Introduction

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1 What is a fluid?

What is the intuitive feel you have about fluids? Surely they are different from solids. But how ...? Solids have a preferred shape - they may deform under the application of external forces but as long as these external forces are not too high, these solids tend to relax back to their original shape after the forces have been released. But fluids don't have a preferred shape. As our middle-school textbooks mentioned - they take the shape of the container; or if poured on to a flat surface they spread out.

We now need a proper working definition of a fluid. So ... a fluid is a substance that deforms continuously under the application of shear stresses *no matter how small the shear stresses may be.*

Note how the last part of the definition has been italicized. That italicized bit is the key to demarcating between solids and fluids. If the stresses are sufficiently small, a solid will not deform continuously. But a fluid will ... always ... no matter how small the stresses are. Thus, a fluid just cannot support shear stresses.

Now what about normal stresses? Solids can support both tensile and compressive stresses. But fluids can support only compressive stresses.

Notwithstanding the above discussions, it is very important to note that there does not always exist a clear-cut distinction between solids and fluids – there do exist many materials that cannot be categorized strictly as solids or fluids. Examples of such materials are toothpaste, jelly, paints, egg white. Note that a chunk of metal under sufficiently small stresses might deform a little but will relax back to its original shape once the stresses are removed. So it might be said to have perfect memory. That's a characteristic of a solid. In contrast, water or alcohol once deformed does not return to its original shape when the stresses causing the deformation are removed. So water or alcohol has zero memory. That's a characteristic of a fluid. But, materials like toothpaste, jelly, paints, egg white (and many more!) tend to revert back to its original shape (of course, to varying amounts) once the deforming stresses are removed. So these materials may be said to have partial memory. They behave a bit like solids and a bit like fluids. And, they are really, really interesting to study. But here, in this introductory course, we will stick to fluids with zero memory.

It will keep the mathematics relatively simple. *Just hold on to your seats – even this mathematics turns out to be quite involved! But ... always very, very interesting!*

2 Why study fluid mechanics?

Engineers make things. Big, small ...every man-made thing has to be made in the first place. The manufacturing steps involve sophisticated designs and an enormous amount of clever applications of fundamental principles from physics, chemistry, and – nowadays – increasingly, biology[1]. Amongst the principles from physics those involving fluid mechanics often play a vital role in the design of many different engineering systems. For instance, the very principle on which aeroplanes fly is one of the most fascinating applications of fluid mechanics. The propulsion of ships (besides the business of keeping them afloat) also involve fluid mechanics. Heating and ventilation systems, energy generation and storage are also some traditional fields where fluid mechanics (coupled with thermodynamics) finds tremendous applications. Many complex biological systems can be understood based on the principles of fluid mechanics - for instance, flow of blood, swimming of sperms, ascent of sap in trees ... the list is endless. The understanding of such biological systems serves as an inspiration for engineers to design novel systems (biomimetic design) that feature enhanced flexibility and functionality compared to traditional engineered systems.

Challenge: Make a list of things whose manufacturing steps you think do *not* involve fluid mechanics.

3 Continuum hypothesis

Matter (including fluids) is composed of a large number of molecules in constant motion and undergoing collisions with each other. Matter is, therefore, discontinuous or discrete at microscopic scales. It is possible – at least in principle – to study the mechanics of fluid by studying the motion of molecules themselves. This is what is done in kinetic theory[2] or statistical mechanics. Often recourse is taken to computer simulations referred to as molecular dynamics simulations. This approach basically involves solving Newton's second law for each molecule for an agglomeration of molecules. But limitations of computational resources restrict the agglomeration to be not larger than a billion or so molecules (even that requires very good computational facilities). Note that since the Avogadro number is 6.02×10^{23}, even a billion molecules is actually not much!

However, more often than not, we are interested in the gross behaviour of the fluid, i.e. we want to see what the combined molecular motion manifests in, in an average sense. Thus, we can ignore the discreteness due to the presence of molecules at

[1] So you see there is, after all, a proper motivation for the subject “Science of Living Systems"!
[2] You did a bit of kinetic theory at the senior secondary level; jut take a look back at H. C. Verma's book.

the microscopic scale, and think of the fluid (or any other matter) as a continuous distribution called the continuum. The continuum hypothesis tells us this that this abstraction from the real molecular structure to a continuous structure should work all right for most scenarios as long as we are careful about the length scales under consideration. Specifically, we have to keep an eye on the mean free path of molecules. For the continuum hypothesis to be valid, the size of the system must be larger than the mean free path of the molecules. Ordinarily, this is not a problem but if the flow system, for instance, is of the dimensions of 1 nm or so then the discrete molecular structure cannot be replaced by the continuum. Again in the upper altitudes of the atmosphere, where air is very rarefied, the mean free path can be quite large; so there too, we have to take recourse to kinetic theory.