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Cryogenic turbulence test facilities at CEA/SBT

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Abstract. Recently, CEA Grenoble SBT has designed, built and tested three liquid helium facilities dedicated to turbulence studies. All these experiments can operate either in HeI or HeII within the same campaign. The three facilities utilize moving parts inside liquid helium. The SHREK experiment is a von Kármán swirling flow between 0.72 m diameter counterrotating disks equipped with blades. The HeJet facility is used to produce a liquid helium free jet inside a 0.200 m I.D., 0.47 m length stainless steel cylindrical testing chamber. The OGRES experiment consists of an optical cryostat equipped with a particle injection device and an oscillating grid. We detail specific techniques employed to accommodate these stringent specifications. Solutions for operating these facilities without bubbles nor boiling/cavitation are described. Control parameters as well as Reynolds number and temperature ranges are given.

1. Introduction

Turbulence is ubiquitous in nature and has been studied intensively for more than one century. Nevertheless, a complete understanding is still lacking. A common number to describe turbulence in isothermal flows is the Reynolds number built with typical length and velocity scales and the fluid

kinematic viscosity ($Re = \frac{UL}{\nu}$). For natural convection, the Rayleigh number (Ra) is the main

governing parameter. The Ra can be expressed as follow:

$$Ra = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} Pr g \Delta T L^3 \frac{1}{\nu^2}$$

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with ρ, T, Pr being the density, the temperature and the Prandtl number (often of order unity) respectively, g the gravitational acceleration, ΔT the temperature difference over the height altitude L , and ν the kinematic viscosity.

Most turbulence theories rely on the limit of infinite Re . On the other hand, numerical computations can only solve problems involving low Re since the mesh has to grow as $Re^{9/4}$ for a 3D flow. Last but not least, turbulence experiments able to reproduce classical atmospheric events on scaled down mock up are difficult as relevant values of Re and/or Ra cannot be reached using standard fluids in a reduced size apparatus (e.g. transition of heat transfer coefficient law to an asymptotic regime at high Ra is predicted but the threshold value at which this transition occurs is still a debate [1]).

One way to reach high Re or high Ra at the laboratory scale is to use a fluid with low viscosity. The best candidate is liquid helium with its very low kinematic viscosity (roughly two decades lower than classical fluid). Figures 1a and 1b show the helium kinematic viscosity and illustrate the possibilities offered by helium as a working fluid.

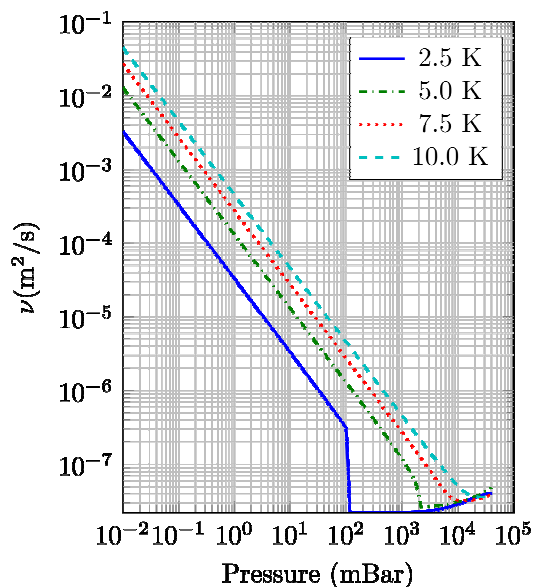


Figure 1a. Helium kinematic viscosity.

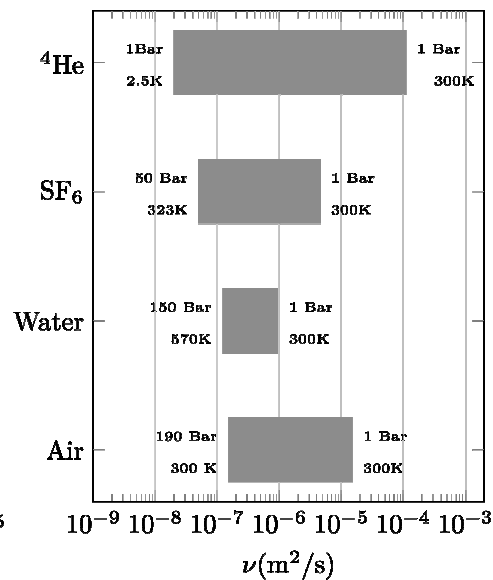


Figure 1b. Kinematic viscosity of the most used fluid for turbulence studies.

Furthermore, below 2.2 K helium exhibits a phase transition towards HeII where superfluid turbulence occurs.

Due to the cryogenics constraints and lack of instrumentation available at this temperature level, helium turbulence experiments remain rare. Nevertheless, results obtained so far in the few available experiments are quite impressive; the highest Ra [2] and the highest Re [3] ever obtained at laboratory scale. Concerning turbulence in closed flow, the von Kármán flow allows probably the highest Re and results obtained in HeI [4],[5] are among the currently highest ever reached. In addition, Maurer and Tabeling [6] showed that the velocity spectra in HeII can be similar to those in classical fluids. This result was recently confirmed in a quasi homogeneous and isotropic turbulence experiment [7].

2. The helium cryogenic facilities dedicated to turbulence studies at CEA-SBT

Following and extending the seminal work of Maurer and Tabeling [6], CEA-SBT experiments intend to study isothermal turbulence both in HeI and in HeII. Furthermore, taking benefit of the very large available cooling power [8], high Re can be easily reached in these facilities. One of the remaining

issues of cryogenic turbulence study is the available instrumentation. To solve this key point, a large French lab collaboration was initiated a decade ago, and significant results have been already obtained with high resolution homemade sensors [9],[10]. In the meantime, seeding and visualization in HeII made tremendous progress [11],[12].

Two facilities namely HeJet [13] for **Helium Jet** and SHREK [14] for **Superfluid at High Re** numbers in a von Kármán flow have been built at CEA-SBT and were recently recognized as major turbulence infrastructures and integrated to EuHit European program (www.euhit.org). A more recent apparatus called OGRES for **Oscillating Grid Experiment in Superfluid** has started operation for one year. These three experiments are presented hereafter.

2.1. The OGRES experiment

The flow generated by an oscillating grid has no mean velocity and is suitable for visualization measurements, as particles remain a long time inside the field of view, the only limitation being the settling time due to gravity. Depending on the particles used (size and density), flow turbulence or preferential concentration can be studied. Small isodense particles can be considered as tracers and tracking them allows turbulent flow to be studied. On the other hand, heavy large particles (as compared to the Kolmogorov scale) can be considered as pollutants, and their dispersion or preferential concentration sites need to be studied. OGRES allows study of both cases, also with superfluid helium. To build this experiment we faced different challenges. The key points were:

- the use of moving parts at low temperature,
- the ability to run the experiment either with subcooled HeI or saturated HeII
- the damping of vibrations inside the cryostat and on the optical devices
- the seeding (in particular with isodense particles),
- the lightening,
- the visualization of particles together with radiation shielding.

Schematics and photos of the facility are shown in figure 2a and figure 2b. The vertical oscillating movement is obtained thanks to a motor driving the grid via a crank and connecting rod system. To avoid rotating feedthrough, the motor is immersed inside the cryostat at the top level where ambient temperature is maintained. As helium gas pressure at this level can vary from a few mbar in case of superfluid to atmospheric pressure during HeI measurements, a motor able to work under vacuum was chosen. The stroke of the grid can be adjusted to the desired value by changing manually the eccentricity on the handle and link system. Connection to low temperature level is realized through an epoxy rod with a stainless steel rod screwed at its end. Three bearings positioned vertically ensured the sliding fit of the low part of the shaft which has been machined accordingly. These “home made” cryogenic ball bearings have a short angular rotation, and no wear signature was found so far. The grid oscillates inside a transparent square cross section box with open top and bottom. To prevent vibrations, a two stage damper using a series of weld-on metallic bellows is used, and the mechanical connections of different parts are connected through silent blocks to the ground or to the wall.

Two cylindrical concentric double-wall glass vacuum tanks allow direct visualization. The outer tank contains liquid nitrogen while the inner tank is supplied with liquid helium. To avoid visualization through bubbles of the boiling nitrogen, its liquid level is kept lower than the visualization area during the measurements. To minimize radiation heat load, there is an aluminum shield with its lower part immersed inside liquid nitrogen. Holes are made at the level of the visualization area. The liquid level is measured optically, and the bath temperature is measured through thermometers located at different liquid depths to quantify the temperature gradient in subcooled HeI.

Measurements are mainly based on backlit shadowgraphy. The lighting is a simple LED, and images are acquired via a high-speed camera equipped with microscope lenses. Hollow glass microspheres (with density slightly higher than liquid helium) are used to seed the flow. With this

equipment, we were able to track individual particles of $70\ \mu\text{m}$ in a $30\times 20\ \text{mm}$ field of view using a frame rate of 3000 images/second.

The measurements are performed in HeI and HeII. In HeII, the liquid is isothermal, and no bubble can appear due to the high conductivity of the fluid. On the contrary, HeI has low thermal conductivity, and boiling is present in the saturated bath.

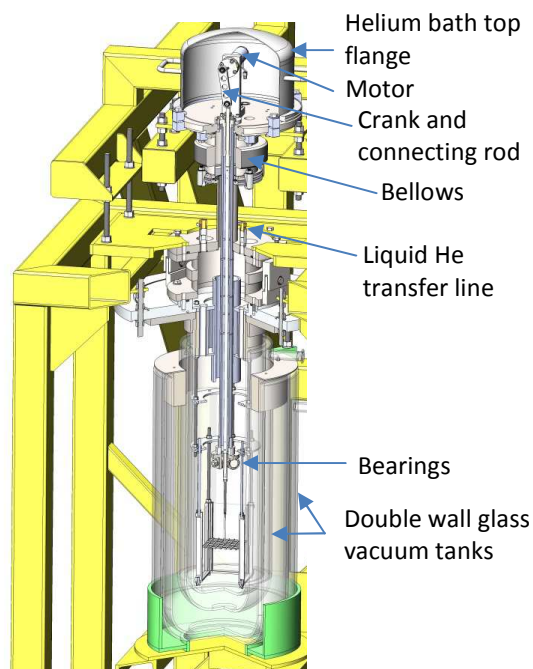


Figure 2a. Drawing of the OGRES facility.

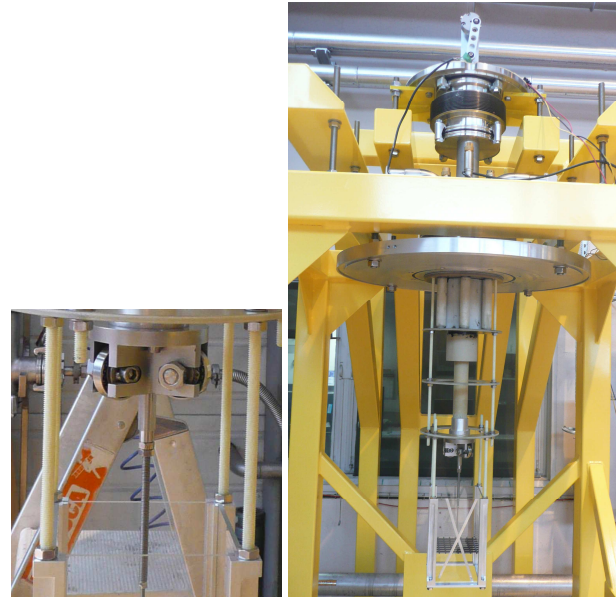


Figure 2b. From left to right: detail of the bearing location and photo of the whole apparatus.

To avoid this presence of bubbles in the field of view, we use the following procedure. After filling with liquid helium, the bath is cooled down to $2.4\ \text{K}$ by pumping, with the liquid level being kept well above the top of the transparent box. Then, helium gas at atmospheric pressure is reintroduced above the liquid interface enabling pressurization and stratification. The time for measurements is then limited by the slow temperature rise; typically half an hour at maximum grid speed is allowed before temperature reaches the saturated line, again generating bubbles. The range of main parameter covered by this facility is summarized in the following table.

Table 1. Main characteristic of OGRES experiment.

Frequency	up to $6\ \text{Hz}$
Stroke	up to $30\ \text{mm}$
Fluid Temperature	$1.6\text{-}4\ \text{K}$
Estimated grid Re number (HeI)	up to $5 \cdot 10^4$
Estimated dissipative scale (HeI)	$> 20\ \mu\text{m}$

2.2. The HeJet experiment

As already mentioned, the highest Re numbers were probably obtained in the gaseous cryogenic helium free jet at CERN [3]. To reach this performance, the facility uses a significant electrical power as the gas comes directly from the gas cycle of the refrigerator.

In the HeJet experiment (see figure 3 and [13]), a dedicated loop thermalized at liquid helium temperature through a heat exchanger is used allowing large mass flow with low evaporated helium mass flow. This saving of power has some drawbacks, mainly the complexity added by the presence of a cryogenic pump and a heat exchanger. Furthermore, HeJet is dimensioned to work either with subcooled HeI or subcooled HeII with internal pressure up to 4 bars, allowing use of hot wires without any risk of bubbles or film boiling surrounding them (remember that the pressure of helium critical point is 2.2 bars). The use of subcooled HeII imposes severe constraints on connections to ambient temperature (safety valve, pressurizing line, lines for pressure drop measurement across venturi flowmeter) to minimize the heat losses due to critical heat flux. The heat exchanger is a simple coil shaped copper pipe immersed in the surrounding saturated bath. The whole loop is filled with a homemade cold valve connected below the saturated liquid level. The same strategy is applied for safety issues by use of a cold burst disk (with the transfer of helium to the saturated bath in case of failure), instead of a safety valve connected to ambient temperature. Pressure measurements across the venturi flowmeter are achieved through Validyne cryogenic pressure sensors. The only connection to room temperature is a capillary pipe used to pressurize the loop.

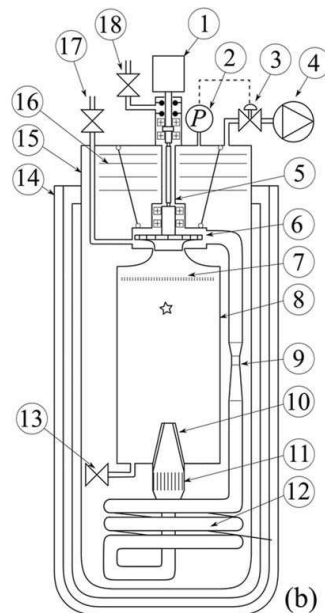


Figure 3.

Cryogenic wind tunnel testing facility (a) before being inserted in the cryostat and (b) schematic drawing (not to scale). 1: dc motor, 2: pressure sensor, 3: throttle valve, 4: cooling bath pumping unit, 5: pump shaft assembly, 6: impeller, 7: grid, 8: testing chamber, 9: flowmeter, 10: nozzle, 11: honeycomb, 12: heat exchanger, 13: filling valve, 14: liquid nitrogen cryostat, 15: liquid helium outer bath cryostat, 16: thermal screens and truss structure, 17: wind tunnel pressurization tube, and 18: rotating feedthrough pressurization and purge tube. The star represents the position of a local probe inside the testing chamber.

The motor driving the centrifugal pump is located at room temperature and atmospheric pressure, and a dedicated 60 cm long stainless steel pump shaft assembly has been installed to assure a leak proof and pressure resistant connection with the impeller of the pump. The upper portion of the system is at ambient temperature and houses a homemade rotating feedthrough sealing made of two x-shaped 10 mm spaced sealing O-rings squeezed on a stainless steel upper shaft rotating on lubricated ball bearings. The lower part of the assembly (at cold temperature) is fitted with the shaft supporting the impeller and rotating on two non lubricated ceramic ball bearings. Particular efforts have been devoted to reduce the additional heat load towards the wind tunnel circuit due to the He II critical heat flux inside the pump shaft line. In the HeI-HeII transition zone, a 65 mm long stainless steel sleeve is installed between ceramic ball bearings to reduce the radial gap.

The ranges of the main parameters covered by this facility are summarized in the following table.

Table 2. Main characteristic of HeJet experiment.

Jet nozzle diameter	5-8 mm
Length of the free jet available for measurements	0-280 mm
Fluid Temperature	1.6-4 K
Re number (based on nozzle diameter)	up to $4 \cdot 10^6$
Estimated dissipative scale (HeI)	$\approx 10 \mu\text{m}$

Knowing the main characteristics of turbulence in free jets, this facility was used to calibrate hot wires both in HeI and HeII [10].

2.3. The SHREK experiment

The SHREK experiment has the same geometry (but with a larger scale) as in the water von Kármán facility located at Saclay [15]. It consists of a cylinder of radius $R=0.39$ m and height $H=1.2$ m (see figure 4) in which the fluid is mechanically stirred by a pair of coaxial impellers rotating in opposite directions. The impellers are disks of radius $0.925R$ fitted with 8 radial aluminum blades of height $0.2R$ and curvature radius $0.4625R$. The disks inner surfaces are $1.8R$ apart setting the axial distance between impellers from blades to blades to $1.4R$. The rotation rate of each impeller can be varied independently of the other. Unlike previous work of Maurer and Tabeling [6], the motors were located at room temperature to allow the use of commercially available motors and maximize the space available at low temperature.

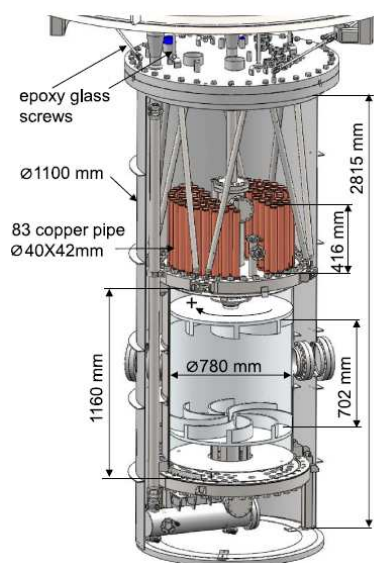


Figure 4. Schematic view of the SHREK experimental setup and the impellers blade profile. The arrow on the shaft indicates the (+) impeller rotation direction.

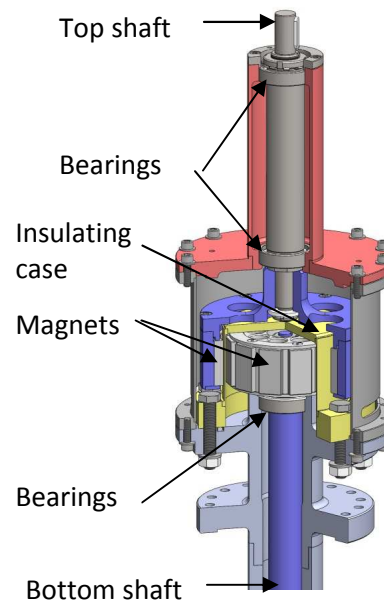


Figure 5. Drawing of the homemade magnetic rotary feedthrough.

As in the HeJet experiment, the SHREK facility is designed to work either with subcooled HeI or subcooled HeII (with pressure up to 4 bars), and the whole cylinder is immersed in a saturated bath. Since the shaft crosses atmospheric pressure, vacuum, saturated liquid helium and pressurized liquid helium, different feedthroughs are needed. We used a standard ferrofluidic rotary feedthrough between atmospheric pressure and vacuum.

Due to the size of the experiment, the thermal contraction of the shaft from room temperature to liquid helium induces a displacement incompatible with the small gap needed to achieve a reasonable heat loss at the HeII-HeI transition. So the transition between vacuum and low temperature (down to 1.6 K) is achieved by a homemade magnetic rotary feedthrough (see figure 5). This feedthrough is based on the magnetic coupling between two permanent NdFeB magnet assemblies (with alternated north / south poles). This kind of magnetic coupling ensures excellent torque transmission, and it allows to insulate the cold part (possibly filled with superfluid helium) from the vacuum part. The insulating part is made with amagnetic stainless steel and is located in the gap between the two magnetic assemblies.

The following table gives some parameters currently covered.

Table 3. Main characteristic of SHREK experiment.

Turbine diameter	722 mm
Turbine rotation frequency	0-2 Hz
Fluid Temperature	1.6-4 K
Re number (based on the inner diameter of the cell)	up to 10^8
Estimated dissipative scale (HeI)	$> 0.7 \mu\text{m}$

The SHREK experiment has been working satisfactorily for four years for turbulence studies. Some failures were nevertheless observed on large ball bearings, and we needed to replace them after every campaign of several weeks. We are still working on more reliable bearings.

3. Conclusion

The CEA-SBT has operated three HeI-HeII facilities dedicated to turbulence study. Their main technological features include the use of moving parts at low temperature and the possibility to work either in HeII or HeI without the presence of bubbles. It was shown that solutions depend on the application. For visualization a simple saturated bath pressurized on the top after pumping can be sufficient. It also allows a direct connection between the moving parts and the motor located at room temperature but inside the helium cryostat. On the other hand, if the turbulence is investigated by means of heated sensors (e.g. hot wires), it can be necessary to pressurize the vessel above the critical helium point and a double bath system has to be used. With the motor located at room temperature, the shaft is partly surrounded by subcooled superfluid and partly by gaseous helium or vacuum. On a small size apparatus, a simple zone of reduced cross section can be employed to minimize the heat loss due to HeI-HeII transition critical heat flux, whereas on larger experiments a complete tight leak decoupling is necessary and can be provided by use of a rotating magnetic feedthrough.

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