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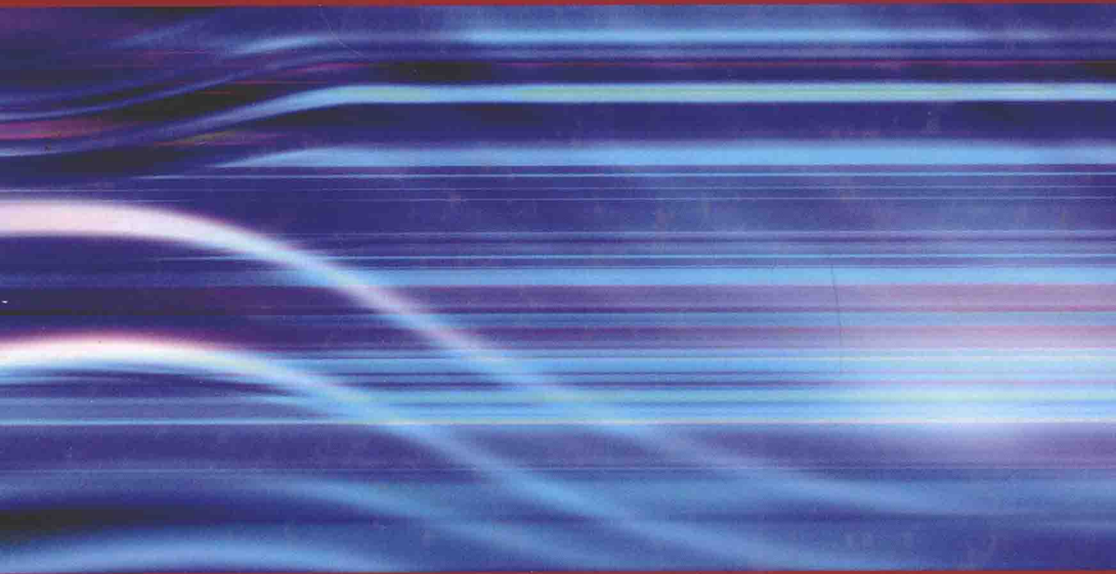

Laser Velocimetry in Fluid Mechanics

Edited by
Alain Boutier

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Preface

This book has been elaborated from lectures given in the context of autumn schools organized since 1997 by AFVL – Association Francophone de Vélocimétrie Laser (French-speaking Association of Laser Velocimetry).

AFVL activities are especially dedicated to foster and facilitate the transfer of knowledge in laser velocimetry and all techniques making use of lasers employed for metrology in fluid mechanics. Among the main objectives, a good use of laser techniques is investigated in order to fulfill requirements of potential applications in research and industry.

The authors of this book have thus shared their expertise with AFVL, which led them to write the various chapters within a teaching perspective, which allows the reader to learn and perfect both his theoretical and practical knowledge.

Alain Boutier
September 2012

Introduction

In fluid mechanics, velocity measurement is fundamental to improve knowledge of flow behavior. Flow velocity maps are key to elucidating mean and fluctuating flow structure, which in turn enables code validation.

Laser velocimetry is an optical technique for velocity measurement: it is based on light scattering by tiny particles used as flow tracers, and enables the determination of local fluid flow velocity as well as its fluctuations. Particles, approximately 1 µm in size, are used because the light flux they scatter is about 10^4 more intense than this due to molecular diffusion. Nevertheless, these particles (which are the fundamental basis of this technique) have two main disadvantages: discontinuous information (because data sampling is randomly achieved) and inaccurate representation of the fluid velocity gradients.

For each technique, the basic principles, along with the optical devices and signal processors used, are described. Chapter 7 is specifically dedicated to flow seeding; it describes products currently used and appropriate aerosol generators. Data post-processing has been also extensively developed: it allows synthetic and phenomenological information to be extracted from the vast quantities of data coming from detailed measurements. As a result, a link can be established between flow physics and predictions from codes.

This book presents various laser velocimetry techniques together with their advantages and disdvantages and their specificities: local or planar, mean or instantaneous, 3D measurements.

Another book by the same authors, entitled *Laser Metrology in Fluid Mechanics* [Bou 12] describes velocity measurements by spectroscopic techniques, which are

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Introduction written by Alain BOUTIER.

based on molecular diffusion and are better suited for very high-velocity flow characterization. In this other book, two chapters are specifically dedicated to light scattering and to particle granulometry by optical means, these measurement techniques being more dedicated to two-phase flow studies. The main recommendations concerning laser security are also recalled.

Bibliography

[BOU 12] BOUTIER A. (ed.), *Laser Metrology in Fluid Mechanics*, ISTE, London, John Wiley & Sons, New York, 2012.

Table of Contents

Preface xi
Alain BOUTIER

Intoduction xiii
Alain BOUTIER

Chapter 1. Measurement Needs in Fluid Mechanics 1
Daniel ARNAL and Pierre MILLAN

1.1. Navier-Stokes equations 2
1.2. Similarity parameters 4
1.3. Scale notion 6
1.4. Equations for turbulent flows and for Reynolds stress tensor 6
1.5. Spatial-temporal correlations 8
1.6. Turbulence models 10
1.6.1. Zero equation model 11
1.6.2. One equation model 11
1.6.3. Two equations model 12
1.6.4. Reynolds stress models (RSM, ARSM) 12
1.7. Conclusion 13
1.8. Bibliography 13

Chapter 2. Classification of Laser Velocimetry Techniques 15
Alain BOUTIER

2.1. Generalities 16
2.2. Definitions and vocabulary 17
2.3. Specificities of LDV 19
2.3.1. Advantages 19
2.3.2. Use limitations 20

2.4. Application domain of laser velocimeters (LDV, PIV, DGV) 21
2.5. Velocity measurements based on interactions with molecules 22
2.5.1. Excitation by electron beams 22
2.5.2. Laser fluorescence 23
2.5.3. Spectroscopy with a tunable laser diode in the infrared 23
2.5.4. Coherent anti-Stokes Raman scattering technique 24
2.5.5. Tagging techniques 24
2.5.6. Summary 25
2.6. Bibliography 28

Chapter 3. Laser Doppler Velocimetry 33
Alain BOUTIER and Jean-Michel MOST

3.1. Introduction 33
3.2. Basic idea: Doppler effect 34
3.2.1. Double Doppler effect 34
3.2.2. Four optical set-ups 36
3.2.3. Comments on the four configurations 39
3.3. Fringe velocimetry theory 40
3.3.1. Fringe pattern in probe volume 40
3.3.2. Interferometry theory 42
3.3.3. Comparison between the three theoretical approaches 44
3.3.4. SNR. 44
3.4. Velocity sign measurement 48
3.4.1. Problem origin 48
3.4.2. Solution explanation 49
3.4.3. Various means to shift a laser beam frequency 51
3.5. Emitting and receiving optics 56
3.5.1. Emitting 56
3.5.2. Probe volume characteristics 61
3.5.3. Receiving part 64
3.6. General organigram of a mono-dimensional
fringe velocimeter 67
3.7. Necessity for simultaneous measurement
of 2 or 3 velocity components 68
3.8. 2D laser velocimetry 70
3.9. 3D laser velocimetry 71
3.9.1. Exotic 3D laser velocimeters 71
3.9.2. 3D fringe laser velocimetry 72
3.9.3. Five-beam 3D laser velocimeters 73
3.9.4. Six-beam 3D laser velocimeters 74
3.10. Electronic processing of Doppler signal 79
3.10.1. Generalities and main classes of Doppler processors 79

3.10.2. Photon converter: photomultiplier 79
3.10.3. Doppler burst detection 84
3.10.4. First processing units 86
3.10.5. Digital processing units 88
3.10.6. Exotic techniques 102
3.10.7. Optimization of signal processing 103
3.11. Measurement accuracy in laser velocimetry 103
3.11.1. Probe volume influence 104
3.11.2. Calibration 105
3.11.3. Doppler signal quality 112
3.11.4. Velocity domain for measurements 114
3.11.5. Synthesis of various bias and error sources 117
3.11.6. Specific problems in 2D and 3D devices 123
3.11.7. Global accuracy 126
3.12. Specific laser velocimeters for specific applications 127
3.12.1. Optical fibers in fringe laser velocimetry 127
3.12.2. Miniature laser velocimeters 132
3.12.3. Doppler image of velocity field 133
3.13. Bibliography 134

Chapter 4. Optical Barrier Velocimetry 139
Alain BOUTIER

4.1. Laser two-focus velocimeter. 139
4.2. Mosaic laser velocimeter 145
4.3. Bibliography 147

Chapter 5. Doppler Global Velocimetry 149
Alain BOUTIER

5.1. Overview of Doppler global velocimetry 149
5.2. Basic principles of DGV 150
5.3. Measurement uncertainties in DGV 153
5.4. Bibliography 156

Chapter 6. Particle Image Velocimetry 159
Michel RIETHMULLER, Laurent DAVID and Bertrand LECORDIER

6.1. Introduction 159
6.2. Two-component PIV 164
6.2.1. Laser light source 164
6.2.2. Emission optics in PIV 168
6.2.3. Image recording 169
6.2.4. PTV (Particle Tracking Velocimetry) 185

6.2.5. Measurement of velocity using PIV 192
6.2.6. Correlation techniques 201
6.3. Three-component PIV 233
6.3.1. Introduction 233
6.3.2. Acquisition of the signal from the particles 234
6.3.3. Evaluation of the particles' motion 236
6.3.4. Modeling of sensor 237
6.3.5. Stereoscopy: 2D-3C PIV 252
6.3.6. 2.5D-3C surface PIV 259
6.3.7. 3C-3D volumic PIV 261
6.3.8. Conclusion 268
6.4. Bibliography 269

Chapter 7. Seeding in Laser Velocimetry 283
Alain BOUTIER and Max ELENA

7.1. Optical properties of tracers 284
7.2. Particle generators 288
7.3. Particle control 292
7.4. Particle behavior 297
7.5. Bibliography 303

Chapter 8. Post-Processing of LDV Data 305
Jacques HAERTIG and Alain BOUTIER

8.1. The average values 306
8.2. Statistical notions 308
8.3. Estimation of autocorrelations and spectra 314
8.3.1. Continuous signals of limited duration 314
8.3.2. Signals sampled periodically (of limited duration T) 316
8.3.3. Random sampling 318
8.4. Temporal filtering: principle and application to white noise 321
8.4.1. Case of white noise 321
8.4.2. Moving average (MA) 323
8.4.3. Autoregressive (AR) process: Markov 324
8.5. Numerical calculations of FT 326
8.6. Summary and essential results 329
8.7. Detailed calculation of the FT and of the spectrum
of fluctuations in velocity measured by laser velocimetry 330
8.7.1. Notations and overview of results regarding the FT 331
8.7.2. Calculating the FT of a sampled function F(t):
periodic sampling 333
8.7.3. Calculating the FT of a sampled function F(t):
random sampling 335

8.7.4. FT of the sampled signal reconstructed after periodic sampling 339
8.7.5. FT of the sampled signal, reconstructed after random sampling 341
8.7.6. Spectrum of a random signal sampled in a random manner 345
8.7.7. Application to some signals 352
8.7.8. Main conclusions 356
8.8. Statistical bias 358
8.8.1. Simple example of statistical bias 358
8.8.2. Measurement sampling process 360
8.8.3. The various bias phenomena in laser velocimetry 368
8.8.4. Analysis of the bias correction put forward by McLaughlin and Tiederman 369
8.8.5. Method for detecting statistical bias 369
8.8.6. Signal reconstruction methods 372
8.8.7. Interpolation methods applied to the reconstructed signal 374
8.9. Spectral analysis on resampled signals 375
8.9.1. Direct transform 376
8.9.2. Slotting technique 377
8.9.3. Kalman interpolating filter 379
8.10. Bibliography 384

Chapter 9. Comparison of Different Techniques 389
Alain BOUTIER

9.1. Introduction 389
9.2. Comparison of signal intensities between DGV, PIV and LDV 390
9.3. Comparison of PIV and DGV capabilities 394
9.4. Conclusion 396
9.5. Bibliography 397

Conclusion 399
Alain BOUTIER

Nomenclature 401

List of Authors 407

Index 409

Chapter 1

Measurement Needs in Fluid Mechanics

Measurements provide useful information for the interpretation of physical phenomena and for code validation. Fluid mechanics is based on nonlinear Navier-Stokes equations, which are very difficult to solve directly; simplifying assumptions or numerical approximations are used in order to make calculation times reasonable. Sometimes empirical relations are established when theory is not available; in particular, turbulent regime analysis leads to the building of new theories that must be verified. All these processes require validation by experiments and accurate measurements.

The most famous names in physics are associated with knowledge evolution in fluid mechanics, from Newton to Euler, Navier and Stokes, and also Bernoulli, Lagrange, Leibniz and Cauchy.

Theoretical approaches consist of mathematical resolution of partial differential equations. When an analytical solution is not possible, numerical approaches are used, but must be verified by well-documented experiments. In fluid mechanics, more than elsewhere, the three approaches (theory, simulation, and experimentation) often cannot be separated.

Theoretical treatment is exact and universal, but requires good physical knowledge of the phenomena. Boundary conditions are often made ideal and solutions are not available for complex flow configurations.

Chapter written by Daniel ARNAL and Pierre MILLAN.

Numerical simulation provides complete flow information, with conditions that can be easily modified. Nevertheless, the process is often very expensive to put into operation, is limited by the computer power, and as turbulence models are not universal, a certain ability is required for correct employment.

Experimental investigations make parametric studies possible, in order to recognize which parameters are influent; sometimes it is the only way to obtain information. Yet they may appear rather complicated and expensive to implement; not all the variables can be measured and the intrusive character of the measuring method must be minimized.

1.1. Navier-Stokes equations

General equations in fluid mechanics are based on mass and energy conservation, as well as on movement quantity equations. These equations, called Navier-Stokes equations, make use of spatial and temporal partial derivatives of velocity and temperature, at first and second order. Even if exact solutions exist for simple laminar flows, for real flows, which are turbulent and 3D, calculations become much too complex to be solved by current computers within acceptable timescales. Therefore, numerical solutions are not exact and generate errors that must be evaluated by experiments and appropriate measurements.

The continuity equation (mass conservation) is expressed by:

$$\frac{\partial \rho}{\partial t} + \operatorname{div}\left(\rho \vec{V}\right) = 0 \qquad [1.1]$$

where ρ is the volume mass and $\vec{V}$ the velocity vector, with (u, v, w) coordinates in the frame (x, y, z) or (u_1, u_2, u_3) in the frame (x_1, x_2, x_3).

For an incompressible flow (ρ = constant), it becomes:

$$\operatorname{div}\vec{V} \quad \text{i.e.} \quad \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad [1.2]$$

The movement quantity equation expresses the fact that the system movement quantity derivative is equal to the sum of the forces acting on the system. Using some assumptions, mainly that of Newtonian flow, this vector equation is written:

$$\begin{aligned}&\rho\frac{\partial \vec{V}}{\partial t} + \rho\,\overrightarrow{\overrightarrow{\text{grad}}}\,\vec{V}.\vec{V} = \overrightarrow{\text{div}\,\overrightarrow{\Sigma}}\\ &\text{with } \overrightarrow{\overrightarrow{\Sigma}} = -\left(P+\frac{2\mu}{3}\operatorname{div}\vec{V}\right)\overrightarrow{\overrightarrow{I}} + \mu\left(\overrightarrow{\overrightarrow{\text{grad}}}\vec{V} + \overrightarrow{\overrightarrow{\text{grad}}}\,\vec{V}^{t}\right)\end{aligned} \qquad [1.3]$$

$\vec{\vec{\Sigma}}$ is the constraint tensor, which makes pressure P and dynamic viscosity μ appear. $\vec{\vec{I}}$ represents the unity tensor.

In incompressible conditions, movement quantity equation along x is reduced to:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad [1.4]$$

where $\nu = \mu/\rho$ is the kinematic viscosity.

The energy conservation equation interprets that total energy variation E of the fluid contained inside a volume is equal to the summation of the mechanical and thermal energies introduced into this volume. It is written as:

$$\frac{\partial(\rho E)}{\partial t}+\operatorname{div}\left(\rho E\vec{V}-\vec{\vec{\Sigma}}.\vec{V}-\lambda_c\overrightarrow{\operatorname{grad}}\,T\right)=0 \quad [1.5]$$

$\phi_c = -\lambda_c \overrightarrow{\operatorname{grad}T}$ is the conduction heat flux, expressed by Fourier's law; in this expression, λ_c is thermal conductivity. We can also derive similar equations for internal energy, enthalpy, total enthalpy or entropy. These equations are deduced from one another using the definitions of considered quantities.

The velocity gradient tensor describes deformation kinematics of a volume element:

$$u_i\left(x_j+dx_j,t\right)=u_i\left(x_j,t\right)+\frac{\partial u_i}{\partial x_j}dx_j \quad [1.6]$$

It is decomposed into a symmetric tensor (deformation) and an anti-symmetric tensor (rotation):

$$\frac{\partial u_i}{\partial x_j}=\underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)}_{\text{deformation}}+\underbrace{\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)}_{\text{rotation}} \quad [1.7]$$

The rotational part of the velocity field is called the vorticity:

$$\vec{\omega}=\overrightarrow{\operatorname{rot}}\,\vec{V} \quad [1.8]$$

Flows having a velocity potential are characterized by $\vec{\omega} = 0$, a condition that is not valid for turbulent flows. A transport equation for vorticity is generally obtained when combining Navier-Stokes equations.

1.2. Similarity parameters

Dynamic and geometric similarity between two flows can be established using general adimensional equations. The following adimensional variables are generally used:

$$\rho^* = \frac{\rho}{\rho_\infty};\ u^* = \frac{u}{V_\infty};\ v^* = \frac{v}{V_\infty};\ p^* = \frac{p}{p_\infty};\ \mu^* = \frac{\mu}{\mu_\infty};\ x^* = \frac{x}{L};\ y^* = \frac{y}{L} \qquad [1.9]$$

where $\rho_\infty, V_\infty, p_\infty$ and μ_∞ are reference values and L a length characteristic scale, for instance, a wing or model chord.

When introducing these adimensional variables into movement quantity equation [1.3], written for a stationary flow (for instance), it becomes:

$$\rho\,\overrightarrow{\overrightarrow{\text{grad}}\,\vec{V}}.\vec{V} = -\frac{1}{\gamma M_\infty^2}\overrightarrow{\text{grad}}\,P + \frac{1}{\text{Re}_\omega}\text{div}\,\overrightarrow{\overrightarrow{\Sigma_v}}$$

$$\text{with } \frac{p_\infty}{\rho_\infty V_\infty^2} = \frac{\gamma p_\infty}{\gamma \rho_\infty V_\infty^2} = \frac{a_\infty^2}{\gamma V_\infty^2} = \frac{1}{\gamma M_\infty^2} \qquad [1.10]$$

$$\text{and } \frac{\mu_\infty}{\rho_\infty V_\infty L} = \frac{1}{\text{Re}_\infty}$$

$\overrightarrow{\overrightarrow{\Sigma_v}}$ is the viscous part of the constraint tensor (terms in μ). γ is the ratio between specific heats at constant pressure (*Cp)* and at constant volume (*Cv*).

The Reynolds number (Re_∞) and Mach number (M_∞) are adimensional numbers. If two flows with the same boundary conditions provide identical values for Re_∞ and M_∞, then general equations of both flows are identical, as are their solutions.

The Reynolds number and Mach number are not the only similarity parameters. When taking into account various effects such as compressibility, instationarity, gravity, etc. other adimensional numbers appear in equations. The following table summarizes the main adimensional numbers used in fluid mechanics.

Geometric similarity is obtained when a geometric homothety allows passage from reality to a model. Thermal and dynamic similarities impose conservation of the adimensional parameters previously defined. Generally, all these conditions cannot be simultaneously satisfied.

Coupling experimental and numerical methods is indispensable for a better handling of phenomena in fluid mechanics. Good validation is achieved only if these two approaches are coupled in a complementary way. Validation requires using appropriate equations and boundary conditions; the nature of numerical solutions must be checked before analyzing the experimental results. For laminar flows, validation does not raise any specific problems. Description of flows with shock waves remains a problem.

Number	Definition	Physical interpretation	Application field
Reynolds	$\mathrm{Re} = \frac{\rho U L}{\mu}$	$\frac{\text{Inertial forces}}{\text{Viscous forces}}$	Always
Mach	$M_\infty = \frac{U}{a} = U\sqrt{\frac{\rho}{\gamma p}}$	$\frac{\text{Fluid velocity}}{\text{Sound velocity}}$	Compressible
Froude	$Fr = \frac{U^2}{gL}$	$\frac{\text{Kinetic energy}}{\text{Potential energy}}$	Free surface (gravity is important)
Weber	$We = \frac{\rho U^2 L}{\sigma}$	$\frac{\text{Inertial forces}}{\text{Surface tension forces}}$	Two-phase flow, capillary effect
Prandtl	$\mathrm{Pr} = \frac{\mu Cp}{\lambda_c}$	$\frac{\text{Dissipation}}{\text{Thermal Conduction}}$	Heat, thermal effects
Strouhal	$Str = \frac{\omega L}{U}$	$\frac{\text{Frequency oscillation}}{\text{Mean velocity}}$	Acoustics
Euler	$Ca = \frac{p - p_v}{\rho U^2}$	$\frac{\text{Pressure}}{\text{Inertial forces}}$	Cavitations
Grashof	$Gr = \frac{\beta \Delta T g L^3 \rho^2}{\mu^2}$	$\frac{\text{Agitation forces}}{\text{Viscous forces}}$	Archimedes thrust, natural convection
Roughness	$k = \frac{\varepsilon}{L}$	$\frac{\text{Roughness scale}}{\text{Length macro-scale}}$	Turbulent boundary layer

1.3. Scale notion

Turbulent flows are also treated by simulation means, but the problem is caused by the fact that these flows present a wide spectrum of space and timescales. In order to obtain an exact solution for a turbulent flow, small and large scales (time and space) contained in the flow must be solved. The ratio between length scales (according to Kolmogorov, small η over large δ) is given by the following relationship:

$$\frac{\eta}{\delta} = \mathrm{Re}^{-3/4} \qquad [1.11]$$

where Re is the Reynolds number formed with characteristic scales (velocity, length) of large structures. It appears that ranges of large and small scales deviate more with increasing Reynolds numbers, which induces increasing difficulties for the resolution of all scales at higher Reynolds numbers. The computation of turbulent flow inside a volume of 1 m^3 would take too much time (depending upon the Reynolds number, velocity and viscosity). Methods that avoid solving all scales make use of models in order to reduce prohibitive *Direct Numerical Simulation* (DNS) calculation times: these use *Large Eddy Simulation* (LES) and *Reynolds Averaged Navier-Stokes* (RANS) methods.

1.4. Equations for turbulent flows and for Reynolds stress tensor

The classic statistical description of turbulent flows is based on velocity and instantaneous pressure decomposition into a mean part (which is time independent) and a fluctuating part (which is time dependent). For the velocity component, u_i becomes:

$$u_i(x_j,t) = \overline{u_i}(x_j) + u'_i(x_j,t) \qquad [1.12]$$

The mean temporal value is:

$$\overline{u}_i\left(x_j\right) = \lim_{T\to\infty}\frac{1}{T}\int_0^T u_i\left(x_j,t\right)\mathrm{d}t \qquad [1.13]$$

The resulting mean Navier-Stokes equations then include additional terms, called Reynolds stresses. For instance, the movement quantity equation along x for a 2D and stationary flow takes the following form:

$$\rho u\frac{\partial u}{\partial x} + \rho v\frac{\partial u}{\partial y} = -\frac{dP}{dx} + \frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x} - \rho\overline{u'^2}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y} - \rho\overline{u'v'}\right) \qquad [1.14]$$