Chapter 1
Introduction

1.1 Flows and Flow Measurements

In industrial applications as well as in scientific research, fluid flows are often utilized to serve diverse functions. The associated physical processes such as those in thermal and fluid engineering, as well as in chemical and biological process controls, constantly require accurate quantifications and optimizations, especially as concerns flow dynamics. The complex flows encountered in diverse industrial applications usually comprise various varieties of turbulent flows, three-dimensional and non-stationary flows, flows with separation and relative eddies, multiphase flows and so forth. To some extent it even deals with non-Newtonian fluid flows. Depending on the application areas and process specifications, most flows are further specified by flow rate, Reynolds number, velocity distribution, turbulence intensity and other relevant flow dynamical parameters. For the flows in heat exchangers, for instance, both the Reynolds number and the related flow state are crucial for the thermal efficiency of the apparatus. In treating flows in aerodynamics the most relevant flow dynamical parameters are directly related to the turbulent boundary layers. Obviously each engineering flow has individual specifications with corresponding flow dynamical parameters. Amongst all of these flows, the flow turbulence acts as the most important and complex phenomenon.

Because of the complexities of most industrial and natural flows, theoretical flow analysis that relies on fluid mechanics mostly appears to be inefficient and unable to quantify the respective flows. This is the case even if simplifications are used. Although nowadays the method of computational fluid dynamics (CFD) has been found to be of wide application in evaluating complex flows and improving the flow processes, its general reliability and applicability still need to be enhanced, especially through experimental validations. Moreover, the CFD method is unable to provide the online analysis of the flow process of interest. For these reasons, experimental flow measurements have often been taken into account, aiming to investigate the flows and thus to optimise the related flow processes.

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1.2 Traditional Methods of Flow Measurements

Traditional flow measurements in the field of flow dynamics basically include the measurements of velocity and pressure distributions in the flow. The most familiar methods for local flow measurements are using the Pitot tubes to measure total pressure and the Prandtl tubes to gauge dynamical pressure. Because such pressure probes all require insertion into the flow, the flow is disturbed. Both the Pitot and Prandtl tubes are usually restricted to stable or quasi stable flow measurements. They are generally not used for measuring flow turbulence or any high frequency flow fluctuations, mainly because of the delay of pressure signals in the pressure probes. This can happen due to the compressibility of the gaseous flow or other causes. Also, the associated velocity fluctuations cannot be calculated from the measured pressure fluctuations in a straightforward way. In addition, it should be kept in mind that the pressure probes are not applicable to the boundary layers nor to flows with streamline curvatures.

A much more appropriate method for turbulent flow measurements are the hot wire anemometers (HWA). This method makes use of the relationship between the heat transfer on the thin hot wire surface and the flow velocity. The hot wire is only a few micrometers in diameter and is usually made of platinum or tungsten. Such a thin hot wire ensures the rapid response of the hot wire temperature and hence of the electrical signals to the fluctuations in the local flow velocity. Thus the method can be well applied to measurements of most turbulent flows, including those in the turbulent boundary layers. The downside of the method is that the hot wire has to be calibrated prior to each application. The thin hot wire also demands that the flow does not contain any hard particles, which could damage the wire. Because of the considerable flow resistance exerted on the hot wire the method is not applicable to water flows of high velocity. In practice, the hot wire anemometer has found wide application in air flow measurement.

There are many other methods that are used in the practical flow measurements. Most of them require that the flow has to be arranged so that it is mechanically accessible for probe insertion. Another well-known method without flow disturbance is using ultrasonic waves. It has found wide application in pipe flows, where neither mechanical nor optical access to the flow is possible.

1.3 Laser Methods and Laser Doppler Anemometry (LDA)

Modern measurement techniques for flow investigations are doubtless marked by use of laser techniques. The laser method obviously provides the far and wide perspective of measuring flows both more accurately and informatively. On one side, traditional measurement methods (Sect. 1.2) will be replaced where high measurement accuracies are demanded and special flow parameters should be quantified. On the other side, the significant progress of making the laser method to be standard and hence to be easily handled has largely extended the application area of flow measurements. The well-known laser methods being extended in the practical applications are Particle Image Velocimetry (PIV) for flow field measurements and the Laser Doppler Anemometry (LDA), also known as Laser Doppler Velocimetry (LDV), for measurements of local flow velocities. In principle, both methods complement each other.

The Particle Image Velocimetry (PIV) is a method of using a laser light sheet to illuminate particles that are seeded and suspended in the flow. Based on measurements of particle displacements in the image of the visualized flow, the flow distribution in the illuminated flow area can be quantitatively evaluated. This can be conducted by means of efficient evaluation software and high-speed computers, which have all reached a very high standard. The PIV method helps to identify the flow pattern which could comprise flow separation and relative eddies. In comparison with conventional methods of flow visualization for instance using smokes, the PIV method additionally provides quantitative flow information. Also to be mentioned is that this advanced property of PIV measurements has often been insufficiently put to use. As known, the flow measurement merely provides data for further analyses and hence behaves as the prerequisite of flow investigation. In many application examples, quantitative velocities measured by the PIV method are barely exploited to show the flow pattern. For the most part, no further intensive and extensive analyses have been or could be completed. Hence, the flow pattern that is outlined through PIV measurements does not provide any more useful flow information than that provided through the simple flow visualization, for instance by using smoke or color. This comparison implies that the flow investigation is not simply restricted to the stage of flow measurements. More about this aspect will be explained in Sect. 1.4.

The Laser Doppler Anemometry (LDA), of which the functionality and application methods constitute the subject of this book, is probably the most effective and widest applied non-intrusive method in experimental investigations of flows and flow dynamics. It represents an optical, state of the art method commonly with high measurement accuracy. Since the first application of the LDA method by Yeh and Cummins (1964), the method has been continuously developed and extended, so that it nowadays becomes a standard instrument for flow measurements in both industrial applications and model flow investigations. The fundamental development in LDA technology includes the progressive hard- and software developments, which are achieved mainly based on the progressive developments of laser and computer technologies. In general, the LDA technology can be categorized into two areas:

LDA fundamentals
LDA applications

In the aspect of LDA applications, significant achievements have been made since the nineties of the last century, as the LDA method had then found its wide application. In accordance with more and more LDA applications at that time and for the purpose of exchanging the application experiences, many local and global associations have been grounded like EALA (European Association for Laser Anemometry, no longer active) and GALA (German Association for Laser Anemometry).

1.3.1 Developments of LDA Fundamentals and Instrumentations

Since the first LDA measurement was successfully tested by Yeh and Cummins (1964), the method is undergoing continuous development. These developments are mainly restricted to the enhancement of opto-electronic performance of LDA system and the hard- and software improvements. Such developments have enabled the LDA nowadays to be a mature and important measurement instrument which is also commercially available. Within the framework of this book, it is not the purpose to make a historic review of LDA developments. For informative LDA developments, the readers are referred to the earlier work of Durst et al. (1981) as well as to the recent work of Albrecht et al. (2003).

Developments on LDA fundamentals also include investigations of diverse optical and flow-specific aspects that are tightly related to LDA applications and could considerably influence the measurement accuracies. Corresponding influencing factors are known, for instance, as the effect of fringe distortion in LDA measurement volumes, the velocity and angular bias effects, the effect of the time and spatial velocity gradients and so on. Because of their importance in LDA measurements, correspondingly extended investigations have been carried out at an earlier time. They are mentioned here, as follows:

(A) *Velocity bias effect*: The velocity bias arises from the effect that the velocity sampling rate in LDA measurements is not time-equidistant but depends on the velocity itself. In concrete terms, high velocities are proportionally more frequently sampled than low velocities. This effect generally exists both in non-stationary flow and turbulent flow with velocity fluctuations. Because of its dependence on flow velocity, the velocity bias effect is indeed a flow phenomenon. It was firstly recognized by McLaughlin and Tiederman (1973) and later had been broadly investigated by a great number of researchers (for instance Buchhave 1975, Erdmann and Tropea 1981). Corresponding investigations are mainly restricted to the correction of the related measurement error. Based on numerical calculations the velocity bias errors were extensively characterized by Nobach (1998) for three-dimensional flow turbulence. Fully analytical specifications of velocity bias and their dependence on the turbulence intensity have been completely accomplished by Zhang (2000, 2002), for three-dimensional flow turbulence and the turbulence intensity covering the range from zero to infinity. It should be here remarked that the velocity bias does not always represent the measurement error. This viewpoint is completely described in Chap. 17 of this book.

(B) *Fringe distortion*: As an optical phenomenon, the fringe distortion in the LDA measurement volume is mainly caused by improper optical layout or by irregular i.e. asymmetrical laser beam refractions on the medium interface. The fringe distortion in the measurement volume due to improper optical layout was carefully dimensioned by Hanson (1973, 1975). By use of a magnified image the distorted fringe pattern in the measurement volume was visualized for instance by Miles and Witze (1994, 1996). The fringe distortion in the LDA measurement volume as a result of laser beam refractions was confirmed to be the effect of astigmatism by Zhang (1995) and Zhang and Eisele (1995a, b). It represents a particularly crucial phenomenon when the laser beam refraction takes place on the inclined plane surface or the surface of a circular pipe (Zhang 2004a, 2004b). The outcome of all types of fringe distortion in the LDA measurement volume is the deterioration of the measurement accuracy. Measurement errors, for instance, are mainly interpreted in the overestimation of all relevant turbulence quantities. For this reason the associated effect is also called the broadening effect in turbulence measurements (Hanson 1973). Quantitative evaluations of the fringe distortion effect on the flow measurement accuracy were performed by Zhang and Eisele (1997, 1998c) for the case of linear fringe distortion in the measurement volume. For other types of fringe distortion in the measurement volume, the respective effect cannot yet be well-estimated.

(C) *Spatial velocity gradient effect*: For flows with spatial velocity gradient, such as the flows in the turbulent boundary layers, LDA measurements suffer from measurement errors in both mean and fluctuation velocities. The reason for these errors is the non-uniform velocity distribution within the length of the LDA measurement volume. Because the standard LDA optics is unable to resolve the velocity distribution within the measurement volume, both the mean velocity and especially turbulence quantities suffer from measurement errors. Corresponding investigations have been carried out by Durst et al. (1996, 1998). As a matter of fact, the existence of the spatial velocity gradient within the LDA measurement volume also leads to ambiguity in representing the measurement result because of the effect of the involved velocity bias.

(D) *Non-stationary flow measurements*: In the enforced non-stationary turbulent flows, flow fluctuations comprise both the enforced velocity variation because of the flow periodicity, for instance, and the stochastic velocity fluctuations because of the flow turbulence. To evaluate such flows based on LDA measurements, the appropriate data processing has to be worked out. Usually it refers to the method of resolving the stochastic from composite fluctuations. Corresponding investigations on the evaluation method have been carried out by Zhang et al. (1996, 1997) as well as by Jakoby et al. (1996).

1.3.2 Developments of LDA Application Methods

As a result of fundamental developments and the developments of hard- and software, the LDA method has been established to be a very efficient optical technique for flow measurements, especially for investigations of complex turbulent flows. Correspondingly the LDA instrument has become a mature commercial product and found the widest applications. Because of this, the LDA technique has been commonly considered as an available tool, although complicated, for direct application in the flow measurements.

In reality and as experienced from applications, the knowledge of LDA fundamentals and the instrument functionalities does not ensure any fully-correct measurement of flows that are practically of countless varieties with respect to the flow itself, the flow arrangement and the related optical specifications. This viewpoint is objective and true, as it has been well-known for instance that the particle size, the velocity bias and the fringe distortions could largely influence the measurement accuracies. Although there have been countless LDA applications in almost all possible flows, only few attempts have been made to improve the optical conditions and enhance the measurement accuracies, to simplify the measurements and correct measurement errors as well as to clarify the application limits and extend the application areas of LDA techniques. Aside from the concerned velocity bias and fringe distortion, practical applications of LDA method in effect suffer from much more undesirable, partly unknown optical phenomena. The most significant disturbing factor in LDA applications is related with refractions of laser beams for internal flow measurements. In facing this situation and to suppress the occurrence of any optical aberration, the refractive index matching method has been occasionally applied. This method, however, acts only as a passive method and is actually not always applicable. The problem arising from the laser beam refractions will be enlarged, if the beam refractions take place on a curved surface like that of a circular pipe. Obviously the LDA technique with respect to its applications and application optimizations still needs to be developed.

(A) *Optical aberration and astigmatism*: In LDA applications, the optical aberrations generally exist in each measurement of internal flows, where the laser beams must transmit through at least one optical window and hence undergo refractions. The most remarkable optical aberration was confirmed to be astigmatism which in worst cases would lead to total interruption of measurements (Zhang 1995, Zhang and Eisele 1995a, b). The phenomenon and the associated disturbances on both the signal quality and the signal rate become crucial, if the LDA optical axis is aligned off-axis i.e. not coincident with the normal of the optical window. Some LDA users might have experienced that at the mentioned optical configuration either no signal or very bad signals will be received. The reason for signal disappearance is the non-intersection of laser beams after refractions on the air-glass and glass-flow interfaces. The reason for bad signals is mostly the bad intersection between laser beams and the deterioration of receiving aperture of the receiving optics. Another issue of astigmatism is the fringe distortion in the measurement volume that could lead to measurement errors (Zhang and Eisele 1996b). Detailed descriptions of influences of astigmatism on LDA measurements and the guideline for correct measurements with correction method can be found in the mentioned references. To minimize the effect of astigmatism the method of configuring the receiving optics is described in Zhang and Eisele (1996a, 1998b).

(B) *Three-component flow measurements in circular pipes*: Another most common case of LDA measurements is referred to flow measurements in circular pipes. In this case, the optical aberration associated with the laser beam refractions is much more complex and serious than that at a plane surface. In reality, measurements could not run without any aid, either of matching the refractive index of the flow, or by the exact calculation of the laser beam intersection in the flow. Because the refractive index matching method is not available each time, direct measurements of pipe flows must often be carried out. Accordingly great difficulties in obtaining signals of high quality in such measurements would have been encountered by lots of LDA users. Some users tried a great deal to track the laser beams in both the pipe wall and the flow (Boadway and Karahan 1981). As a matter of fact, the optical aberrations in the receiving optics and the corresponding most serious influence on both the signal strength and quality have often been overlooked. As shown by Zhang (2004a, b) the optical performance of direct flow measurement can be greatly enhanced by making the outside surface of the circular pipe to be plane (Fig. 1.1). This contributes not only to the reduction of optical aberrations in both the transmitting and receiving optics, but also to the simplification of calculating the laser beam intersection in the flow for measurements of all three velocity components.

(C) *Dual Measurement Method (DMM)*: As is known, LDA measurements are measurements of velocity components. Because of this property, there are sometimes difficulties in accurately resolving a component, say that one in the secondary flow, which is much smaller against the other components. Usually the direct measurement of such a small velocity component requires exact optical alignment, which is, however, often impossible or very complicated and time-consuming. A method which enables the lowest secondary flow to be exactly measured has been developed by Zhang (2005) and is denoted as the Dual Measurement Method (DMM). The method has been successfully applied to resolve the secondary flow structure in a high speed jet flow, see also Zhang and Parkinson (2001, 2002).

(D) *Zero Correlation Method (ZCM)*: In measuring the turbulent flows, it is often required to measure both the mean velocity and the turbulence quantities such as the turbulence intensity and turbulent stresses in the Reynolds stress matrix. For measurements of turbulent shear stresses, usually two-component LDA system should be applied to enable the fluctuations in two velocity components

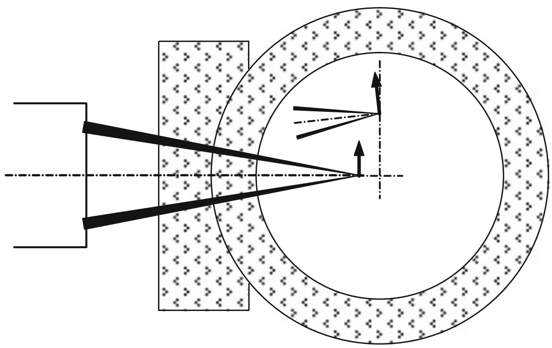

Fig. 1.1 Effective method for measurements of all three velocity components of the flow in a circular pipe (Zhang 2004a)

to be measured simultaneously. The corresponding technique is known as the two-component coincident measurement technique. Although most LDA systems are designed and equipped for doing such measurements, turbulence measurements can be simplified by accounting for the common randomness of velocity fluctuations. For stationary flows, this fluctuation randomness indicates that velocity fluctuations occur symmetrically around the mean flow direction. Based on such an assumption a special method that is called the Zero Correlation Method (ZCM) has been developed by Zhang (1999). The method enables the complete turbulence quantities to be simply measured without requiring the two-component coincident measurement technique.

As outlined above, LDA application methods represent an important category of LDA techniques and play a crucial role in correctly and efficiently carrying out the flow measurements. They form the main subject of this technical book.

1.4 Purposeful Flow Measurements and Rational Measurement Evaluations

Each flow encountered in the engineering applications is arranged to execute the given functions and thus specified by corresponding relevant parameters. It appears to be always important to LDA users to be aware of such parameters prior to starting each measurement. Although the LDA technique nowadays is greatly progressed and the LDA system becomes highly efficient and most convenient for use, it only serves as a useful application tool for flow measurements. In reality, flow investigations will just begin after the measurements have been carried out. For this reason, preliminary studies to specify and clarify the most relevant flow parameters should be made. Such preliminary studies also include how the interested flow quantities can be measured either directly or indirectly, and how accurate the measurement should be. They therefore provide the prerequisite for choosing the available measurement technique and the appropriate measurement method.

On the other hand, it is often a hard task for engineers and researchers to properly evaluate the measurement data. As indicated in Sect. 1.3 referring to the PIV method, the simple graphical mapping of the flow field directly from the PIV measurements, even quantitative, is often no more informative than the qualitative flow visualization. With the graphical mapping of the interested flow field, investigations should indeed just begin rather than just be finished. On one side, more deep studies and evaluations of measurement data require the knowledge of both the flow mechanics and the associated physical (thermal or chemical) processes. On the other side, the poor time-resolution of the achieved measurement data is obviously the significant shortage of the PIV method that prevents the user from further studying the flow. Against this shortage, the LDA method provides highly time-resolved measurements. It is therefore highly suitable for diagnosing the flow for instance by detecting the flow instability, turbulence intensity and exact flow profiles in the region of boundary layers and so on. For this reason, the LDA method is sometimes considered to be comparable with the method of blood test in a clinical laboratory, while the PIV method is comparable with the x-ray method. That is why the LDA method as a diagnostic tool, which provides a lot of useful flow information, is widely applied in practice.

1.5 Purposes of this Book

Since the first LDA application and for a long time thereafter, developments in LDA technology are mainly restricted to LDA fundamentals and instrumentations, as stated in Sect. 1.3. Great advancements in this category of LDA technology enabled the LDA method to become the most favorite technique for flow measurements. The LDA method has thus found its widest applications in experimental flow investigations. As also stated in Sect. 1.3, unique intimate knowledge of LDA fundamentals and instrumentations does not fully ensure correct flow measurements. For LDA users in practical applications, the application methods appear to be as much important and helpful as LDA fundamentals.

The current book therefore tries to completely summarize knowledge that is available in the aspect of LDA application methods. For completeness, the basic fundamentals of LDA measurement techniques and many other relevant aspects like the particle dynamics and velocity transformation algorithm will also be shown. To certain optical aspects, like those in specifying the LDA measurement volume in the circular pipe flows, the mathematical calculations seem to be rather complex. They are nevertheless all crucial for clarifying the background of each optical aspect and for estimating the extent of corresponding influences in measurements. Moreover, they also serve as the basis for further investigations of related optical aspects.

Finally some special applications of LDA methods will be presented. It will also show that the LDA method is just as suitably applicable for solid mechanics as for flow mechanics.

This book with its main subject thus serves as an extended reference for guidance on the LDA applications to users who are attempting to optimize the optical conditions and to gain the maximum results from measurements. Because it is the first book dealing with LDA application methods, it would contribute to the further build-up of LDA technology. Although the book has its weight in the application methods which mainly addresses LDA users, it can also be referred to by developers and manufactures of LDA systems.