$\sim 10^{9}$
aerospace applications	—	$\sim 5 \times 10^{8}$

TABLE 1. Some examples of high Rayleigh and Reynolds numbers

3 The need for systematic studies at conditions approaching ultra-high parameter values

While it is clear that there exist flows with ultra-high Reynolds numbers—henceforth, where there is no confusion, we shall simply use "Reynolds number" as a short form for "Reynolds and Rayleigh numbers"—it is not immediately obvious that one ought to make laboratory studies under such extreme conditions. What compelling problems could benefit from such studies? In a brief attempt to address this question, we shall consider both applications and basic research, although the issues are different in the two cases: usually, basic research requires "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 turn-around times and low operating costs—that are paramount in applications.

3.1 Model testing and difficulties with extrapolation

Consider, for example, 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 (for instance) the latter's performance tremendously. The sound generated from these regions of intense interaction radiates outwards 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 totality of the flow field including far-field acoustics, cavitation on the propeller blade, and so forth. 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 makes extrapolation to higher

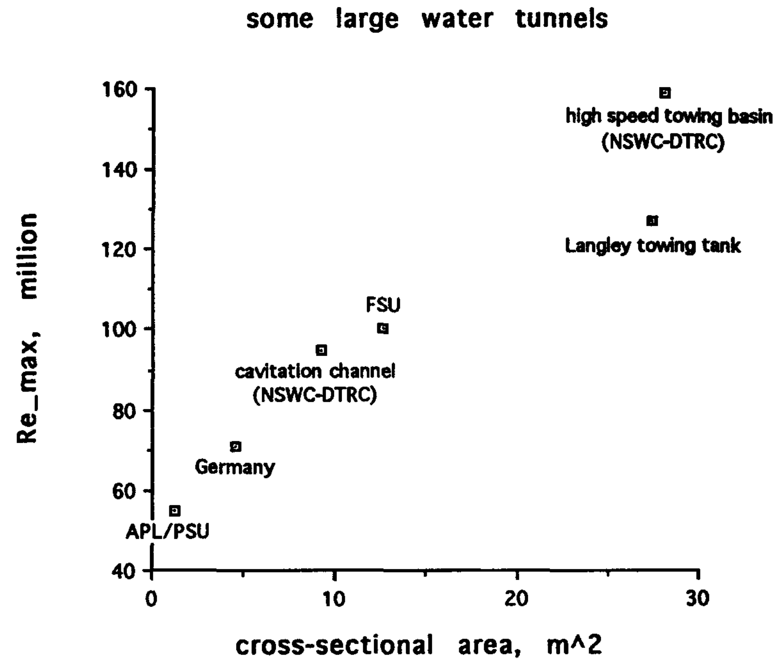

FIGURE 3. A representation of some large-scale water tunnels in existence.

Reynolds numbers difficult if not impossible. 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. 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 usefully. In fact, two arguments can be given in favor of this proposal. First, no surprising and *qualitatively* new physical phenomena may occur once one reaches "sufficiently high" Reynolds number; the meaning of "sufficiently high" here is arbitrary to some degree, but one imagines that is still "much lower" than, say, 10^9. If so, the returns for working at these ultra-high Reynolds numbers are meagre but the costs tremendous. Second, such *quantitative* changes as might occur beyond this "sufficiently high" value of the Reynolds number are slow, and so extrapolations for a decade or two in Reynolds number should be reasonably adequate. If so, a reasonable strategy for understanding the flow at Reynolds numbers of 10^9 is to acquire solid information for

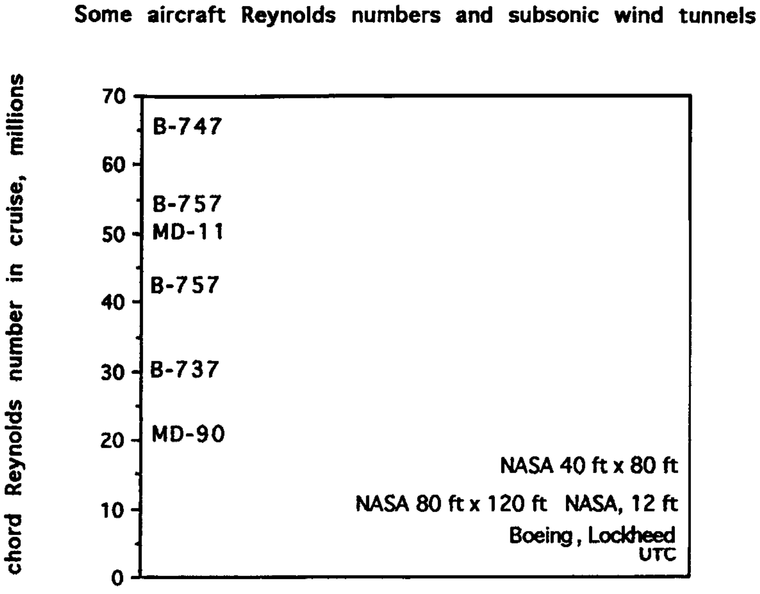

FIGURE 4. Some aircraft Reynolds numbers and existing subsonic wind-tunnels.

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 3.2.2), some are not (section 3.2.1)—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 acquired 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 costly and nearly realistic tests do not yield satisfactory results for full-scale submarines. Here is a case where almost nothing but a full-scale test can produce satisfactory answers; if there are differences in the operating environment—which cannot be avoided—they, too, may not be entirely satisfactory. *Completely correct answers for very complex situations can be obtained only by testing full-scale objects in the environment in which they are designed to work.*

The same circumstances exist for aerodynamic testing. In Fig. 4, we show on the left ordinate the types of chord Reynolds numbers estimated for various aircraft while on the right are listed a few available test facilities. By convention, chord length is taken as $\frac{1}{10}$-th the square root of the cross-sectional area. Again, the Reynolds-number gap between flight conditions and wind tunnel tests is an order of magnitude or larger.

In summary, in both aerodynamic and navy testing, there is a large Reynolds-number gap between the test and operating conditions. This gap can lead to "almost unmanageable risks" [6], as illustrated above with respect to navy vessels.

The above discussion is rather sketchy, and more thorough accounts of the wind tunnel situation can be found in various NASA documents of limited availability and AIAA information papers. Our limited purpose is to point out that full-scale testing cannot be done in any existing facilities. The one important exception is the National Transonic Facility (NTF) at NASA Langley [7]; 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, and our advocacy of helium is the natural next step. *It should be stressed, however, that this is as big a step as can ever be undertaken without leaving the domain of classical fluids.*

3.2 Other applied issues

A few Reynolds-number-dependent issues of interest to navy and airforce are the dynamic response to nonlinear maneuvers, transition to turbulence and the 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 & Greene [6] cite other practical instances of low-speed aerodynamics where research at ultra-high Reynolds numbers would be of immense value. Their first example is the hazard to lighter aircraft encountering strong wing-tip vortices 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 which are smaller by about two orders of magnitude. It is thought that this mismatch is responsible for the observed discrepancy between 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 only be understood by controlled studies at ultra-high Reynolds numbers. Helium flows offer tremendous opportunities here.

3.3 Basic turbulence problems at high Reynolds numbers

We now turn to the need for ultra-high Reynolds numbers in basic research. Vortex dynamics and breakdown at high Reynolds numbers is an important issue. A prime candidate is fluid turbulence—which is intrinsically a high-Reynolds-number phenomenon. We assume that there is no need to stress here the importance of understanding and predicting turbulent flows, or the value of basic research in the subject. We know a lot about turbulence (e.g., Ref. [8] and the many hundreds of papers flooding journal pages year after year) and yet, little of that knowledge is impeccable. The theory is very hard for good reasons, and is still a long way from being satisfactory (e.g., Ref. [9]). From an experimental perspective, the so-called "universal aspects" of turbulence can be found (if at all) only at very high Reynolds numbers. One can study high-Reynolds-number turbulence in atmospheric and oceanic flows, but they are not controlled; laboratory experiments fall far short of the range required.

What, specifically, are the types of questions that one supposes will be answered by studying flows at high enough Reynolds numbers? How high is "high enough"? These questions are considered below.

Large-scale phenomena

Historically, one has always encountered surprises when the Reynolds number boundary has been pushed behind by one or two orders of magnitude. The drag crisis for the sphere (e.g., see, Ref. [10]), Roshko's [11] work on the drag coefficient for the circular cylinder, the more recent measurements [12] for the same flow, Kistler and Vrebalovich's [13] data in grid turbulence, measurements of Grant *et al.* [14] in the ocean, Saddoughi & Veeravalli's [15] experiments in the NASA AMES wind-tunnel are some examples worth citing. The Nusselt number measurements of Libchaber and colleagues (see, for example, Ref. [16]) have revealed unexpected features. The recent mean velocity measurements in pipe flow at very high Reynolds numbers [17] possess elements that were previously unexpected. In all these instances, new elements of the large scale behavior have come to surface; even if some findings confirmed what one previously suspected, their contributions cannot be exaggerated.

It is somewhat mind-boggling to observe that one does not yet know the asymptotic value of the drag coefficient of a smooth sphere. It is equally difficult to accept our ignorance of why the recent experiments in helium convection yield a Nusselt-Rayleigh number power-law relation with an exponent of $\frac{2}{7}$ ([16], [18]) while a plausible theory yields $\frac{1}{3}$ ([19]-[21]). What is the effect of the aspect ratio of the apparatus on the observed power-law, and what is the asymptotically correct form for large aspect ratio? 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 very high Reynolds numbers? Can one be certain that the large scale completely sets the average value of the energy dissipation rate? How much does the large-scale motion depend on initial conditions?

Instead of listing more such questions, we wish to emphasize that a sound theory of turbulence would not be possible without putting these and other basic issues on firm foundation: one well-executed experiment at very high Reynolds numbers is superior to a host of others at low Reynolds numbers.

Small-scale turbulence

Let us now shift emphasis to the scaling properties of turbulence in inertial and dissipative ranges. This is an active area of research, propelled not the least by the extraordinary success that has occurred in critical phenomena over the recent two or so decades (e.g., Ref. [22]); this success is in no small measure due to the concurrent progress in theoretical and experimental work. A reasonable goal for small-scale turbulence is to reach a comparable state of certainty with respect to scaling. Some typical problems are mentioned below.

As is well known, for more than fifty years, Kolmogorov's [23] ideas have ruled the horizons of research in turbulence physics (see, e.g., Ref. [24]), and yet we are unclear about their status. Experiments have consistently revealed deviations from Kolmogorov's theory (e.g., Ref. [25]), and these deviations are attributed to the intermittency of small scales. The role of intermittency is not fully understood. The finiteness of the Reynolds number, the presence of shear, inhomogeneity and anisotropy of turbulence render the observed departures from Kolmogorov's phenomenology susceptible to varied interpretations [26]. The kinematic and dynamic effects of the sweep of small scales by the large scale are not understood (e.g., Ref. [27]). The much simpler problem of passive scalars mixed by turbulence consists of many ill-understood aspects as well; for example, the fractal character of the isotherms [28] and the effect of shear on it; the asymptotic shape of the probability density functions of temperature increments and derivatives ([29],[30]); the anomaly or otherwise of scaling exponents [31]; the limitations of Kolmogorov's [32] refined similarity hypothesis, and so forth.

To improve the state of long-standing uncertainty, first and foremost, one needs solid experimental data. As already noted, the Navier-Stokes based theory in fluid turbulence is extremely hard, and good experiments are needed to anchor the theory. However, for experiments to be taken seriously 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. 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 [33], the number of effectively independent layers in wall-bounded flows [34], plausible corrections for finite Reynolds number effects [35], the weak Reynolds-number dependence of the volume occupied by the dissipation field and of the fine-scale vortex structures [36], and so forth. One may state a broad guiding principle in turbulence, which one may call the *logarithmic principle*:

The largeness of the Reynolds number is to be measured by its logarithm.

Before we address the question of how high the Reynolds number should be for unambiguous scaling to be observed, there are further questions to be answered. Is the scaling range a unique function of the Reynolds number? Is there a unique inertial scaling range (i.e., what quantity may be held as the standard bearer for deciding this range)? The answer to the first question is that the *scaling range depends, besides the Reynolds number, on the nature and strength of forcing.* If the forcing is strong and occurs at several scales (in a sense that needs to be—and can be—quantified), the scaling region shrinks because it gets encroached by the complexity of forcing at the upper cut-off scale. If the forcing does not occur entirely at the large scale but over a wide range, again, the scaling region shrinks significantly. When we discuss the extent of scaling region below, we are not considering flows that are too close to solid boundaries, or driven by extremely large shear.

It is equally hard to be precise about the answer to the second question above. One expects that the behavior of the third-order structure function, for which the theory is best-developed [23], would provide the needed guidance. Unfortunately, this is not so straightforward. The status of the third-order structure function in inhomogeneous and anisotropic flows is uncertain [25], and its experimental verification is plagued by the application of Taylor's hypothesis in dubious circumstances; it is beginning to be understood that odd-order structure functions are notoriously sensitive to Taylor's hypothesis [37]. Even so, one has a rough idea from measurements at different Reynolds numbers in flows with modest shear, from which one may make the following empirical statement:

For flows where the forcing is 'not unduly strong nor distributed over many scales', the number of decades of inertial scaling varies with the Reynolds number roughly as

$$decades = log_{10} R_\lambda - 1.75, \;\; R_\lambda \geq 200,$$

where R_λ is the microscale Reynolds number based on the root-mean-square velocity fluctuation and the Taylor microscale (see, e.g., Ref. [38]). This suggests that one need an R_λ of the order of 50,000 to obtain three decades of scaling. Translating the R_λ to bulk Reynolds number is not unique but, roughly, the equivalent Re is on the order 3×10^8.

4 Opportunities and uncertainties with helium

4.1 Arguments in favor of helium

We have so far argued that there is a true 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 tunnels.

Even those that can be met in principle by existing facilities cannot always be explored in them because of their meagre availability and enormous operating expenses. In particular, it is nearly impossible to obtain the services of large test facilities for fundamental research in turbulence. For example, the NTF at NASA Langley is not meant for high turn-around and its use is heavily committed. As for high-Rayleigh-number research, no suitable facilities are in existence. Alternatives are clearly needed.

This granted, one may question whether helium offers the best alternative: for instance, it has been argued [2] that compressed air at very high pressures is a desirable route to take. Helium I at 2.5 K and 1 atmosphere, the critical gas at a temperature of 5.4 K and 2.9 atmospheres, and compressed air at room temperature and about 200 atmospheres all possess roughly the same kinematic viscosities. Thus, to obtain the same 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 meter diameter and a flow velocity of about 50 ms^{-1}. (Thus, issues such as allowable surface roughness and the resolution required of the instrumentation are of equal import in both cases.) The issues that render one of them more or less suitable are the dynamic pressure (which directly determines the forces on the model), the flexibility of use, possibilities for further development, sophistication of available instrumentation, and so forth. For useful comparisons to be made, reliable cost estimates (these run into several tens of millions of dollars) and power requirements (these run in the range of megawatts) should be made to the same degree of detail in all the cases. We have not made such detailed studies (nor has anyone else).

Without the benefit of such studies, we shall have to be content with making some general remarks in favor of helium. First, the forces on the model are correspondingly smaller for helium. In Fig. 5, we show the ratio of the dynamic head of compressed air at 300 K to that of liquid helium at two temperatures, as functions of the air pressure, for a fixed Reynolds number. It is seen that this ratio is appreciably larger than unity even for air pressures of a few hundred atmospheres. Second, helium is unsurpassed as a working fluid if the interest is in high-Rayleigh-number convection, or in flows combining forced and free convection. Third, Donnelly [1] has made the case that, by using helium at different points in the phase diagram, one can simultaneously match more than one non-dimensional parameter between the model and the prototype—for instance Reynolds and Froude numbers. We know of no other fluid with such versatile properties. Fourth, one could ultimately use the interesting properties of helium II for further increasing the Reynolds number and exploring turbulence properties [1]; although, as already noted, much more basic work is required before this view can be advanced with confidence [39], it is clear that serious experience with helium I will be an invaluable precursor. Thus, helium work

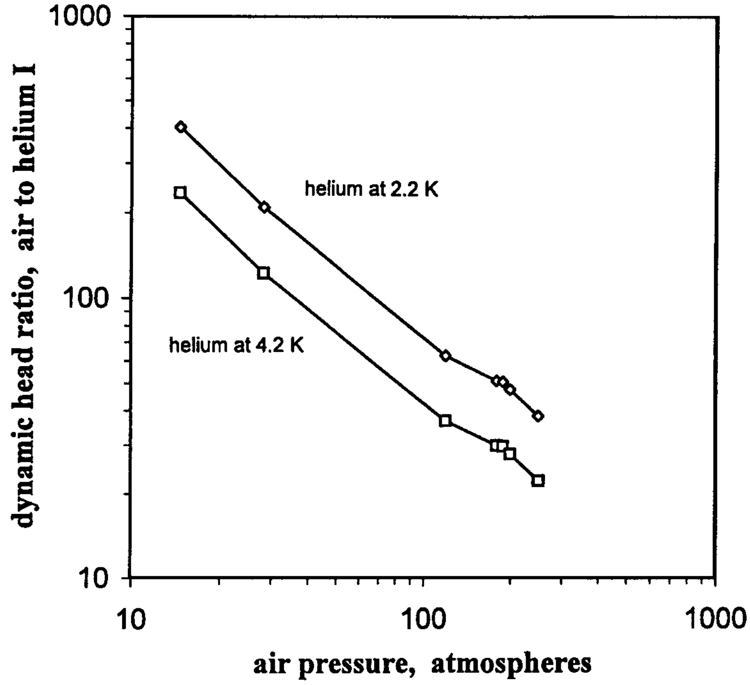

FIGURE 5. The ratio of the dynamic head in compressed air flow at 300 K to that in helium I at 2.2 K and 4.2 K, as a function of the air pressure in atmospheres.

is not a dead-end chapter. Fifth, the array of instrumentation available at low temperatures is enormous because of the superconducting technology (see, for example, section 4.3 of Ref. [40]), which multiplies the options for measuring classical flow properties.

In the following section, we discuss these issues in more detail for a specific facility proposed for basic research at ultra-high Rayleigh and Reynolds numbers.

4.2 The BNL experiment

A proposal has been made [40] to build a large convection cell (10 m height) at BNL so use could be made of the high-capacity refrigeration plant available there. It is important to realize that this opportunity would not exist without the large refrigeration facility built originally for fundamental experiments in high energy physics.

The convection cell is a large cryostat designed with many uses in mind (see Fig. 6, taken from Ref. [40]). It has been estimated that a Rayleigh number of the order of 10^{19} could be attained using critical gas at a density of about 70 kg m^{-3}. This Rayleigh number would be unprecedented

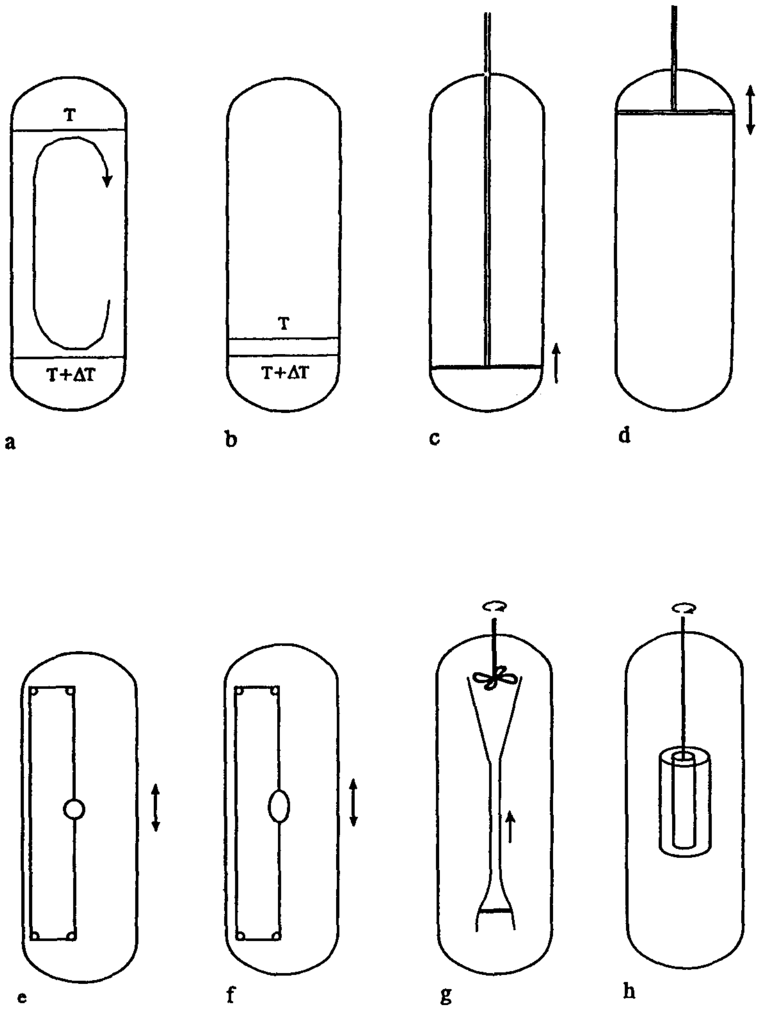

FIGURE 6. The BNL cryostat and its potential uses: (a) ultra-high-Rayleigh number convection, (b) convection with variable aspect ratio, (c) towed grid, (d) oscillating grid, (e) towed sphere, (f) towed ellipsoid, (g) a tunnel insert, and (h) a Taylor-Couette insert. From [40].

and would answer a host of questions mentioned earlier. Because its aspect ratio could be varied at will (with a corresponding sacrifice of the largeness of the Rayleigh number), one could study the effect of aspect ratio and the variation in the Nusselt-Rayleigh number relation. One could also tow or oscillate a grid, thus creating a homogeneous and nearly isotropic turbulence field at very high Reynolds numbers. The grid experiments were deemed especially valuable for basic scaling studies in turbulence because there would be no complicating effects of shear, buoyancy or other non-uniformities due to broadband forcing—as is common in other turbulent flows. It was thus thought that the grid experiments would provide baseline data suitable for comparison with those from more complex flows. A third experiment could be to tow a relatively large sphere at a Reynolds number of the order of 5×10^8; more general shapes such as ellipsoids could be towed as well. Fourth, a huge Taylor-Couette apparatus could be housed in the cryostat, yielding a Reynolds number larger than 10^9. Finally, the cryostat could also be used as a helium tunnel by using a proper insert, yielding a Reynolds number of the order 5×10^8. Given the multi-purpose nature of the cryostat, the facility was conceived for use by a broad community of fluid dynamicists interested in ultra-high Reynolds and Rayleigh number research.

4.3 Instrumentation

A fairly detailed discussion of instrumentation can be found in Refs. [1], [40], and other contributions at the meeting, for example, by Castaing, Lipa, Murakami, Swanson, Tabeling, Tong, and Wybourne. Here, we shall be quite brief.

In the flows just mentioned, the mean characteristics such as the Nusselt number and skin friction, requiring only average temperature and pressure measurements are quite feasible: the instrumentation needed is already available and has been used successfully [16], [41]. The aerodynamic moments such as drag, lift and moments can be measured professionally (for a summary, see papers by Goodyer, Lawing, Brichter in [1], and that by Kilgore in this book).

However, fluctuating measurements are not so easy to make with needed resolution. At high Reynolds numbers, the smallest scales in turbulence will be small and oscillate rapidly in time. While the relatively large size of the proposed apparatus alleviates this problem to a considerable degree (since all length and time scales would be scaled up correspondingly), the problem still needs serious attention. For two of the experiments mentioned above and a high-Reynolds-number pipe flow (which requires a different experimental set-up from the cryostat), Table 2 lists estimates of the expected length and time scales. Clearly, these measurements require some upgrading of instrumentation capability.

Among the fluctuating quantities, pointwise temperature measurements have already been made by fine bolometers (e.g., Ref. [16]), although their response has to improve significantly [42]. This improvement seems to be within reach (see other papers in this volume). Single-component velocity measurements with superconducting hotwire probes have been made by Castaing [43] and Tabeling *et al.* [44], although none has been attempted with a cross-wire. Even for single-wire probes, there are some unresolved issues relating to probe response ([42], [45]) but, on the whole, single-point

flow	R_λ	$\eta, \mu m$	f_η, Hz	comments
convection	30,000	3	10^7	inertial range well resolved, but not dissipation range
	3,000	100	10^6	dissipation scales are well-resolved, not the far-dissipation range
grid	4,000	$5-20$	$10^5 - 5 \times 10^5$	can resolve inertial to dissipation ranges
	600	$85-350$	$6,000-$ 30,000	can resolve dissipation to far dissipation ranges
pipe	3,000	2	10^7	comparable to Princeton pipe [17]

TABLE 2. Scales and frequencies in a few proposed experiments. η is the Kolmogorov scale and f_η is the corresponding frequency.

single-component velocity measurements in helium flows is quite feasible.

An important aspect of research in fluid dynamics is the ability to visualize flows. This is a nontrivial issue in helium because of its low density. However, hollow glass particles have been used to visualize Taylor-Couette flow [46] and Hydrogen-Deuterium combination particles [47] have been used for seeding turbulent jets. While these techniques appear highly promising, significant development work will be needed before they can be used routinely.

Once successful seeding is realized, classical optical measurements such as laser Doppler velocimetry become possible (see [1] and other articles in this volume). It should also be possible to make Particle Image Velocimeter (PIV) measurements, but the latter have not yet been attempted. It is clear that there are several challenges to be faced given the special nature of helium flow facilities.

4.4 Limitation of helium as a test fluid

In Ref. [40], a conceptual flow facility of 1.25 m in cross-section has been shown to be capable of attaining Reynolds numbers of the order 3×10^8. In Ref. [1], several other possibilities have also been mentioned. It is in principle possible to approach full-scale Reynolds numbers with helium. While this satisfies the high Reynolds number requirement, it does not guarantee—as already discussed—that fully satisfactory answers about the overall field can be obtained. For example, one does not know the nature of interaction between vorticity and acoustic fields, or cavitation properties. Some worries have also been expressed that the 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 its extreme sensitivity to temperature changes); these local sources of heat due to energy dissipation may act like 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 awkwardly but succinctly, as "Is helium a Navier-Stokes fluid"? The worry is less that some unknown stress-strain behavior is required to describe helium flows; it is more that there may be several aspects of the *total* flow environment—interaction between sound and vorticity, sound propagation through the medium, its far-field properties and reflection from boundaries (because of differences in acoustic impedance), cavitation effects, and so forth—where faithful similarities between water and helium may break down.

Some of these questions are relevant only to model-testing, but others are relevant to basic research in turbulence as well. We have not pursued these questions to great depth but examined them via back-of-the-envelope calculations. They suggest that no "show-stoppers" of principle exist, at least for basic research.

Let us now turn to aerodynamics. Usually ultra-high Reynolds numbers occur simultaneously with sizeable 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 could also depend to some degree on γ, and so could 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 helium tunnel using critical 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 sizeable helium facility would be significant.

5 Some useful and near-term goals

The questions just discussed need more careful attention and research than we have invested so far. It is clear that there are some purposes for which helium is an excellent option, and some for which it is not. The reason for suggesting the large scale experimental facility at BNL was that it could be used in versatile ways for addressing many of the questions discussed so far. As we have seen, however, there are lingering uncertainties and justified worries. Therefore, it is thought that, even before embarking on the BNL experiment, smaller scale experiments should be undertaken with the following objectives:

a. 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;

b. gain experience on those aspects of flow physics that are the same (or different) in helium and air, as well as helium and water. A typical issue would be the transmission of pressure waves generated by an oscillating body in still helium;

c. build a small-scale flow facility which looks like a traditional water or wind tunnel and mount a small object such as a sphere, using superconducting technology, and demonstrate the proof-of-concept by obtaining drag coefficients at a few Reynolds numbers above and below the 'critical' value;

d. make a detailed design of a helium tunnel and tow-tank and of cost estimates;

e. identify and nurture a wide user community for the BNL facility once constructed.

Such efforts should begin in short order lest the convergence of interests that has recently occurred on this problem should disappear.

6 Concluding remarks

This article has strived to provide some perspective on the use of helium as a test fluid for research and applications in classical fluids. Our view is that helium offers tremendous opportunities and advantages which should not be buried under the cloud of uncertainties. Even well-known technologies, when applied to a different domain, pose unforeseen problems; with helium, this needs no stressing. Yet, 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, technology of large-scale refrigeration plants, and so forth. One should not lose sight of the uniqueness of this opportunity. Even if, in the end, one may not attain full-scale Reynolds numbers suitable for navy testing, it would appear that the uniqueness of data that can be acquired by this means would amply justify the effort—on both fundamental and applied fronts.

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