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Fluid Particles: A Review

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Abstract

The concept of fluid particle is fundamental to study the Physics of fluid flow. Three types of fluid particles are currently used: the finite, the infinitesimal and the point particle. The finite particle renders the atomic-molecular structure of matter and is particularly relevant in flow measurements. The infinitesimal and the point concepts are mathematical abstractions used in modeling fluid flow. The subject is reviewed on the basis of well-known fluid flow related textbooks (all in English), comprising authors of different backgrounds and spanning over fifty years of editions.

Keywords: Fluid particles; Fluid kinematics; Fluid dynamics; Fluid flow description

Introduction

The study of kinematics and dynamics of fluid flow is based on the concept of fluid particles. However, the concept doesn't have a simple and unique meaning. A direct quote from Meyer [1] supports this view: "Continuum dynamics – to which this book is restricted – is then defined as the study of a limit in which the number of molecules in a "unit volume" tends to infinity, while the typical time and distance between successive collisions for any individual molecule tend to zero by comparison with "unit time" and "unit length." (But it is not at all implied that a body of fluid consists of the same molecules at all times. The term "particle" has different meanings in continuum mechanics and in kinetic theory, and is partially misleading in both fields.)".

In a relatively recent book on the history of Fluid Mechanics, Tokaty [2] argues that the concept of fluid particle was introduced by Leonhard Euler. According to the author Euler was the first to tackle the fundamental contradiction of using abstract geometrical concepts like "points" and "lines" to describe phenomena occurring with material bodies, which are characterized by features of extension and shape. Tokaty didn't quote Euler but rather summarized his view: "A fluid particle is imagined as an infinitesimal body, small enough to be treated mathematically as a point, but large enough to possess such physical properties as volume, mass, density, inertia, etc". Ahead he enforces it: "From then on, everyone knew that a fluid particle was not a mathematical, but physical point possessing volume, weight, mass, densities, specific heats, etc". From the above it seems that "infinitesimal" in Euler's writings, at least in this case, meant a "very small" body of fluid, that is, finite.

Interestingly, Truesdell [3], whom ranked Euler in the highest position within the science of modern Mechanics, has criticized the above view of fluid particles rather acidly: "to speak of an element of volume in a gas as "a region large enough to contain many molecules but small enough to be used as an element of integration" is not only loose but also needless and bootless".

Three Conceptions of Fluid Particles

Finite fluid particles

The original idea behind the concept of fluid particle is that of a small, however finite, building block for fluids. In a qualitative sense, fluid particles are analogous to other well-known building blocks of matter: atoms regarding chemical elements and molecules regarding chemical substances. However, quite differently from atoms and molecules which are characterized by relatively precise dimensions and geometry, the size and also the shape of fluid particles are not uniquely defined. Additional complications arise from the fact that under flow, such a finite fluid particle would undergo continuous deformation implying in changes in size and shape.

The most common definition of a finite fluid particle is that of a limiting volume of fluid throughout which physical quantities associated with the fluid would be spatially uniform and free from macroscopic fluctuations. On an intuitive basis one might expect the size of this limiting volume to depend on the fluid or flow property being considered and also on the scale of the problem under analysis.

Consider for example the density and viscosity of fluids. It is well established that these physical properties depend on temperature and pressure in very different ways. Consequently the fluid particle volume necessary for a uniform density may differ from that required by viscosity, for the same fluid under given temperature and pressure. Consequently, around some spatial point in a flow field at a given instant, one could have, at least in principle, say, the fluid particle regarding density enclosing the one regarding viscosity. In this regard it should be mentioned that fluid density is, by far, the preferred physical property used to introduce the concept of a limiting finite volume in basic courses on Fluid Mechanics [4,5]. It should be mentioned that this physical limiting process has nothing to do with the concept of limit of functions in Calculus.

Consider now the velocity of water flowing in a pipe with an internal diameter of one inch, as compared to the velocity of the Mexican Gulf Current. For practical purposes, representative fluid particles in each of these cases are likely to have sizes differing by several orders of magnitude.

Furthermore, the fluid particle volume can vary along the flow. For example, consider the pipeline flow of a gas and its density, a pressure sensitive physical property. Since fluid internal friction causes pressure

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drop, the gas expands along the pipeline, and downstream fluid particles' volume (low pressure) should be bigger than upstream ones (high pressure).

Additionally, as quoted from Meyer, fluid particles cannot be treated as strict closed thermodynamic systems. Leaving aside effects related to external heat transfer, natural thermal agitation coupled with viscous thermal dissipation, cause molecules to be continually exchanged between neighboring fluid particles. For this reason, it is likely that one can only speak of a "mean uniformity" in a given position and time in a flow field. Up to a limit, which varies from case to case, the increase of the fluid particle, size adopted lessens the effects of fluctuations upon the property value. Notice that the number of molecules increases with the third power of the size increase, while its surface area available for ingoing and outgoing molecules increases with the second power. Thus a size is eventually reached such that any unbalanced exchange of molecules decreases to a level where the property fluctuations are minimal and can be disregarded. This size is the lower limit for the fluid particle regarding that particular property. There will also exist an upper limit for the size of the fluid particle, beyond which the considered fluid property could also vary spatially, for instance due to changes in the flow cross section. For future reference, we will represent the lower and upper limits of fluid particle sizes, respectively, by the linear dimensions L_q and U_q where the subscript q is representative of a given fluid or flow property. Fluid particle sizes between these extreme values will be represented by M_q. Notice that L_q and U_q hold only for the property q of a given fluid under known conditions.

Infinitesimal fluid particles

The concept of an infinitesimal magnitude is a mathematical abstraction introduced early in the study of Calculus. There, the set of real numbers suffice to convey the idea of limit of a function. The continuity of that set guarantees that a real variable x can take the value $x_0 + dx$ where dx has a differential magnitude, a plain abstraction, only schematically represented via diagrams. Nevertheless, the relation between dx and differentials of functions of x are readily obtained via well-defined mathematical rules.

Thus the concept of infinitesimal fluid particle require us to model the fluid as filling, one might say, mathematically (rather than physically) a delimited region of a Euclidean space of three dimensions. This idealized fluid is called a continuum. Its use corresponds to disregard for the atomic-molecular structure of matter with its plenty of spacing between electrons and nuclei and even more between atoms and molecules.

The adoption of the continuum model allows for the existence of an infinitesimal gradient of the physical or flow property across such fluid particles. This is in contrast with the requirement of uniformity of property values throughout finite fluid particles. Additionally, the shape of infinitesimal fluid particles depends on the type of coordinate system used.

Point fluid particles

The concepts of point fluid particle and infinitesimal fluid particle discussed previously are closely related since both are based on the continuum assumption.

Simply put, at each instant the point fluid particle coincides with a spatial position within the flow field. Mathematically this corresponds to the mapping of point fluid particles onto R^3, the Euclidean three dimension vector space. Fluid flow then corresponds to the motion of a point fluid particle between two such spatial positions. For the typical undergraduate student, the concept of a point fluid particle may sound more abstract than the infinitesimal fluid particle. This is probably related to the simple fact that applications of Calculus are fully based on the concept of infinitesimal volumes and integration of functions to give finite volumes.

However, the use of Calculus to derive conservation laws associated with fluid flow, naturally led to equations in terms of differentials of the various physical quantities involved. Even when no explicit reference is made to infinitesimal fluid particles, the sketch will be there, either on the book, board or slide, strongly suggesting the existence of a differential corpuscle of fluid.

As for the student, the difficult with the concepts of infinitesimal and point fluid particles is a little harder than that with the abstract mathematical concepts of limits and differentials of functions. Since fluids are palpable material things of everyday and since a differential amount is learnt to be as small as one can imagine it, the student is led to a paradox: he can easily picture an infinitesimal or point fluid particle, inside an atom or even inside an electron. As a matter of fact he would be correct in imagining an infinite number of infinitesimal or point fluid particles inside the electron. How could that be possible, once fluid molecules are much bigger than electrons? This is a contradiction similar to that faced by Euler in the eighteen century, related to the description of material phenomena using "points" and "lines" of Euclidean geometry. The classical way-out of this paradox is the utilitarian argument that in the real world, or in practice, an infinitesimal or point fluid particle can be approximated by a very small finite body of fluid, provided it is much larger than the prevailing mean distances between fluid molecules. Of course this strategy must be fully supported by a reasonable matching of theoretically predicted values and measured ones.

Authors on Fluid Particles

In what follows we summarize the viewpoints of well-known authors of fluid flow related textbooks regarding the concept of fluid particle.

Finite fluid particles

In this case, the qualitative and quantitative diversity of sizes attributable to finite fluid particles require focusing authors individually.

According to Yih [6], regarding flow velocity (v), a volume of 1 μm^3 is representative of the minimum size of fluid particles of gases and liquids under ordinary conditions. Using the nomenclature introduced previously, this figure corresponds to L_v=0.001 mm.

By examining the density of air, Campbell [7] proposed to compute the minimum volume of gas particles as $(2\lambda)^3$, where λ is the mean free path of its molecules, corresponding to $L_\rho=2\lambda$.

Streeter and Wylie [8] refer generically to the lower (L_q) and upper (U_q) limits of fluid particle size as ranging from "a few thousand molecules" to "thousands of cubic feet in a large swirl in a river or in an atmospheric gust". For those authors, fluid particle sizes are unequivocally given in proportion to the relevant lengths in the full scale practical problem under analysis.

Tritton [9] argues that the natural choice to analyze the concept of fluid particle size would be the fluid velocity. However to avoid complications related to its vector nature, he used the fluid temperature

(T) instead. The existence of lower (L_T) and upper (U_T) limits are clearly acknowledged, and a mean fluid particle size (M_T) is claimed to be required so as to comply with the continuum hypothesis. According to the author L_T is one order of magnitude larger than the distance between a molecule and its nearest neighbor, while U_T would be on the scale of the flow problem under consideration, that is, "a typical distance over which the macroscopic properties vary appreciably".

For water and air at 15 ºC, Vardy [10] sets the lower limiting volume specifically regarding velocity (v) at "much less than one micron (one micrometer) in diameter" or L_v<<0.1 mm.

Potter and Wiggert [11] gave the limiting volume of fluid particles regarding the density (ρ) of air at STP as "much less" than 1 mm^3, corresponding to L<<1 mm. According to White (2003)[5] and specifically regarding the density (ρ) of gases and liquids at STP, the lower limiting volume of fluid particles is about 10^{-9} mm^3 for both types of fluid, corresponding to L_ρ=0.001 mm.

Fox, Pritchard and McDonald [4] consider the limiting volume of fluid particles regarding the density (ρ) of gases at STP, to be around 10^{-12} m^3 corresponding to L_ρ=0.1 mm.

Infinitesimal fluid particles

Lai, Rubin and Krempl [12] adhered to the concept of infinitesimal material particles: "Thus, in this theory, one speaks of an infinitesimal volume of material, the totality of which forms a "body". One also speaks of a "particle" in a continuum, meaning, in fact, an infinitesimal volume of material." It should be mentioned that amongst the surveyed books, the one by Lai, Rubin and Krempl is unique regarding the explicit and exclusive use of infinitesimal fluid particles.

Point fluid particles

Truesdell [13] is a strict follower of the point continuum approach: "A body is a manifold of particles, denoted by X. These particles are primitive elements of mechanics in the sense that numbers are primitive elements in analysis. Bodies are sets of particles. In continuum mechanics the body manifold is assumed to be smooth, that is, a diffeomorph (*author note: diffeomorphism in today's nomenclature*) of a domain in Euclidean space. Thus, by assumption, the particles X can be set into one-to-one correspondence with triplets of real numbers X_1, X_2, X_3, where the X_α run over a finite set of closed intervals." Some ten years later, in another book, Truesdell [14] would change the nomenclature: "The points X of B were called "particles" until recently, but in order to avoid any possible confusion with physics we shall call them body-points". Most authors of continuum mechanics and also from other fluid flow related areas adopt this point of view, often referred to as a field approach. In continuum mechanics instead of point fluid particles one refers to point material particles for obvious reasons. Other terms are also in current use (e. g., flow particle and material point). Other authors following this approach include Jaunzemis, Yuan, Malvern, Meyer, Fung, Gurtin, Shames and Bowen [1, 15-21].

Finite and point fluid particles

According to Panton [22], "The term fluid particle has at least two meanings in common usage. The first is a point concept. Here we envision a point, which floats along, moving with the local fluid velocity at each place in space at that particular time. A line traced through the flow field by this method is called a particle path. We say that the point that traces the path is a fluid particle, or material point. For some purposes – for instance, to talk about the expansion of the fluid – it is necessary to consider a small chunk of fluid. This second meaning for the term fluid particle is made precise by considering a small material region (MR) and allowing the size of the region to tend to zero. Which of the two meanings is intended is usually obvious from the context. Note that because of molecular diffusion, a fluid particle does not always consist of the same molecules. As a particle moves through the flow it gains and loses molecules because of random molecular motions."

Authors referring to these two concepts of fluid particle include Landau and Lifshitz , Owczarek , Paterson , Massey and Ward-Smith and Mase and Mase [23-27].

Infinitesimal and point fluid particles

Batchelor [28] linked point and infinitesimal fluid particle via the concept of center of mass: "Since material elements of fluid change their shape as they move, we need to identify the selected element in such a way that its linear extension is not involved; one suitable method is to specify the element by the position (a) of its center of mass at some initial instant (t_0), on the understanding that the initial linear dimensions of the element are so small as to guarantee smallness at all relevant subsequent instants in spite of distortions and extensions of the element." In a footnote few pages ahead of the above text the author states plainly: "the word "element" is used here and elsewhere to imply infinitesimal size and (usually) a passage to an appropriate limit".

Authors adhering to the above point of view include Eskinazi , Chorlton and von Mises and Friedrichs [29-31].

Findings

In spite of the relatively small number of books quoted in this review, perhaps a double number was examined in search of some explanation regarding the concept of fluid particles. It should be mentioned that many authors simply start referring to fluid particles without any previous definition of the concept; few discuss it at some length.

A plethora of terms was found in current use to refer to fluid particles in general. In this regard "finite fluid particles" and "point fluid particles" are the commonest. As for infinitesimal fluid particles an important finding was the current use of the term "element" referring to small finite portions of fluids. This brings in unnecessary ambiguity to the text for the term "element" is currently used in Calculus with the meaning, however abstract, of an infinitesimal magnitude. Even the adjective "infinitesimal" or terms like "infinitely small" do not always have the Calculus connotation. Apparently this fact led Batchelor [28], already mentioned, to call attention in a foot note for the meaning of the term "element" in his book. In this respect colloquial terms frequently used (chunk, blob, bit, piece of fluid) have the great advantage of leaving no doubt as for what they represent: a small finite portion of fluid. Also, many texts refer to small portions of fluids, but seldom is a scale of size mentioned by authors.

There is a reasonable lack of uniformity between authors regarding not only the size of finite fluid particles but also on the choice of the best representative fluid property to specify it. By far fluid density is the preferred one. Fluid velocity and temperature are also used.

Conclusions and Suggestions

Since the finite, the infinitesimal and the point concepts of fluid particle are currently used in fluid flow related texts, textbooks on basic fluid mechanics should introduce students early to the three concepts which, by the way, do not conflict with each other. This could be done easily on two or three pages of a standard book format.

The concept of finite fluid particles renders the atomic-molecular structure of matter and is by far the easiest one to be grasped by students, since the level of abstraction required is minimum. It should be the first one to be presented. Motivation for introducing this concept is mainly related to experimentation with fluids and particularly with local flow measurement instruments. A detailed account should be made as for the link between finite fluid particles size, the type of fluid property considered and the scale of the problem under analysis.

The concept of infinitesimal fluid particles should be introduced as a simple mathematical consequence of applying a well-established mathematical theory, namely Calculus, to continuous fields, i.e., a set of spatial points called point fluid particles, where fluid physical and flow properties are defined. In this regard one should remember that the concept of continuous function existed long before Calculus was invented.

Nomenclature

In the following list M, L, T and θ at the right column stand for the fundamental dimensions of respectively, mass, length, time and absolute temperature.

a, radius vector at the center of mass of a fluid particle (L)

B, a material body obeying the continuum model (no dimensions involved) (-)

L_q, lower limit of fluid particle size regarding variable q (L)

L_v, lower limit of fluid particle size regarding velocity (L)

L_T, lower limit of fluid particle size regarding temperature (L)

L_ρ, lower limit of fluid particle size regarding density (L)

M_q, mean fluid particle size regarding variable q (L)

M_T, mean fluid particle size regarding variable temperature (L)

q, a generic fluid physical or flow property (unspecified)

R^3, Euclidean vector space of three dimensions (-)

t_0, a reference time (T)

T, temperature (θ)

U_q, upper limit of fluid particle size regarding variable q (L)

U_T, upper limit of fluid particle size regarding temperature (L)

v, velocity (L/T)

x, a generic real variable (-)

x_0, a constant value of x (L)

X, a point particle of a continuum material body (-)

X_α, a real number representing a generic coordinate of X (-)

X_1, X_2, X_3, real numbers representing coordinates of X (-)

λ, mean free path of gas molecules (L)

ρ, density (M/L^3)

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