Make Flow Metering Scientific!

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The paradigm of fluid mechanics, now classified as classical physics, has long had a rather self-deprecating characteristic. Leibovich states that it takes at least 20 years.[1] This has a lot to do with the rigorous mathematical treatment. In the UK, the home of science, fluid dynamics, especially theoretical work, is still carried out in the Department of Mathematics and the Institute of Applied Mathematics. The fact that our Navier-Stokes (NS) equations, with their strong nonlinearity, cannot in principle be solved analytically, as Reynolds found, and that deterministic methodology is not feasible, does not make statistical fluid mechanics any less accepted. This is also true.

Naturally, the same is true for experimental studies. Although Da Vinci's vortex sketches are well known, what he was able to do was to note qualitative characteristics, an observation method that led to subsequent flow visualization techniques. It took about 30 years after the publication of the principle for the use of hot wire anemometry (HW) and laser Doppler anemometry (LDA) to become commonplace as experimental science, whose main purpose is quantitative observation.

The author developed the Ultrasonic Velocity Profiler (UVP) for experimental fluid dynamics research. The first conference paper[2] was published in 1985 and the first printed paper[3] was published in 1986.[4] The Particle Image Velocimetry (PIV) was also developed by Adrian[5] at the University of Illinois at about the same time as the author's.

Both UVP and PIV have brought about a significant change from the earlier point measurements to line and plane measurements. The need for such observational techniques was described by Frisch[6] of Nice in 1988 in Physics Today, the journal of the American Physical Society. Today, these new techniques are finally being recognized and used in research. For those of us who developed them, it is indeed a world apart.

On the other hand, what about the more common and technically and industrially very important flow metering technology? First, there are a few things that need to be mentioned here. First, flow rate is the amount of movement of any object. Not only in industry, but also in all social activities, there is never a time when objects are not moving. Knowing the amount of movement of an object in any state - gas, liquid, solid, or a mixture of these - is the most important basic item for understanding the situation. Second, the general flow field we are dealing with is spatially extending and temporally fluctuating. Most of these spatial fields are pipes and ducts with strictly fixed boundaries, but if we consider flow in nature in a broader sense, it can occur in any situation, including rivers, culverts, and even debris flow. Not only are they considered to have

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a wide spatial extent, but it is easy to forget that they are generally not steady flows that are also constant in time, but rather fluctuating flows.

Flow metering in general deals with a very wide range of phenomena. When the natural environment is included, the morphological extent is too diverse and the size to be handled is too enormous. Although the importance of quantifying the amount of movement in such a situation cannot be ignored, here we will consider flow rate for pipes that are more commonly handled industrially, especially circular pipes that are commonly used for piping.

Figure 1 shows a classification of the current state of flow metering methods or flow meters.[7] The target objects are 65% liquids and 35% gases. In fact, gas-liquid two-phase flow and powder flow, which are solids, are also industrially important, but it is no exaggeration to say that current flow metering technology is completely undeveloped. In terms of the dimension to be determined as flow rate, there are volume flow (L^3/T) and mass flow (M/T). Especially for gases, density is used to convert between volume and mass, but because of the compressibility of gases, other physical quantities such as pressure and temperature have a significant effect on this relationship, so separate methods are used to determine each separately.

There are two measurement methods: the direct method, which directly determines the amount (volume or mass) of a moving object, and the indirect method, which uses the fact that the amount of movement (often the average velocity) is correlated with other physical variables. It is very difficult to directly determine the volume of a substance moved, and most of the flow metering methods currently in use are indirect methods, and direct methods are rarely used for volumetric flow rates. For mass flow, the Coriolis method, which has been developed recently, can be mentioned. The following discussion will focus on volumetric flow metering.

The basic principle of the flow metering method currently used is Q=AV, where A is the cross-sectional area of the pipe and V is the mean flow velocity. The velocity in a flow field is generally a three-dimensional vector, but for flow in a pipe, only the axial component needs to be considered. Since the dimension is L^3/T, Q is the volumetric flow rate, and the mass flow rate can be obtained by multiplying by the density of the fluid. In addition, the cross-sectional area of the pipe can be known with good accuracy if it is constant. Therefore, it can be said that the quality of flow metering depends uniquely on the degree of measurement of the mean flow velocity. However, there was no method to correctly determine the average flow velocity. In other words, although the flow is spatially distributed in the pipe, there was no way to know this at the measurement location, and therefore there was no way to directly determine the area-averaged flow velocity in a complete form. Therefore, there was no way to directly determine the area-averaged flow velocity in a complete form. The indirect method is to determine the flow rate by using various physical phenomena and the relationship between them and the average flow velocity. In fact, many of the various measurement methods were developed and put into practical use as flowmeters by Japanese technological researchers. In doing so, they used a lot of knowledge and theories of so-called fluid engineering, and employed experimental coefficients and correlations to support them. Therefore, the current flow metering paradigm simply appears to be based on science.

In the first place, this basic principle of Q = AV itself does not involve any science. The reason for this is that the method of determining flow rate in such a way has been in place since before Roman times.[8] Moreover, this was the time of Alexandria, before the transmission of Greek science = natural philosophy to Rome, which of course was long before the emergence of modern science. Moreover, it was the age of *Technique*, which did not yet include *Logos*, and could not even be called *Technology*. It is not clear how the average flow velocity was obtained at that time, but even the genius da Vinci would not have had the idea that there is a distribution of flow velocity. In terms of the conservatism of the paradigm mentioned at the beginning of this article, it would mean that the paradigm that was established more than 2,000 years ago has not been incorporated into the viewpoint of science at more than 300 years after the emergence of modern science.

So, let us consider how to think about it. To do so, we need to redefine flow rate in a proper scientific way. As mentioned above, flow has a velocity distribution. If it is the amount of movement of an object through a certain cross-section in a pipe, it is a vector quantity because the flow velocity has a direction. And since modern science is characterized by its ability to use mathematical expressions with the means of differentiation and integration, the flow rate can be defined using this tool and expressed by the following equation

$$Q(t) = \iint_A \boldsymbol{u}(\boldsymbol{x}, t) d\boldsymbol{A}$$

Here $\boldsymbol{u}$ is the velocity distribution of the vector quantity, where position and time are variables. $\boldsymbol{A}$ is a plane vector representing the measurement cross section. Since the velocity distribution is spatiotemporally variable and time and space are not separable variables, the flow rate represented by the area of the velocity distribution is time-varying. Naturally, such a definition may have been thought of before, but it could not be adopted because the velocity distribution at the critical measurement location could not be captured. This is probably the reason why we could not break away from the Q=AV paradigm.

In experimental fluid dynamics, however, a revolutionary development has occurred in the means of observing flow fields. When flow metering was first adopted for industrial use in the form of flow meters and various types of measurements were made, so-called point measurements at a single spatial point, such as hot-wire anemometry (HW) and later laser Doppler anemometry (LDA), could not instantaneously determine the shape of the spatial distribution. However, with the development of ultrasonic velocimetry (UVP) and laser PIV about 40 years ago, it became possible to determine the shape of the distribution by line and areal measurements instead of point measurements. It is now almost generalized, and point measurements are rarely employed anymore. I will not go into details, but it is common knowledge among those involved in fluid dynamics that this is the general practice at present.

An example of how the understanding of flow fields is no longer based on point measurements or simple spatial averaging is the most familiar flow field, weather forecasting. The fact that the state of the atmospheric flow distribution varies with time is already being shown and used as a matter of course. The status of wind direction and its changes are displayed. However, in the camp that specializes in flow metering, there has been little movement to adopt such developments. As Merzkirch, a leading expert in flow metering, states[9], "It is an exaggeration to say that this is because most of the people in charge are electronic and electrical engineers, and it would be more correct to say that fluid mechanics and engineering have not been taken seriously." In other words, no fluid dynamics researchers have emerged to deal directly with the behavior of the fluid inside the flowmeter. Or, it could be said that there has been a lack of effort to develop the Q=AV paradigm, even if it destroys it.

Regardless of the type of flowmeter used today, installation conditions are quite demanding and have been standardized by ISO and JIS. To summarize briefly, most flowmeters are based on the assumption that the flow is well developed at the measurement point and that the flow velocity distribution in the pipe is axially contrasted, so upstream and downstream conditions of the installation site, flow range limitations, and full water conditions must be met, making it very difficult to achieve the highest specification performance that the flowmeter is capable of. There are some things that would make it seem like it would be. Whether users can fully understand and use them will depend solely on the efforts of the supplier.

In order to reinforce such weaknesses, the author has proposed the need to consider the Profile Factor and Factory Factor[10] at each stage, including the flowmeter, its verification method, and calibration method. The Profile Factor is a coefficient to correct the difference between the velocity distribution shape assumed in the flow calculation and the actual flow distribution shape, and the Factory Factor is a coefficient to correct the difference between the velocity distribution shape at the verification device and the distribution shape at the measurement section of the actual flow. In other words, it was required that the situation at the measurement location of the actual flow be properly understood. Unfortunately, however, there is no sign of its adoption.[11]

In the midst of this paradigm that cannot be broken out of, problems that have not yet been publicly acknowledged are becoming apparent in response to the demands of the times. This is not just a problem in Japan. Since flow metering is the grasping of basic quantities in engineering processes, it is equally problematic everywhere in the world. The following chapters will discuss in detail two points in particular that are inevitable for the future development of the industry.

Figure 1: Flowmeter Type Classification