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Literature Review: Using Liquid Nitrogen to Investigate High-Reynold's Flows.

The Reynold's number is a dimensionless quantity that depends on the characteristic velocity, characteristic length, and viscosity of the flow. For room temperature experiments, air and water are commonly used. However, it is difficult to reach a high Reynold's number ($>10^6$) because either the experiment itself must be large, or the velocity of the flow must be high, or both. The only other way to achieve a high Reynold's number is by reducing the viscosity of the fluid. One resolution to achieving a high-Reynold's flow without the need for large or high-energy experiments is by using cryogenic test fluids.

The first concept of using cryogenics in the study of high-Reynold's flows appeared in the 1970's. A paper from the NASA Langley Research Center in 1973 outlined a strong theoretical basis for the benefits of cooling test gas to cryogenic temperatures that promised 'a large increase in Reynolds number with no increase in dynamic pressure while reducing the tunnel drive-power requirements' (Goodyer. M.J, Kilgore. R.A, 1973). This was later followed by a conference paper in 1982 for the International Cryogenic Engineering Conference which reported the construction of a cryogenic wind tunnel at the Langley Research Center that worked by 'cooling the test gas to cryogenic temperatures by spraying liquid nitrogen into the tunnel circuit' (Kilgore. R.A, 1982).

Since then there has been a growing interest in the use of cryogenic test fluids to explore high-Reynolds flows. One particular experiment described at CERN in a conference paper from 2002 describes the use of cryogenic helium gas cooled to 5K to reach a Reynolds number up to 10^7. This allowed the investigation of turbulence close to the "ultimate regime".

Another appearance of cryogenic helium, this time in liquid form, comes from a paper published in 2002 in the Journal of Fluid Mechanics. The paper states that 'liquid helium at 4.2K has a viscosity that is about 40 times smaller than that of water at room temperature, and about 600 times smaller than that of air at atmospheric pressure'. This allows turbulence to be studied in small scale experiments which would usually require much larger facilities. The paper then says that one of the difficulties with using liquid helium to study turbulence is making measurements of the flow due to the small scale of the vorticity. Also, the refrigeration capabilities are demanding. Liquid nitrogen is then suggested as a good replacement for all but the most specialized cases since its refrigeration and viscosity are an intermediary between air/water and liquid helium. Liquid nitrogen also has the advantage of being easier to find appropriate seeding particles (White. C.M, Karpetis. N.K, Sreenivasan. R, 2002). Lastly, liquid nitrogen is a renewable resource, unlike helium, giving it a huge advantage other helium as a cheaper alternative for small scale experiments.

This case study reviews a particular piece of literature from 2012 that investigates the possibility of using liquid nitrogen as the test fluid to examine high-Reynold's flows. The paper, named 'Liquid nitrogen in fluid dynamics: Visualisation and velocimetry using frozen particles' (Fonda. E, Sreenivasan. R, Lathop. P, 2012) states that it is common practice to extend the Reynold's number range by replacing the standard use of air or water with 'pressurized air, sulphur hexafluoride, cryogenic nitrogen gas, and liquid and gaseous helium'. Liquid nitrogen has seldom been used however despite having a kinematic viscosity of one fifth that of water at room temperature. The paper then explores the suitability of liquid nitrogen as a test fluid in the context of using Particle Image Velocimetry (PIV) as the measurement technique to examine the flow.

The study highlights the advantages of using liquid nitrogen over helium, such as the uncertainty in the measurements for density, thermal conductivity, and viscosity of the fluids; the uncertainty of each variable is at least a factor of five smaller for the nitrogen than the helium. Also, the liquid nitrogen flows can be better illuminated by more powerful light sources because it has a much higher coefficient of thermal expansion. For PIV in particular, neutrally buoyant tracers are required to ensure the flow is traced as faithfully as possible. The higher density of liquid nitrogen makes finding suitable tracers much easier than for helium. The higher viscosity also means that the turbulence size scales are larger, so bigger tracers can be used. The measurement equipment required then need not be as specialized as for studying turbulence in liquid helium.

One of the issues of previous studies involving liquid nitrogen is the fact that there is no established standard of seeding liquid nitrogen flows, and that attempts to use commercial seeding particles had resulted in clumping because a suitable surfactant had not been found. This problem is what the study attempts to solve by instead injecting various different seeding gases into the liquid nitrogen that freeze at the operating temperature of 77K, therefore creating frozen particles for use as tracers.

The seeding gases tested in the study were various mixtures of nitrogen and hydrocarbons such as methane, propane, and butane, as well as others. The different gas types result in varying densities and refractive indexes of the frozen tracer particles. The aim being to find the best mixture from the selection that produces the smallest neutrally buoyant tracer size while refracting as much light as possible. The estimates for the amount of light the particles scatter was done by using the Mie scattering model.

The experiment setup is relatively simple. The liquid nitrogen sits in a square column inside a cryostat with a gas mixing tube submerged within the nitrogen. The gas mixing tube is connected to a nitrogen gas and seeding gas bottle. At the end of the tube, the PIV equipment, consisting of a 3mW laser and a CCD camera, is setup to record the frozen gas particles for analysis.

The size of the particles was statistically estimated. The laser sheet was approximately 175μm while the particle sizes range from 0.2 to 1μm. The beam is a Gaussian beam. The particle size was estimated by assuming that the most scattered light came from the largest particle size situated within the centre of the laser sheet that would scatter that amount of light according to the Mie scattering model.

The study was successful in meeting its aim of being a “proof of concept” for showing that liquid nitrogen can be a relative cheap alternative to study high-Reynolds flows where the size of the experiment or budget may prohibit the use of other test fluids such as helium.

Further research into refining the technique of using PIV to measure turbulence in liquid nitrogen would be the next logical step. One way to do this would be to develop a standard of seeding liquid nitrogen, perhaps by testing more seeding gases. It was stated in the paper than methane was quite successful as a seeding particle and had a high fidelity, as well as a good refractive index. According to a paper published in Icarus in 2010, ammonia has a refractive index of approximately 1.49 at a temperature of 80K (Romanescu. C, 2010), while also having a density of 0.7491 kg/m3 at room temperature, similar to that of methane which has a density of 0.7057 kg/m3 (Evans.P, 2015). Furthermore, ammonia has a freezing point of 196K. With methane only having a refractive index of 1.32, the properties of ammonia, and the inexpensiveness, make it an excellent replacement for methane as a seeding gas particle.

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