Fluid Mechanics Developments and Advancements in the 20th Century

by

Franz Durst

Institute of Fluid Mechanics, University of Erlangen-Nuremberg
Cauerstr. 4, D-91058 Erlangen, Germany

ABSTRACT

The development of fluid mechanics is briefly reviewed and the importance of fluid flows to heat and mass transport in nature as well as to science and engineering is outlined. The early theoretical developments are explained and it is indicated that the basic equations were available at the end of the 18th century. Methods to solve these equations for engineering flows were not, however, developed until the second half of the 20th century. This was an important period for fluid flow research during which all the experimental fluid mechanics methods particularly the optical methods that are available today were also developed.

Fig. 1 provides a chronological summary of important scientists in fluid mechanics. It gives an impression when certain contributions to the subject were made, but measuring techniques are not covered in this figure. Various measuring techniques will be reviewed in the paper emphasising those techniques to which the author and his co-workers were able to make recognised contributions.

The presentation summarises the development of flow visualisation, laser Doppler anemometry, phase Doppler anemometry, particle image velocimetry, etc. and demonstrates their applicability to carry out detailed studies of laminar and turbulent flows.

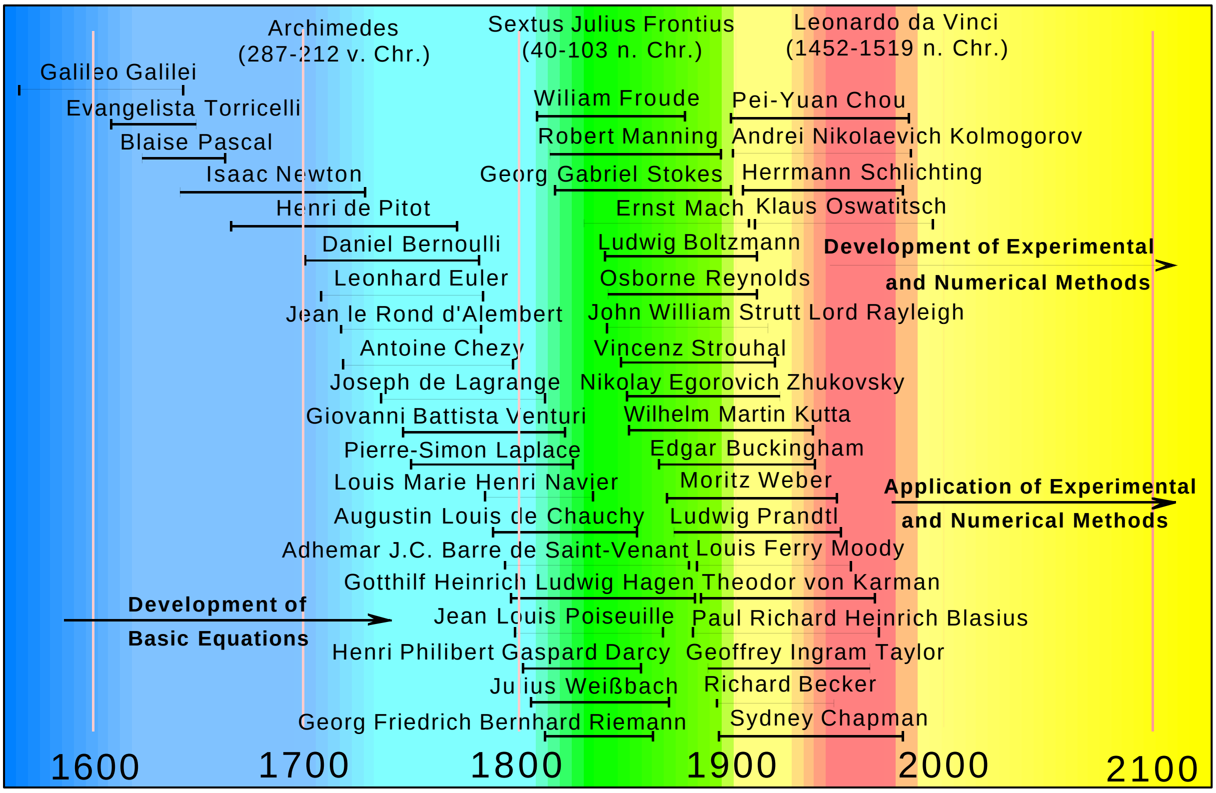


Fig. 1. Historical developments of fluid mechanics

1. INTRODUCTION

Fluid flows are present everywhere in nature and are widely experienced by those people who observe nature with open eyes. They see that many processes in nature are vitally dependent on the convective transport of heat and mass. Hence, without fluid motion, life in the form we know it on Earth could not exist. Fluid flows are vital to plants, animals and people living on the Earth, as indicated in Fig. 2.

The technical importance of fluid flows is also observable in many engineering fields where heat and mass transfer processes are strongly controlled by fluid motions. The conversion of chemically bounded energy into heat by premixed combustion is mainly controlled by the flow transport of the chemically reacting species and, as Fig. 3 shows, there is other technically relevant equipment that would not function without fluid flows within it. Hence fluid flows are also essential to all fields where engineering equipment is employed.

Titel:
durst-1.eps
Erstellt von:
Micrografx Graphics Engine
Vorschau:
Diese EPS-Grafik wurde nicht gespeichert
mit einer enthaltenen Vorschau.
Kommentar:
Diese EPS-Grafik wird an einen
PostScript-Drucker gedruckt, aber nicht
an andere Druckertypen.

Titel:
durst-2.eps
Erstellt von:
Micrografx Graphics Engine
Vorschau:
Diese EPS-Grafik wurde nicht gespeichert
mit einer enthaltenen Vorschau.
Kommentar:
Diese EPS-Grafik wird an einen
PostScript-Drucker gedruckt, aber nicht
an andere Druckertypen.

Fig. 2. Importance of fluid flows in nature

Fig. 3. Importance of fluid flows in fields of technology

The above introductory remarks that underline the importance of fluid flows might explain why fluid mechanics has a long history and goes back as long as historical records of human culture exist. However, as far as the subject as a science is concerned, it only dates back to the 17th century. Although there were contributions by Archimedes and Sextus Julius Frontius to the subject, as well as the first flow visualizations by Leonardo da Vinci, fluid mechanics as a science really began with Galilei. This is indicated in Fig. 1, which shows the long list of researchers who have contributed to the subject over the last four centuries.

Among the fluid mechanics scientists of the 17th, 18th and 19th centuries one finds the names of famous mathematicians and physicists, indicating that fluid mechanics as a basic engineering subject is fairly new if one looks at it in a historical time context. Nowadays, any serious engineering education in fields such as aeronautical engineering, mechanical engineering and chemical engineering is heavily based on a sound fluid mechanics education. This will also remain so in the future.

Major contributions to the scientific development were made by Newton, Euler, Lagrange, Navier and Stokes, by contributing to the derivation of the basic equations of fluid mechanics. If one looks at the dates in Fig. 1, one can see that by the end of the 18th century, the equations of fluid mechanics were basically known in the general form given below for ? = constant:

Continuity equation:

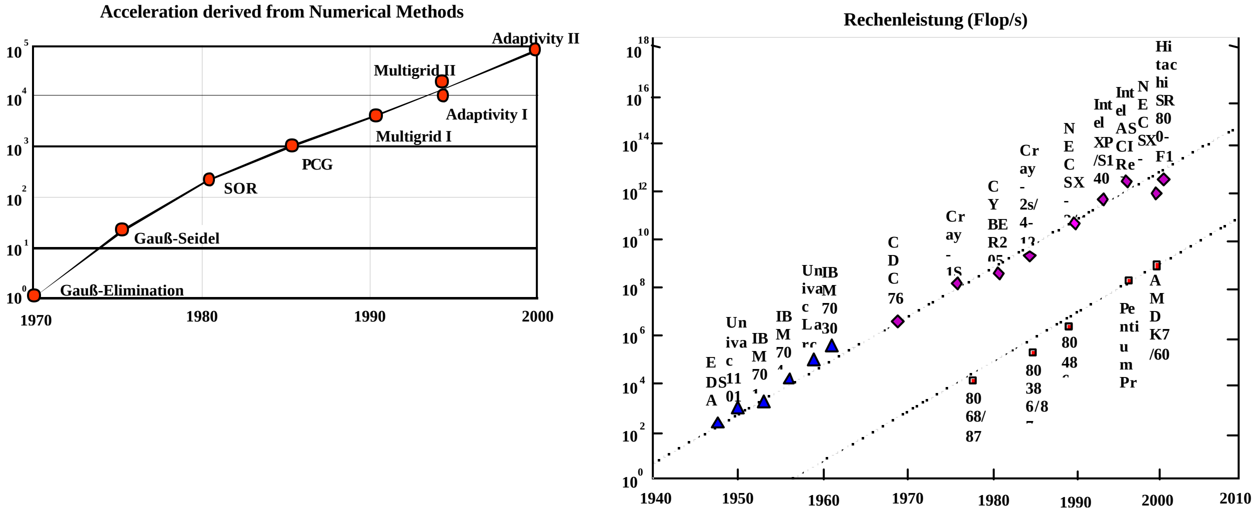
$$\frac{\partial r}{\partial t}+\frac{\partial\left(rU_i\right)}{\partial x_i}=0$$

Momentum equation (j =1, 2, 3):

$$r\left(\frac{\partial U_j}{\partial t}+U_i\frac{\partial U_j}{\partial x_i}\right)=rg_j-\frac{\partial P}{\partial x_j}-\frac{\partial t_{ij}}{\partial x_i} \qquad t_{\mathrm{ij}}=-m\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)$$

For ? = constant, the three velocity components and the pressure can be named as the unknowns of the above set of four differential equations. Hence four unknowns and four partial differential equations to obtain them exist and, because of this, all fluid flow problems seem to be solvable if the appropriate set of initial and boundary conditions exist.

In spite of the fact that these equations were known by the end of the 18th century, solutions to them could not be obtained because of the lack of solution methods. The present paper stresses that all methods to solve the above set of equations for engineering flow problems were developed in the second half of the 20th century owing to tremendous advancements in developments of numerical methods and also to huge developments in computer power. As Fig. 4 shows, high-performance computer developments have provided an increase in computational speed by a factor 10 every 5 years. In the last three decades, a factor of 10 every 8 years was also achieved by advanced numerical techniques. All these developments together now permit numerical solutions of the above set of equations to be obtained for a number of engineering problems.



(a) (b)

Fig. 4. Speed-up of numerical computations due to numerical methods (a) and increase in computer power (b)

The above-mentioned developments and the second half of the 20th century brought about numerical solutions to the above set of equations of fluid mechanics. In the same way, the second half of the 20th century also brought about tremendous developments in the field of experimental fluid mechanics. The development of fast electronic components, lasers, integrated optics, various sensors, micro-techniques, etc., has resulted in a wide range of developments of measuring techniques that are now available for studying fluid flows. The present paper concentrates on the development of optical techniques such as photography and cinematography, laser-Doppler anemometry, phase-Doppler anemometry, particle image velocimetry and other field methods. The developments are summarised and emphasis is given to those developments carried out in the author's research group initially at the University of Karlsruhe and later at the University of Erlangen-Nürnberg.

2. FLOW VISUALIZATION: PHOTOGRAPHY AND CINEMATOGRAPHY

It is a matter of opinion of the observer to define clearly where and when fluid mechanics as a science started. However, if one looks at the first contribution that had an impact on the subject as it is treated today, it is the flow visualisation carried out by Leonardo da Vinci (1452-1519) that can be considered as the start of experimental work based on the visualisation of flows. Since this early work, flow visualisation has advanced with major developments being based on modern illumination techniques, as well as developments in photography and cinematography. This is indicated in Fig. 5, which compares photographic records of flows with the early sketches of observed vortex motions by Leonardo da Vinci.

The presentation of numerical results in terms of path, streaks or streamlines makes clear that the visualisation of these features of a flow is still considered to be very useful for understanding flow structures and their effects on flow obstructions. Hence flow visualisation is still a very important means of obtaining an insight into the physics of fluid flows.

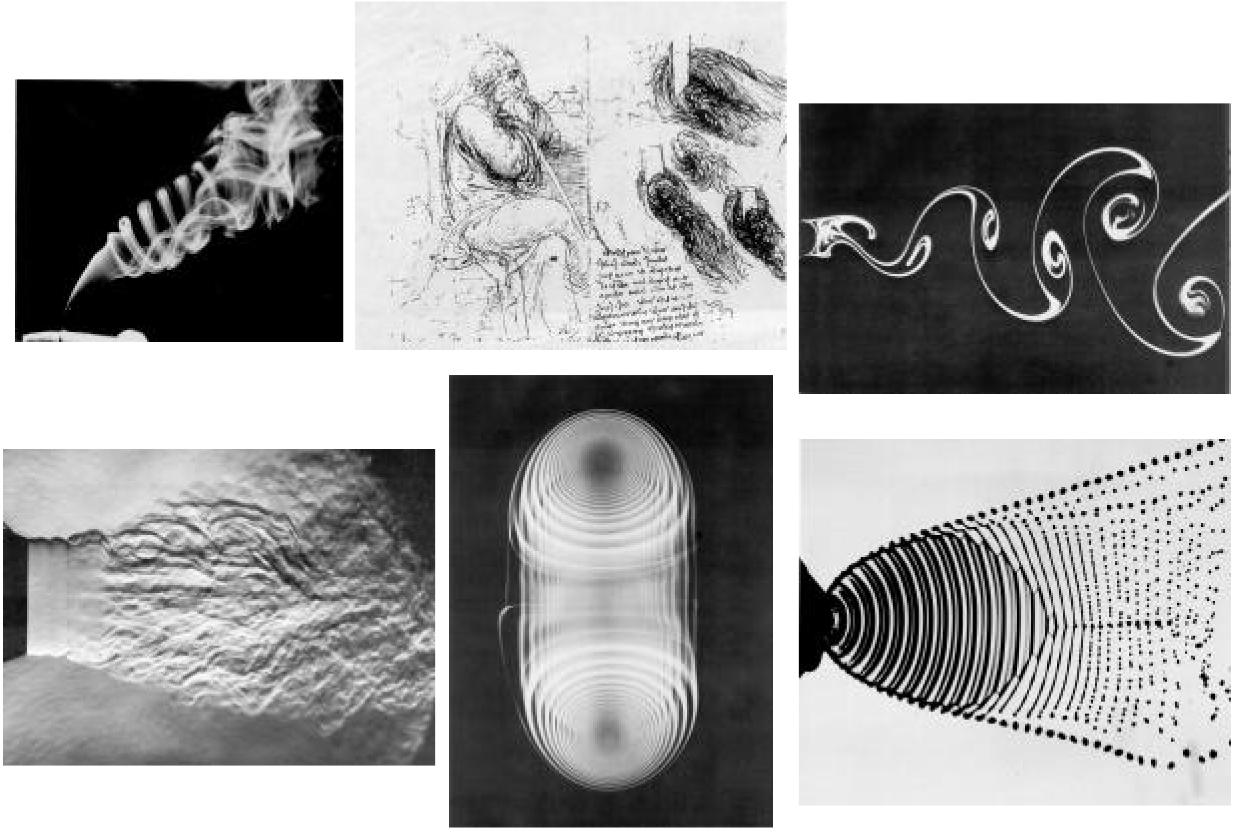


Fig. 5. Flow visualisation is the start of good fluid mechanics research

A summary of flow visualisation results is given in the Album of Fluid Motion assembled by van Dyke [1]. This assembly of pictures makes clear that photographic records of fluid motion can result in path lines, streak lines or streamlines of the flow. All of them are difficult to analyse in terms of local velocity information. Hence, to obtain results in the terminology of the basic equation of fluid mechanics, flow visualisation techniques are difficult to use. Nevertheless, they provide a good physical insight into the flow so that it has become common practice also to extract flow visualisation-like information from results of flow predictions, e.g. see Fig. 6.

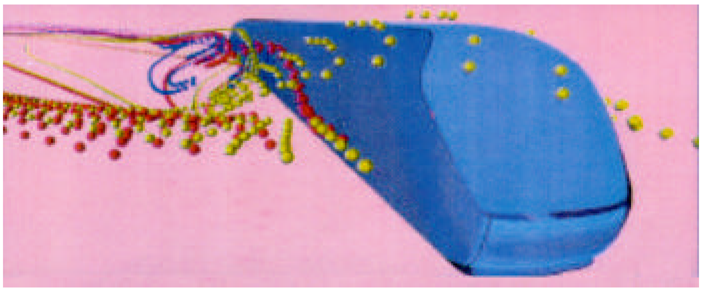
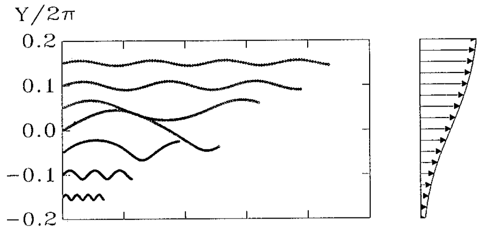


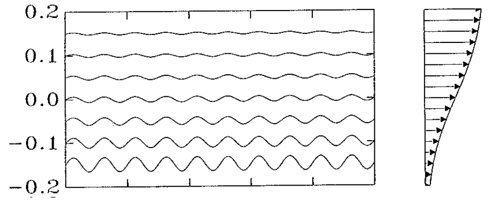
Fig. 6. Flow visualisation based on results of numerical flow predictions

The impressive pictures that flow visualisation provides often makes the flow researcher forget that it is very difficult to interpret correctly the resultant flow motions. This was outlined by Hama [2] and demonstrated by Eckelmann [3], from which the example below is taken.

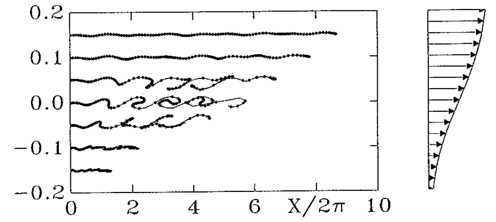
Although Leonardo da Vinci showed the power of flow visualisation as a basis for physical insight into flows, and modern methods of flow illumination and recording of fluid motion have become available, flow visualisation is not applied to its best in modern fluid mechanics. This is partially due to the fact that these days complex flows are being studied that yield complex flow visualisation pictures. In addition, modern fluid mechanics is interested in turbulent flows and mainly aims at quantitative information. This is difficult to obtain by flow visualisation.



Path lines of tracer particles



Stream lines of the velocity field



Streak lines

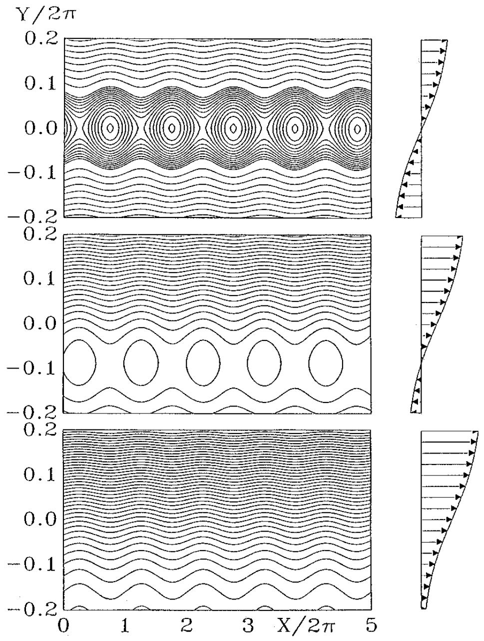


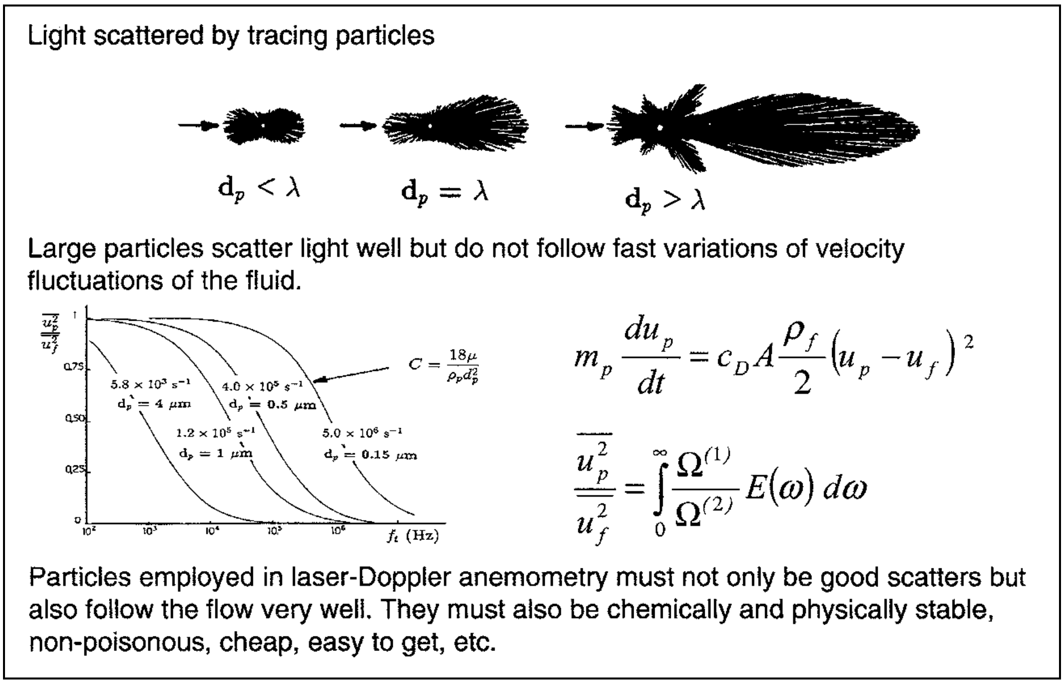
Fig. 7. Demonstration of complex flow information in path, streak and stream lines

3. LASER-DOPPLER ANEMOMETRY

During the second half of the 20th century, rapid developments in electronics and optics components provided the basis for the advancement of methods to measure local and time-resolved flow velocities. Fast operating electronic feedback amplifiers permitted the development of constant-temperature hot-wire anemometry, e.g. see Bruun [4]. With the help of this technique, first detailed velocity information became available about turbulent flows, providing an insight into the complexity of turbulence. Detailed turbulent flow studies provided the basis for advanced analytical treatments of flows, e.g. see Lumley [5]. However, the application of hot-wire anemometry was, and still is, limited to flows with low levels of turbulence. The method also was intrusive, yielding flow disturbances that are unacceptable in recirculating flows. These shortcomings of hot-wire anemometry triggered new developments. Laser-Doppler anemometry emerged from these development efforts, providing new means to study fluid flows.

Laser-Doppler anemometry is a well documented measuring technique, e.g. see Durst, Melling and Whitelaw [6]. Light scattering particles are needed that follow the flowing fluid so that the particle velocity is close to that of fluid, e.g. see van de Hulst [7] and Kerker [8] and Hjelmfelt and Mockros [9]. These basic requirements for LDA scattering particles are summarised in Fig. 8.

From the many scattering mechanisms that can be employed to deduce the local particle velocity from laser frequency shift information, e.g. see Durst [10], the dual scattering beam laser-Doppler effect has shown to be the most efficient and most robust for use in LDA velocity measurements. Hence optical systems of the fluid shown in Fig. 9 are these days employed to measure local flow velocities by laser-Doppler anemometry. Multi-component measurements, as indicated in Figure 10, are available.



Light scattered by tracing particles

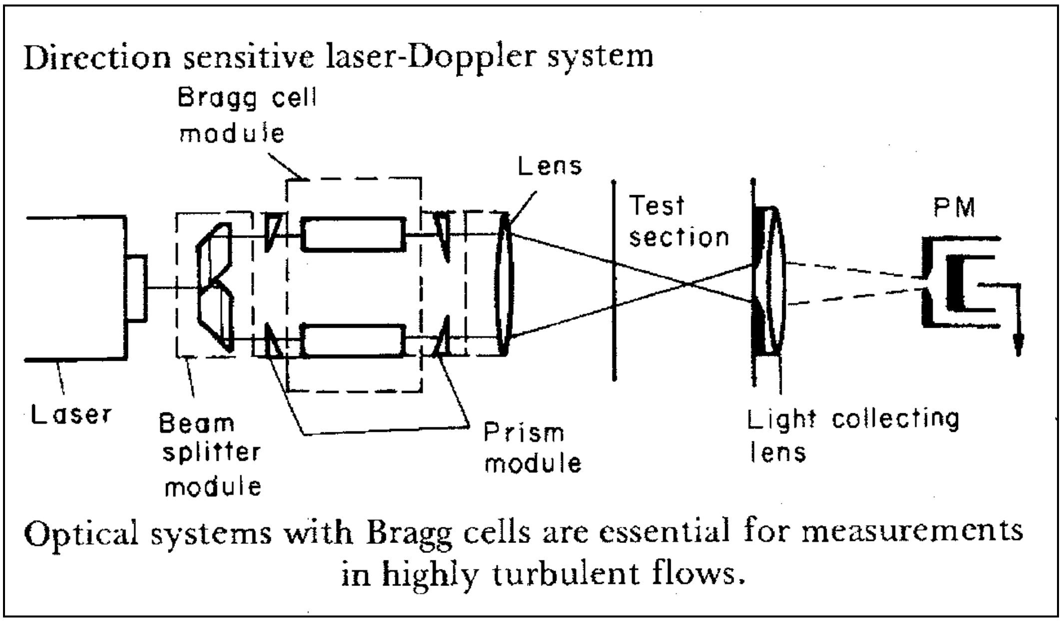
Large particles scatter light well but do not follow fast variations of velocity fluctuations of the fluid.

$$m_p \frac{du_p}{dt} = c_D A \frac{\rho_f}{2}\left(u_p - u_f\right)^2$$

$$\frac{\overline{u_p^2}}{\overline{u_f^2}} = \int_0^\infty \frac{\Omega^{(1)}}{\Omega^{(2)}} E(\omega)\, d\omega$$

Particles employed in laser-Doppler anemometry must not only be good scatters but also follow the flow very well. They must also be chemically and physically stable, non-poisonous, cheap, easy to get, etc.

Fig. 8. Scattering particles with high scattering efficiency and good flow velocity response



Direction sensitive laser-Doppler system

Optical systems with Bragg cells are essential for measurements in highly turbulent flows.

Fig. 9. Dual-beam laser-Doppler optical system

Fully developed systems to carry out laser Doppler measurements are now available and can be applied to carry out flow measurements that are not feasible with any other fluid flow measuring technique. Fig. 11 shows a channel flow test facility providing a fully developed channel flow. With the help of a laser-Doppler anemometer, detailed flow measurements were carried out, yielding the velocity information sketched in Fig. 11. Analysing these data revealed a *Re* dependence of the wall value of the turbulence intensity, as shown in Fig. 12.

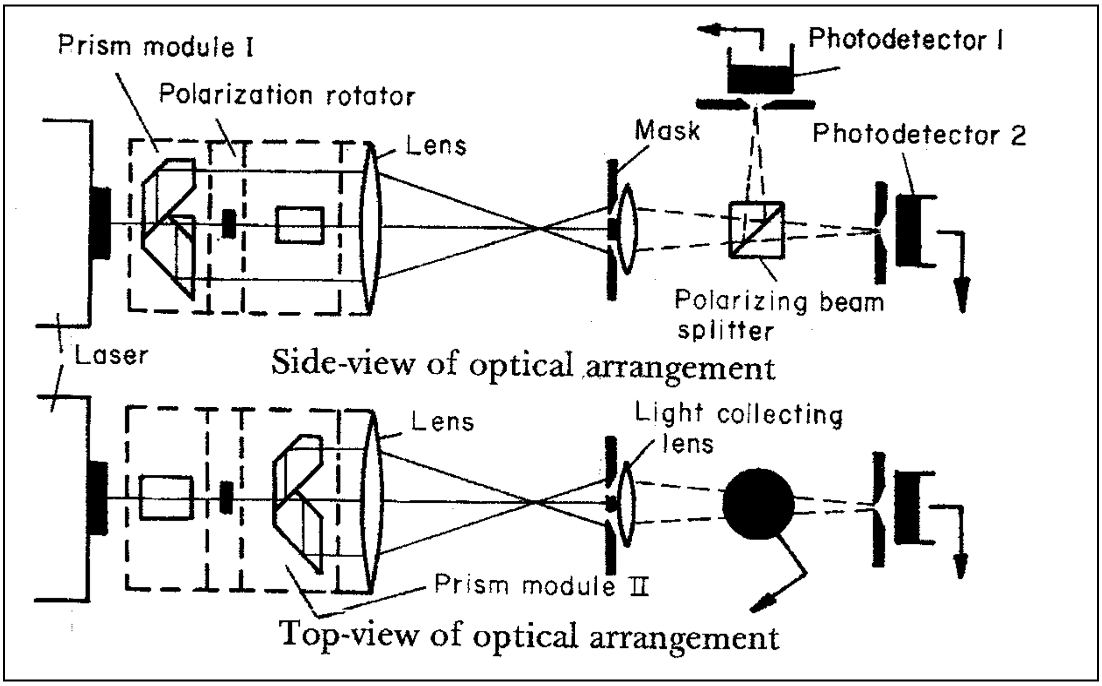


Fig. 10. Two-component laser-Doppler optical system

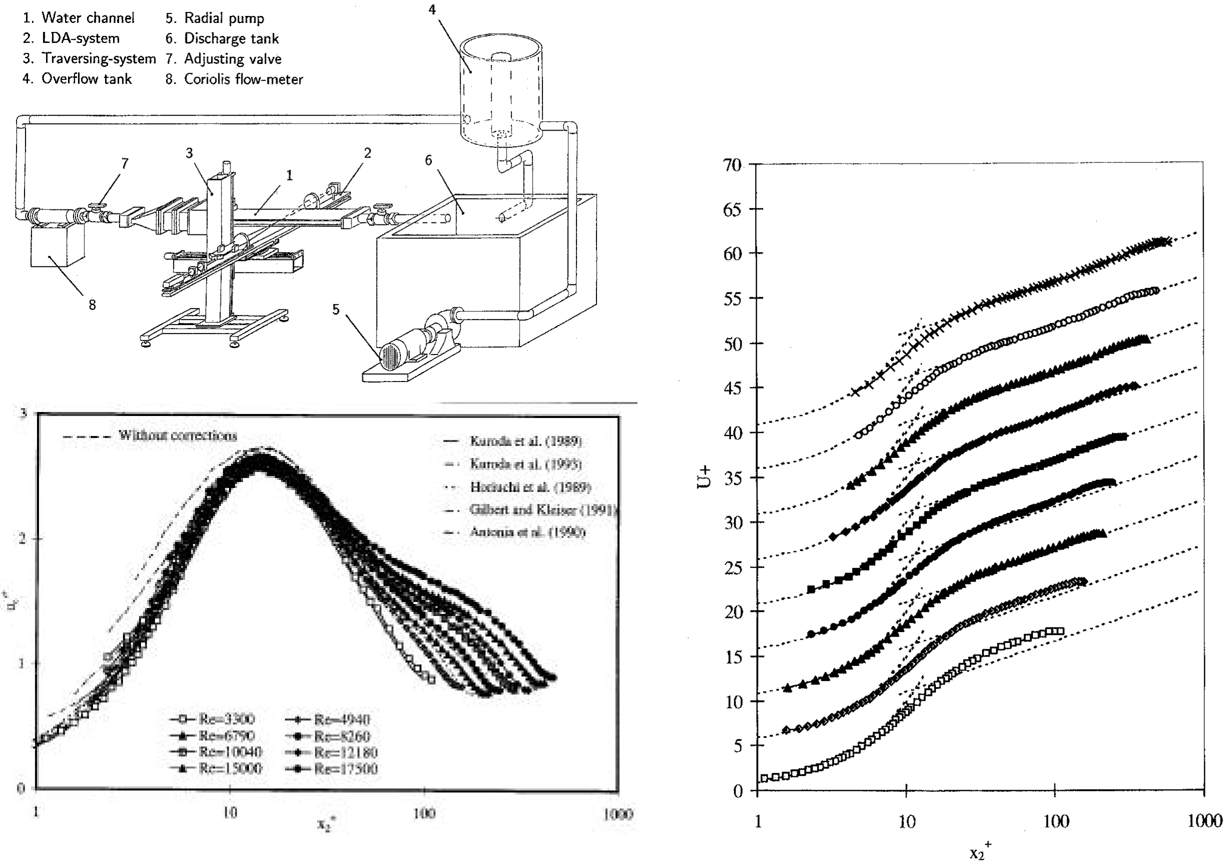


Fig. 11. LDA investigations of turbulent channel flows

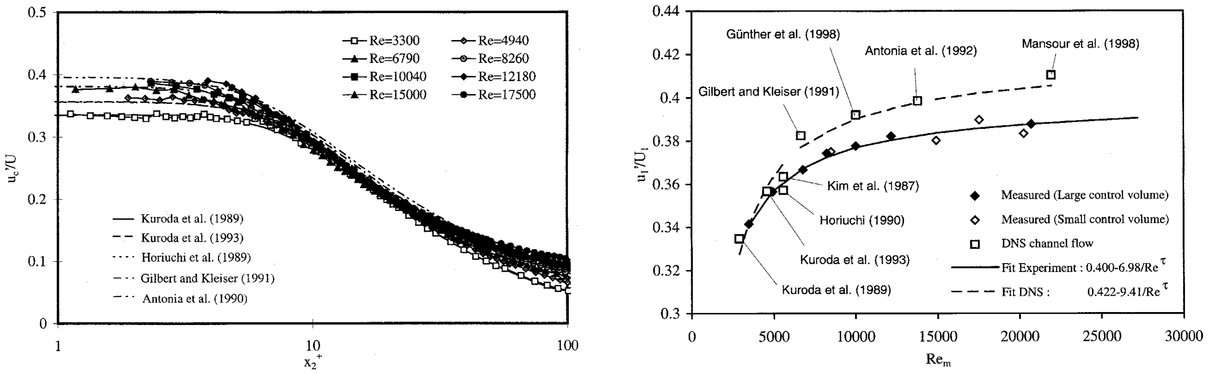


Fig. 12. Wall values of tubulence levels in fully developed channel flows

It is interesting to note that at present the Reynolds-number dependence of the wall value of the turbulence intensity is not understood. However, experimental and numerical studies show this dependence. The difference between the experimental and numerical results cannot readily be explained. It is possibly due to the finite size of the computational grids and the finite size measuring control volume of the LDA systems employed. The evaluation of the final data requires finite size volume corrections to be applied. It is worth noting that the experimental data in Fig. 12 were obtained with optional systems showing size differences of their measuring control volumes.

4. PHASE-DOPPLER ANEMOMETRY

When light from two inclined laser beams is refracted or reflected from a particle, interference fringes result in space, e.g. see Durst and Zaré [11]. For a given particle location, the fringes exist only in the direction in which the beams are reflected or diffracted. As the particle moves, the fringe system changes its location and, for this reason, a mask in front of the photomultiplier is crossed by fringes that cause varying light intensity at the pinhole. The fringes change their shape as they move through space, and are linear in the backward direction and highly non-linear in the forward direction.

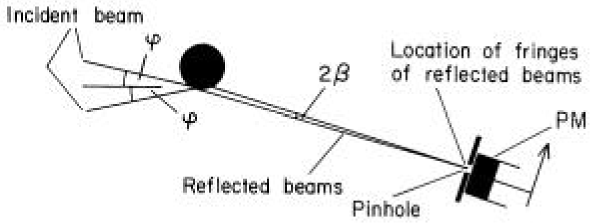


Fig. 13. Phase Doppler measurements in two-phase flows

Irrespective of the shape of the fringes, the derivation by Durst and Zaré [11] revealed that the resultant frequency due to the fringes crossing a mask in front of the photodetector is given by an equation that is independent of the photomultiplier location:

$$n_D = \frac{2}{l}\left[U_\perp \cos b \pm U_{||} \sin b\right]\sin j$$

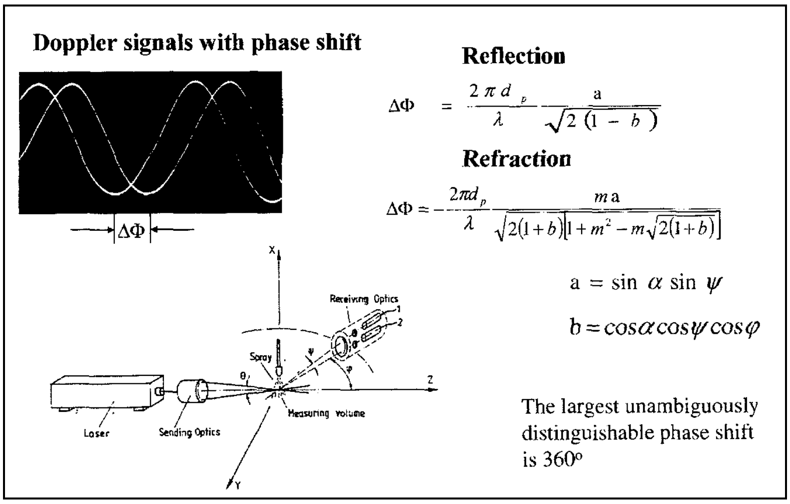
This equation indicates that the frequency of the resultant signal is sensitive to the velocity component perpendicular to the axis of the two incident beams and also to the component parallel to it. For most practical cases, however, the angle β is fairly small and, hence, the term $U_{||}$ sin β is small in comparison to the term $U_\perp$ sin β so that the evaluation equation reads

$$n_D \cong \frac{2U_\perp \sin j}{l}$$

The angle β is a function of the angle between the two incident beams and the ratio of detector distance to particle diameter. For large values of L/R, where L is the detector distance and R is the particle radius, the angle β tends to zero; β also decreases with decreasing angle φ. The same arguments apply to light beams refracted by transparent particles. In this case, linear interference fringes result in the forward direction and the Doppler frequency is not dependent on the velocity component parallel to the axis of the two incident light beams. The equation for the Doppler frequency reads in this case

$$n_D \cong \frac{2U_\perp(\sin j - \sin b)}{l}$$

In addition to measuring the particle velocity, phase-Doppler systems also permit the measurement of particle size by measuring the phase difference between signals from two detectors, as indicated in Fig. 14. The resultant equation employed to deduce the particle diameter from the measured phase difference depends on the location of the photodetector with respect to the transmission optics, i.e. whether reflected or refracted light is used for signal detection. Hence information of the kind shown in Fig. 15 is obtainable with phase-Doppler systems at every location in a flow field. Therefore, particulate two-phase flows can be studied by phase-Doppler anemometry.



Reflection

$$\Delta\Phi = \frac{2\pi d_p}{\lambda}\,\frac{a}{\sqrt{2(1-b)}}$$

Refraction

$$\Delta\Phi = -\frac{2\pi d_p}{\lambda}\,\frac{m\,a}{\sqrt{2(1+b)}\left[1+m^2-m\sqrt{2(1+b)}\right]}$$

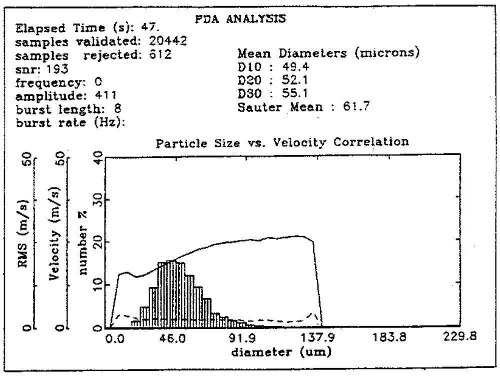
$a = \sin\alpha\sin\psi$

$b = \cos\alpha\cos\psi\cos\varphi$

The largest unambiguously distinguishable phase shift is 360°

Fig. 14. Principle of operation and sketch of optics of a phase-Doppler anemometer

Spray measurement results



```
                         PDA ANALYSIS
Elapsed Time (s): 47.
samples validated: 20442
samples  rejected: 612            Mean Diameters (microns)
snr: 193                          D10 : 49.4
frequency: 0                      D20 : 52.1
amplitude: 411                    D30 : 55.1
burst length: 8                   Sauter Mean : 61.7
burst rate (Hz):
```

Information achieved:

- **Drop size number distribution**
- **Size / velocity correlation**
- **Mean / RMS velocity correlation**
- **Moments of the drop size spectrum**

Fig. 15. Typical result of local time and velocity measurements in sprays

The phase-Doppler method has also been extended to yield information on the refractive index of the ligh- refracting particles in a flow. Extended phase-Doppler anemometers have been suggested for this purpose using four detectors located in different directions. This is indicated in Fig. 16, which also provides the equation employed for particle refractive index measurements utilising the ratio of two phase difference measurements. Results of application of an extended phase-Doppler system are shown in Fig. 17.

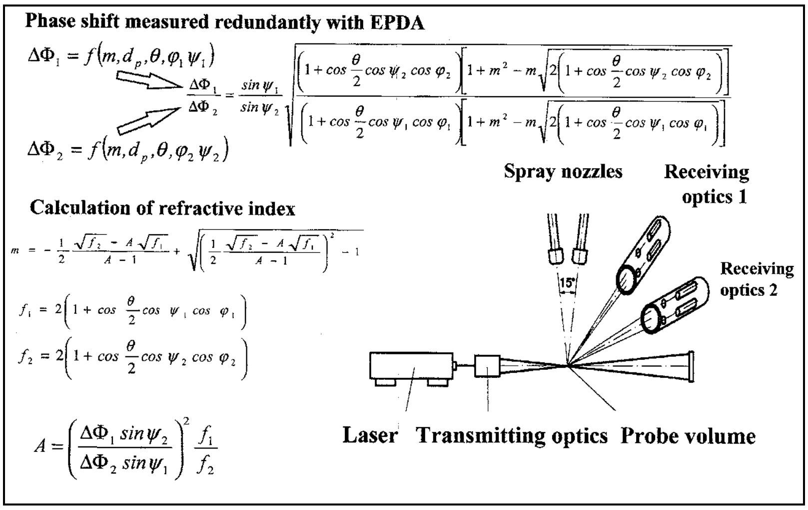


Fig. 16. Optical system for extended phase-Doppler measurements

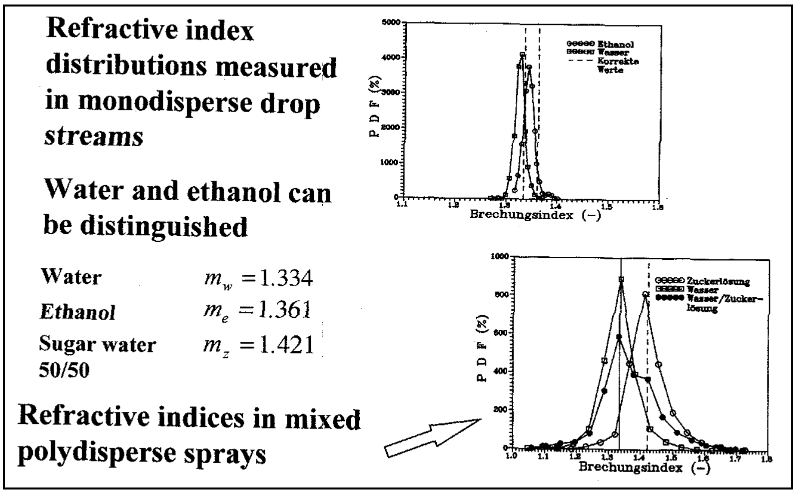


Fig. 17. Refractive index measurements using extended phase-Doppler anemometer

Without any doubt, phase-Doppler anemometers work best with spherical particles and that is also where they should be applied. The application of PDA systems to study two-phase flows could lead to interesting results on laminar and turbulent particulate two-phase flows if the available phase-Doppler anemometers were to be employed to their optimum extend. The time has come when fluid mechanics research should concentrate on the employment of the phase-Doppler anemometers that are available rather than placing emphasis on the continuous extension of existing phase-Doppler anemometers to yield information on particle material, measurements of non-spherical particles, etc.

There have been numerous contributions to the development of phase-Doppler anemometry and a good summary of the earlier work was given by Hirleman [12], with useful later contributions by Naqwi et al. [13] and Gouesbet et al. [14].

5. PARTICLE IMAGE VELOCIMETRY AND OTHER FIELDS

When flows are described in terms of the local time varying velocity field, i.e. as $U_j(x_i, t)$, there are basically two way to analyse experimental and/or numerical data.

- Local analysis: This approach fixes the measuring location x_i = constant and analyses the velocity data as a time series. This is the usual way in which hot-wire and laser-Doppler anemometers are operated.

- Spatial analysis: This approach fixes the measuring time t = constant and analyses the velocity data as a distribution of velocities in space. This is the usual way in which particle image velocimetry works.

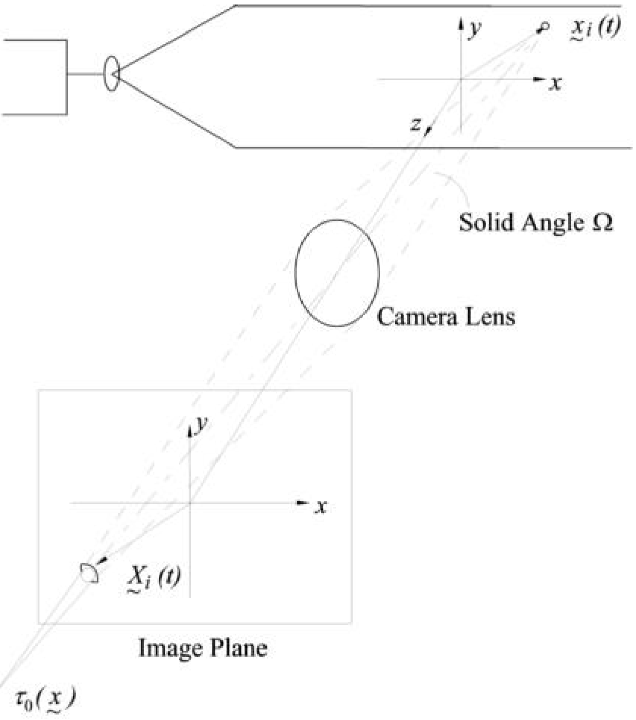


Fig. 18. Pulsed illuminating beam and photographic image plane

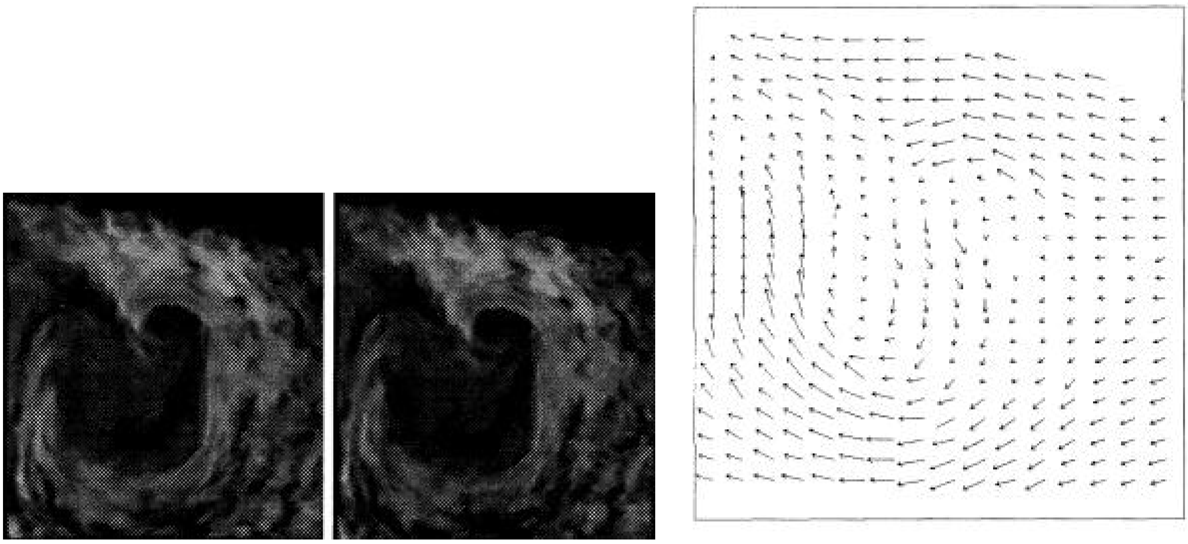


Fig. 19. Flow against a vertical plate visualised by smoke and velocity distribution measured by PIV, results by Uemura et al. [15]

Particle image velocity (PIV) employs an optical set-up of the kind shown in Fig. 18, as described by Adrian [16]. Field information results are sketched in Fig. 19. In the illuminated plane of thickness Δs, all those pairs of components of the velocity fields are recorded that were represented by a scattering particle and fulfilled the following requirements:

- enough light is scattered by the corresponding particle to yield a good record of the particle, hence the particle, was large enough to be seen;

- the particle had good properties, size, density and shape to follow the flow, hence the particle was small enough to follow the flow;
- the velocity component of the particle perpendicular to the light sheet was small so that the following relationship holds:

$$U_\perp \le \frac{\Delta s}{\Delta t}$$

where $U_\perp$ = velocity component perpendicular to light sheet,

Δs = thickness of illuminated sheet and

Δt = time between particle images

Hence conditional information on the velocity field is obtained.

Another method that should be mentioned as a field method is Doppler global velocimetry (DGV), e.g. see Meyers and Lee [17]. With this technique the absorption properties of iodine are used to obtain direct Doppler shift information for the scattered light optical systems of the kind shown in Fig. 20.

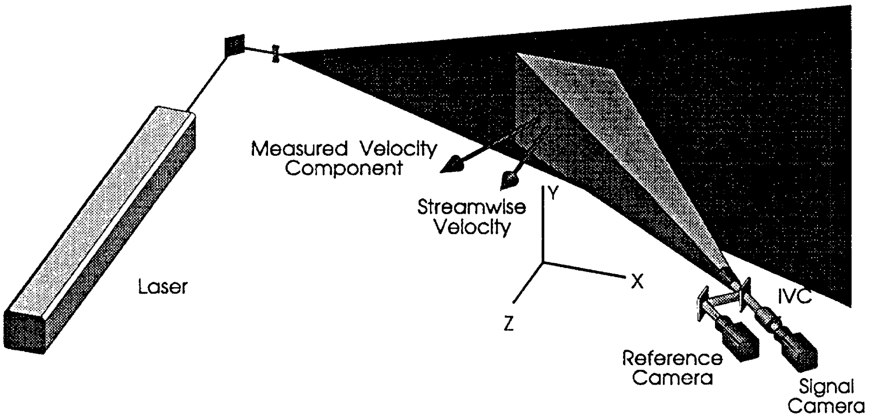


Fig. 20. Sketch of optical arrangement of Doppler global velocimeter, Meyers and Lee [17]

Rayleigh scattering, laser-induced fluorescence, etc., are other techniques that have been suggested, developed and built to yield field information on flows. However, all these field methods have not yet reached the stage of development where they can readily applied in fluid flow studies to yield detailed information on laminar and especially on turbulent flows.

6. CONCLUSION

In this review we have tried to show that fluid mechanics research has a long history and was initially embedded in fields such as mathematics and physics. Hence, basic equations of fluid mechanics were available at the end of the 17th and the beginning of the 18th century, but the equations could not be solved for engineering types of flows. The necessary developments of methods were carried out in the second half of the 20th century to yield those experimental and numerical techniques which can now be employed to investigate laminar and turbulent flows. There is basically no flow these days below a Reynolds number of 50 000 which cannot be studied in detail by either experimental or numerical techniques. It is worth noting, however, that higher Reynolds number flows cannot be investigated in detail because the available experimental techniques cannot resolve in a sufficient way the velocity gradients that occur in such flows and numerical methods require computer powers that are not yet available to solve directly the Navier-Stokes equations. Hence turbulence at high Reynolds number is the only remaining basic problem to be solved in fluid mechanics. Low Reynolds number flows can be investigated with the methods that have been developed in the second half of the 20th century.

Without any doubt, developments of experimental methods will continue in the years ahead. Development of numerical methods will also continue but one should be aware that there will be a change in fluid mechanics research, as can already be observed today, which will be directed towards the application of methods to study fluid flows rather than to emphasise their development. The golden age of fluid mechanics has started. Fluid flows can be studied using fully developed experimental and numerical techniques that are currently available.

REFERENCES

[1] Van Dyke, M. (1982). “An Album of Fluid Motion”, Parabolic Press, Stanford, California

[2] Hama, R.F. (1962). “Streaklines in a Perturbed Shear Flow”, Physics of Fluids 5, pp. 644-650

[3] Eckelmann, H. (1997). “Einfuehrung in die Stroemungsmesstechnik”, Teubner Studienbuecher Mechanik, B.G. Teubner, Stuttgart

[4] Bruun, H.H. (1995). “Hot-Wire Anemometry: Principles and Signal Analysis”, Oxford University Press Inc. New York

[5] Lumley, J.L. (1970). “Stochastic Tools in Turbulence”, Academic Press, New York

[6] Durst, F., Melling, A., Whitelaw, J.H. (1981). “Principles and Practice of Laser-Doppler Anemometry”, Second Edition, Academic Press, New York

[7] van de Hulst, H.C. (1957). “Light Scattering by Small Particles”, Wiley Press, New York

[8] Kerker, M. (1969). “The Scattering of Light and Other Electromagnetic Radiation”, Academic Press, New York

[9] Hjelmfelt, A.T., Mockros, L.F. (1966). “Motion of Discrete Particles in a Turbulent Fluid”, Appl. Sci. Res. 16, 149

[10] Durst, F. (1973). “Scattering Phenomena and Their Application in Optical Anemometry”, Zeitschrift fuer Angewandte Mathematik und Physik 24, 619

[11] Durst, F., Zaré, M. (1975). “Laser-Doppler Measurements in Two-Phase Flows”, Proceedings of the LDA-Symposium Copenhagen, pp. 403-429

[12] Hirleman, E.D. (1996). “History of Development of the Phase-Doppler Particle-Sizing Velocimeter”, Part. Part. Syst. Charact. 13, pp. 59-67

[13] Naqwi, A., Durst, F., Liu, X. (1991). “Two Optical Methods for Simultaneous Measurement of Particle Size, Velocity and Refractive Index”, Applied Optics, Vol. 30, No. 33, pp. 4949-4959

[14] Gouesbet, G. (1994). “Generalized Lorenz-Mie Theory and Applications”, Part. Part. Syst. Charact. II, pp. 22-34

[15] Uemura, T., Yoshimoto, M., Tatumil, M., Kaga, A. (1997). “Simultaneous Multiple Pixel Processing Algorithms for PTV and PIV”, Developments in Laser Techniques and Fluid Mechanics, Selected Papers from the 8th Int. Symp. on Applications of Laser Anemometry to Fluid Mechanics, Ladoan, Portugal

[16] Adrian, R.J. (1988). “Statistical Properties of Particle Image Velocimetry Measurements in Turbulent Flow”, Laser Anemometry in Fluid Mechanics – III, Selected Papers from the Third Int. Symp. on Applications of Laser Anemometry to Fluid Mechanics, Ladoan, Portugal

[17] Meyers, J.F., Lee, J.W. (1993). “Three Component Doppler Global Velocimeter Measurements of the Flow Above a Delta Wing”, Proceedings of the 6th Int. Symp. Lisbon, Portugal, 20-23 July 1992, Springer-Verlag, Berlin, pp. 345-363