The turbulent superfluid cascade

Stirring a honey pot with a spoon is awkward because the fluid viscosity damps the flow very efficiently. By contrast, in a less viscous fluid such as coffee in a cup, a slight movement of a spoon will generate eddies of different sizes. If the fluid is even less viscous, or if the mechanical stirring is more intense, a hierarchy between eddies of different sizes appears: the flow is turbulent. In 1941, the Russian mathematician Andrei Kolmogorov described this hierarchy of eddies with the image of an energy cascade : mechanical stirring feeds the largest eddies, which transfer their energy to smaller eddies and so on until the viscosity effectively inhibits any further whirling motion and dissipates energy into heat.

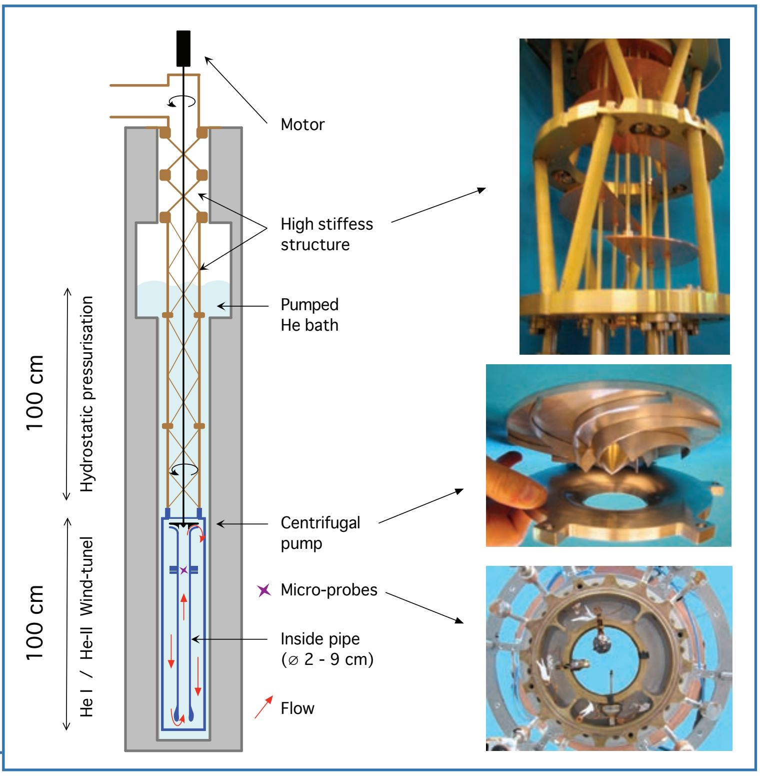

Figure 1: At left: The TOUPIE wind-tunnel. At right: Details of the high-stiffness, low-conductivity mechanical structure (top); Cryogenic propeller specially optimised for liquid helium (middle); Probe holders with miniature Pitot-tube velocity sensors (bottom).

What does this cascade of energy become in a fluid with zero viscosity ? An exotic liquid allows us to address this question experimentally : superfluid helium. Below 2.17 K, liquid helium enters a quantum phase, the "He-II" state. It then acquires the remarkable capability of flowing without experiencing any viscosity. Exploring the turbulent cascade of a superfluid, however, raises two experimental challenges: creating a suitable cryogenic flow and probing the velocity fluctuations in the superfluid.

To answer these questions, the Institut Néel has developed a cryogenic "wind tunnel". We have named this apparatus "TOUPIE" (our acronym for "TOUrne Par l'Intérieur et l'Extérieur", refering to the rotational degrees of freedom in the design of the experiment, and also the French word for a spinning top). It produces a closed, permanent flow of liquid helium along a record path of 2 metres (see Fig. 1) at temperatures from 4 K down to 1.5 K. It can operate with superfluid helium (He-II), and also with "viscous" liquid helium (the "He-I" state, above 2.17 K), thereby allowing direct comparison between the two cascades. The second challenge was to improve significantly the spatial resolution of the best probes for measuring velocity in a superfluid. Among the innovative sensors devised and developed, the one shown in Fig. 2 is a micro-machined silicon cantilever, coupled to an ultra-sensitive superconducting resonator diverted from its original astrophysics destination: the detection of cosmic particles.

The combination of this unique cryogenic wind tunnel with the smallest superfluid probes allowed us to compare the turbulent cascades of a classical fluid with those of a superfluid, with an unprecedented resolution. In particular, we found the first direct evidence that superfluid eddies can cascade from large to small scales in a fashion similar to that of classical eddies. This evidence came from the Kármán-Howarth "4/5 law", the only exact relation in turbulence (named after a factor 4/5 in the equation that relates the amount of energy carried by the turbulent cascade and a dissymmetric statistics of the velocity gradients). Comparing our data with the Kármán-Howarth law, we found that this law remains valid in a superfluid.

The next challenge is to understand how, in the superfluid, a non-viscous dissipation process replaces the effects of viscosity, especially in the limit of relatively low temperatures (~ 1 K). A second version of the TOUPIE wind-tunnel is in preparation to reach this lower temperature range.

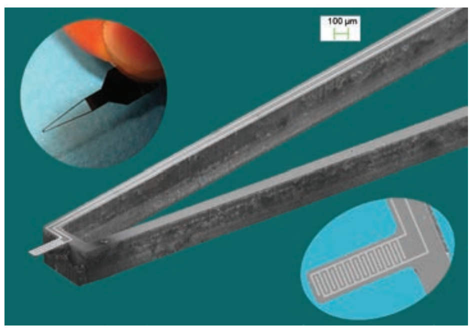

Figure 2: Micro-machined velocity probe based on the deflection of a 1 micron thick, 100 micron wide, silicon cantilever by the moving fluid. Main image shows the V-shaped probe-holder with the cantilever at its tip. The upper insert shows a general top-view onto the probe holder. The bottom insert is a zoomed top-view of the cantilever itself, carrying a circuit which is part of a superconducting resonator whose frequency varies with the cantilever's deflection. Device fabricated at Grenoble's "Plateforme Technologique Amont".

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FURTHER READING

ENERGY CASCADE AND THE FOUR-FIFTHS LAW IN SUPERFLUID TURBULENCE
J. Salort, B. Chabaud, E. Leveque, and P.-E Roche, Europhys. Lett. 97, 34006 (2012).