Flow and Transport Processes with Complex Obstructions

Edited by

Yevgeny A. Gayev and Julian C.R. Hunt

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Series II: Mathematics, Physics and Chemistry – Vol. 236

Flow and Transport Processes with Complex Obstructions

Applications to Cities, Vegetative Canopies, and Industry

edited by

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Preface

The NATO Advanced Study Institute "Flow and Transport Processes in Complex Obstructed Geometries: from cities and vegetative canopies to engineering problems" was held in Kyiv, Ukraine in the period of May 4 - 15, 2004. This book based on the papers presented there provides an overview of this new area in fluid mechanics and its applications that have developed over the past three decades. The subject, whose origins lie both in theory and in practice, is now rapidly developing in many directions.

The focus of applied fluid mechanics research has steadily been shifting from engineering to environmental applications. In both fields there has been great interest in the study of flows around obstacles; initially single isolated obstacles, and then groups, together with the effects of nearby resistive surfaces, such as the walls of a pipe, the ground or a free surface in hydraulics.

Simplified theoretical analysis began with studies of axisymmetric and cylindrical free-mounted bodies. However other methods had to be used for quantifying the complete flow fields past arbitrary bluff bodies, either by using experiments or, when powerful computers became available, by direct calculation and solution of the full equations of fluid dynamics. In most practical cases the Reynolds numbers are too large to compute all the small scale eddy motions which therefore have to be described statistically. There are various approaches to deriving these models, all of which are approximate. The models have to account for the way in which the obstacles interact with the spectrum of random eddies in the approach flow and, on the downstream side, how they interact with eddies shed from those obstacles. For some practical applications only the mean flow properties are required, for example mean heat transfer. B.E. Launder and J.L. Lumley have shown (starting with the concepts of A.N. Kolmogorov in 1942) that Reynolds stress closure models can provide 'engineering approximations' in many cases. However, if fluctuating loads on the obstacles or the noise produced by them have to be predicted, for example, it is necessary to calculate the full spectrum and how it is distorted. Useful concepts and estimates have been derived from G.K. Batchelor's rapid distortion theory and from 'flow receptivity', or 'shear sheltering'. With a better understanding of these different methods, it is becoming possible to predict when and where different models are appropriate. General concepts of flow patterns around bodies with complex shapes have been proposed, based on M.J. Lighthill's analysis, using topological ideas; by classifying and locating singular points where the velocity (or certain components) are zero, it is possible to describe complex flows very efficiently.

The first fundamental study of the flow through groups of obstacles (for calculating the performance of aircraft radiators) was conducted by G.I. Taylor in 1944. This was later applied by P.R. Owen to the estimation of the flow between tall cooling towers which collapsed in high winds at Ferrybridge in the UK in 1965. Meteorologists who investigate the energy balance between the whole atmosphere and the Earth's surface require detailed information about the flow within forests and agricultural canopies, where heat, moisture and gases are produced and transported aloft. Researchers from different countries, including early pioneers H. Penman and I. Long, Z. Uchijima, E. Inoue, O. Denmead, J. Wright and E. Lemon, I. Cowan, R. Cionco, A. Thom, L. Allen, M. Budyko, A. Konstantinov G. Thurtell, and researchers of the younger generation J. Finnigan, M. Raupach and R. Shaw, A. Dubov, G. Menzhulin, G. Thurtell, Y. Brunet, D. Baldocchi were among the first who investigated such "obstructed flows" experimentally and theoretically. Wind engineers, such as M. Jensen, J. Cermak, R. Meroney and E. Plate, recognised that similar flow distortion occurs in human settlements and showed how laboratory experiments in wind tunnels, based on well-established scaling laws, could accurately simulate the field measurements, along with contributing to the further development of penetrable roughness theory.

Similar problems emerged in the study of hydraulics of vegetated channels or flood plains, although these were addressed quite independently. Penetrable structures of aquatic vegetation considerably change features of the water flows. Investigations initiated by N. Kouwen, I. Nickitin, K. Kosorin, D. Knight, E. Pasche and S. Petryk, in different countries, are now being continued by H. Nepf, I. Nezu, H. Stefan, T. Tsujimoto, F. Lopez and others. Experiments in water flumes, together with theoretical studies, have highlighted the significant features that are common with the air flow and turbulence determined earlier by meteorologists. However, there is still insufficient collaboration between the experts in meteorology, engineering and hydraulics.

Research on flow through canopies is especially relevant for understanding the general quality of the urban environment, which is under great threat as an increasing proportion of the world's population, above 70%, will be living in these areas by the year 2050. The main environmental hazards are associated with high concentrations of pollutants in the air, water and ground. The contribution of applied fluid mechanics lies in the improved prediction of the dispersion of hazardous materials within complex obstructed geometries. An important special problem is concerned with the sudden release of pollutants from accidents or terrorist action. The European programs TRAPOS, SATURN and FUMAPEX have contributed useful results, as have similar programs in the USA. Some aspects of the research by meteorologists for vegetative canopies have been relevant to these flow problems. Equally, there are other significant features of the urban wind environment that are quite different. These include the large variation in the height and spacing of buildings, and the effects of the heat island that drives the urban flow when the approaching atmospheric boundary layer flow is relatively weak. These issues are being considered in recent research and are addressed in papers presented here.

A flow interacting with a number of obstructions is also important for many engineering applications. For example, the Institute of Hydromechanics of UNAS has adopted this approach to improve the performance of the large spraying cooler at the Zaporizhzhya nuclear power plant. The small droplets produced by the spraying cooler have a sufficiently high concentration that they resist the air flow entering the spray by a similar mechanism to the flow distortion in a vegetation canopy layer. On a larger scale, engineering designers of wind 'farms' have observed how the mean velocity and higher turbulence downwind of groups of wind turbines can reduce the average power output. To estimate these effects designers are making use of research on flow through resistive layers. The scales of these flows are sufficiently large that mesoscale meteorological phenomena, such as wind jets in coastal areas, have to be considered.

Clearly, there are a number of special but similar features of turbulence and transport processes in various types of obstructed flows whether in air or water, or uniform or non-uniform canopies, whose elements may be rigid or mobile. The basic mean flow characteristic is that the drag decelerates the flow within the canopy, but as it interacts with the free flow outside the obstructed layer, it tends to cause stagnation or/and vortical zones upwind, whilst leading to mean acceleration above the canopy. The turbulence that arises within the canopy from the small scale eddies shed from individual obstructions interacts with the mean velocity profile and with the large distorted eddies above the canopy generated within the approaching boundary layer. These mechanisms significantly change the statistical structure, resulting, for example, in the formation of larger scale coherent vortices in the shear layer. The "mixing-layer analogy", recently suggested by M. Raupach and J. Finnigan [530], provides a powerful model. These concepts are highly relevant to many aspects of the natural or agricultural environments that are affected by flow processes in canopies, both in the atmosphere and in riverine or coastal flows through vegetated beds in natural conduits and also during flood events [172, 347, 350, 492].

Many expert colleagues contributed to this book. Prof. Robert Meroney (Colorado State University), a pioneer of the use of wind tunnels for simulating complex wind engineering phenomena, has, in this volume, reviewed important new research into numerical simulation of the propagation of fires in forests and urban canopies.

Prof. Roger Shaw (University of California, Davis) describes new developments in the analysis of the turbulent velocity fields in vegetative canopies, using proper orthogonal decomposition (a technique for eddy identification first introduced by J. Lumley in 1967). He argues that this technique complements the previous studies based on statistical models and large eddy simulation numerical methods.

Dr. John Finnigan from Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia in his chapter extends his analysis of the eddy structure of canopy winds to include the effects of complex topography. He shows that there are special features of airflow through forests and over hills that significantly affect the weather and the ecology in these very common situations.

Prof. Yevgeny Gayev (Institute of Hydromechanics UNAS, Ukraine) gives a general review that shows how, by taking an engineering approach to canopy flows, both fundamental insights and useful mathematical models are obtained in addition to those derived from environmental considerations. His field measurements in industrial spraying coolers provide a unique experimental database for this phenomenon.

Prof. Julian Hunt (University College London) introduces a classification of the types of turbulent flow through canopies of different kinds of geometry and length scale. He shows how, by integrating recently developed concepts by many authors, a more comprehensive understanding of eddy structure and turbulence statistics is now emerging. In the atmosphere where canopies may extend over tens of kilometres in urban areas, the combined effects of the earth's rotation and buoyancy forces play a significant role.

Canopy flows are critically dependent on how the wakes of the obstacles interact with each other. Dr. Ian Eames (University College London, UK) analyses how the vorticity is both diffused and annihilated, depending on the spacing and the form of the spatial distribution of the obstacles.

Prof. Heidi Nepf (Massachusetts Institute of Technology, USA) focuses on the similarities between flows through aquatic (deformable) and terrestrial (mainly rigid) canopies. In both cases the flows can be analyzed by assuming the effect of the obstacles, can be approximated by a distributed drag force. However, special features of the aquatic canopies have to be included. Diffusion and dispersion processes within aquatic vegetation are of comparable importance to those in atmospheric and engineering canopy flows.

Dr. Alexander Baklanov (Danish Meteorological Institute, Copenhagen) applies the recent achievements of the theory of canopy flow and diffusion and provides further development and improvement of models for urban meteorology and pollution to emergency preparedness and urban weather prediction.

An extended list of references has been added to this book, for the reader's convenience, along with an index of the most important terms and names and a list of figures.

We hope that this book will be useful to scientists and engineers entering the field of canopy dynamics, architecture, planning, engineering, agriculture and ecology. There has undoubtedly been real progress in research, but we hope this book will stimulate new discoveries and new applications.

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We would like to thank also Dr. Valery Oliynik for designing the Book of Abstracts [300] and Dr. Pavlo Lukianov (both from the Institute of Hydromechanics NASU) for designing this book in LaTeX 2_ε text processor.

Finally, we are grateful to all the co-authors whose names are mentioned at the beginning of each chapter, and whose generous contributions made this book possible.

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Chapter 1

Variety of problems associated with Canopies, or EPRs

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Classical fluid mechanics developed during the XVIIIth and XIXth centuries and the first half of the XXth century dealt mainly with flows over smooth or rough surfaces. The idealization of a sand roughness suggested by L. Prandtl and I. Nickuradze was quite sufficient and successful for contemporaneous problems and brought light to many engineering inventions, as well as for the applications of fluid mechanics in hydraulics and meteorology of that time. No real attention was paid to the fluid motion between roughness elements.

By the middle of the XXth century, new flow-related problems arose in the area of environmental science, particularly in the study of "tall" roughnesses, i.e. structures submerged in a flow and interacting with it. These structures can be treated as a kind of roughness, especially for the flow sufficiently far away over them.

Meteorologists investigated the air motion through vegetation canopies. Hydrologists studied water flows in vegetated channels and in ducts with tall artificial structures. Heat exchangers with a developed roughness required to consider the cooling medium motion between roughness elements, whilst the knowledge of air motion, heat and mass transfer inside a droplet layer is required to correctly specify and operate the spraying cooling systems. Studies of wind engineers and urban ecologists include the experimental investigations of the wind motion and its turbulence between buildings within residential or industrial urban areas, see Chapters 2 and 8. Some of these very

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distinct structures in the flow will be shortly overviewed in what follows. The analysis indicates their several common features, so that a universal approach to study them could be suggested.

The logarithmic velocity profile of a flow over structures in the turbulent flow regime demonstrates that they resemble, indeed, a roughness. However, one needs to know the motion within the roughness, i.e. between the structure elements, as well as to know some associated physical phenomena like diffusion, excitation of elements, and so on. Regardless of the physical nature of the submerged obstructions, the intense shedding of vortices takes place so that the level of the flow turbulence is significantly high. This is an explanation of the 'penetrable roughness' (PR) or 'easily penetrable roughness' (EPR) term used by Brutsaert [90] and Gayev [208] and applied here along with the 'canopy' term.

Common physical features may evidently lead to a uniform theoretical representation of the phenomena. Many authors, particularly those presented in this book, introduced a distributed mass force in the momentum equations (or a distributed source term for the diffusion problem) to represent the influence of obstructions on the flow. The question was whether these mathematical models can cover the main flow features. Below, the overview of several such models will be given. We will start from simple one-dimensional models allowing an analytical investigation, generalize the results to two-dimensional problems, and apply them to some practical problems.

The models and their solutions could be useful both in teaching and research. They confirm once more that distinct structures in different disciplines may be similar from the viewpoint of generalized fluid mechanics.

1.1 Vegetative canopies in meteorology

Natural wind in forests is the most evident and historically first example of a flow through an obstructed geometry. The first qualitative deductions were done yet in the XIXth century. The famous Russian naturalist A.I. Voeikov concluded in his book of 1894: "*The question is very important what happens with the air currents when they meet a high and dense forest... The wind still penetrates into the forest, filtrates through it. But passing it slowly, air changes its properties, especially in temperature and in humidity...*". How the wind changes while moving through the forest was considered by the next generation of scientists who were able to apply already quantitative methods to studying the phenomenon.

Ludwig Prandtl, the originator of many of our recent concepts about fluid motion, also noticed a significant change in the "air properties" when it moves through a tall vegetation. Figure 1.1 reproduced from his book of 1939 [510] demonstrated the qualitative ideas about the wind distribution within a vegetated layer at that time. The logarithmic portion of the mean wind profile 1 was expected over the vegetated layer but nothing was known concerning the distorted portion 2. A number of efforts was still required to parametrize the wind distribution within the forest stand. This was stimulated by practical ecology (forest microclimate or crop microclimate and harvest forecast) as well as by the fundamental problems of the soil-vegetation-atmosphere interaction and its influence on the global Earth surface energy balance.

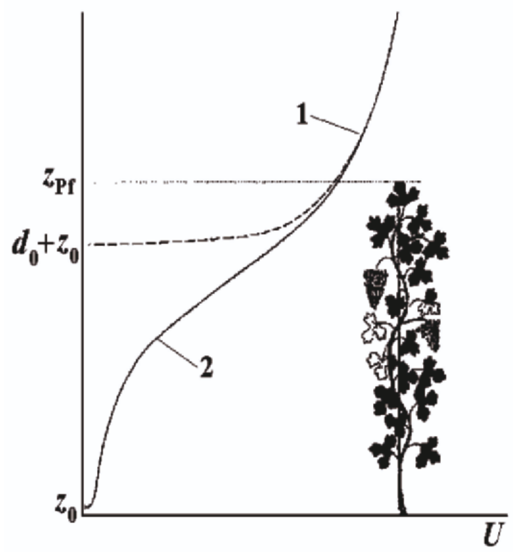

Figure 1.1: Prandtl's [510] qualitative idea of the air flow in vegetative canopies: 1 – logarithmic portion of the wind profile; 2 – distorted profile portion.

Intensive investigations in this field were started in 1950 and 1960 [6, 343, 410, 520]. The first theoretical considerations were suggested in the works of Inoue, Cionco, Lemon, Cowan, and Menzhulin [155, 407, 409, 522]. The recent state of the field has been summarized in the publications of Raupach and Thom, Dubov et al. (1981), Finnigan (2000) [155, 187, 522], as well as in Chapters 4 and 5 of this book. Let us briefly consider the most significant results in this field.

Typical measured vertical wind distributions within two distinct vegetation stands, in a maize crop [366] and in a deciduous forest [520], have been presented in Fig. 1.1 and look similar. The character of the air motion is obviously very different within and over stands. Over the stand, the velocity distributions follow a logarithmic shape. The known logarithmic formula for a rough surface, $U = \frac{U_*}{k} \ln \frac{z}{z_0}$, with the roughness coefficient z_0, or roughness length has been generalized and may be applied in the form

$$U(z) = \frac{U_*}{k} \ln \frac{z - d_0}{z_0} \tag{1.1}$$

where d_0 is an additional fitting parameter called the 'displacement height', $U_* = \sqrt{\frac{\tau_h}{\rho}}$ is the friction velocity, and κ is the von Karman parameter that is equal to 0.40 in the neutrally stratified atmosphere. Several empirical relations for the roughness coefficient and the displacement height have been mentioned in the Chapter 8.

Within the canopy stands, the air motion is significantly decelerated, but nevertheless it is of a considerable value and evidently of vital importance for agrometeorological practice. The internal motion is expected to be less or more depended also on how dense is the vegetated layer. The most popular relation derived theoretically by Inoue

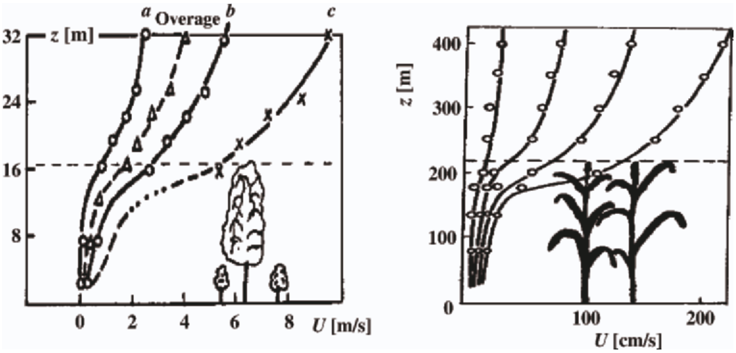

Figure 1.2: Measured mean velocity profiles in (A) maize crop [366] and in (B) deciduous forest [520].

[306] and Cionco [124] takes the form

$$U(z) = U_h e^{\alpha\left(\frac{z}{h}-1\right)} \tag{1.2}$$

where h is the canopy height, and U_h is the velocity at this level. The constant α is dependent on the canopy stiffness (density). We take as an imperfection of this and similar formulas that the velocity does not vanish at the surface, $z = 0$. The Inoue equation [306]

$$U(z) = U_h \frac{\sinh\left(\frac{\alpha z}{h}\right)}{\sinh(\alpha)} \tag{1.3}$$

avoids this flaw. The reason for the flow deceleration within the canopy is evidently the resistance caused by vegetation and its elements. This proves the introduction of forces suggested below.

It is interesting to note that the shapes of many internal wind profiles measured in natural forests reveal a weak ‘bulge’ on them. R. Shaw [572] paid attention to this remarkable phenomenon called the “secondary maximum” that occurs even in vertically homogeneous canopies, see also Section 5.1 of this book. In the discussion commenced afterwards, few new turbulence closures were suggested to reproduce this bulge in the flows through forest canopies. Particularly, a non-traditional hypothesis of a non-local way of the turbulent exchange was published [599] with a suggestion that the turbulence exchange between separated points A and C may be more pronounced than that with an intermediate point B. However, no wind tunnel simulation having used vertically homogeneous arrays confirmed this phenomenon. Therefore, we keep this question still open.

It is also worth noting that the early measurements in forests or in agricultural stands were done with the use of mechanical cup-anemometers placed on several levels of high masts, as was mentioned in [186]. Because of their inertia, they were adequate for recording the average speeds, but insufficient to reflect the turbulence properties.

Nowadays, one applies mainly sonic anemometers in meteorological measurements, [186].

Turbulence of the flow is greatly increased inside the canopy. Turbulence intensity divided by mean longitudinal velocity has been shown in the Fig. 1.1 for several types of forests, [155]. The high level of the turbulence, up to 40% and 60%, can be attributed to vortices in the flow shed from obstructions like tree branches, trunks, and leaves constituting the forest.

There are several theoretical approaches to the canopy flows considered by meteorologists, [17, 155, 187, 522]. In the simplest one-dimensional mathematical model, the canopy is of an infinite extent along the axis Ox of the flow direction. The following mathematical model with coupled ordinary differential equations is the usual approximation in this case [155]:

$$\begin{aligned} \frac{d}{dz}\left(\nu_T \frac{dU}{dz}\right) &= -kV + f_U(z), \\ \frac{d}{dz}\left(\nu_T \frac{dV}{dz}\right) &= k\left(U - U_g\right) + f_V(z). \end{aligned} \tag{1.4}$$

A two-dimensional model is required for the wind running onto a forest edge or onto a finite-length fetch (green belts or shelterbelts). In this case, the significant two-dimensional transformation of the air flow takes place from the entry towards the downstream region, where the flow adjusts to an equilibrium state (1.4). A suitable mathematical model uses partial differential equations [155]:

$$\begin{aligned} U\frac{\partial U}{\partial x} + W\frac{\partial U}{\partial z} &= \frac{\partial}{\partial z}\left(\nu_T \frac{\partial U}{\partial z}\right) + kV - f_U, \\ U\frac{\partial V}{\partial x} + W\frac{\partial V}{\partial z} &= \frac{\partial}{\partial z}\left(\nu_T \frac{\partial V}{\partial z}\right) - k\left(U - U_g\right) - f_V, \\ \frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} &= 0. \end{aligned} \tag{1.5}$$

Here, U and V are horizontal flow velocity components of the geostrophic wind U_g directed, respectively, along Ox and Oy axes, and W is its vertical Oz-component. Nothing is changed in Oy-direction in the two-dimensional case (1.5) and also in Oz-direction in the one-dimensional case (1.4). ν_T is the effective kinematical turbulence viscosity that varies over Oz and Ox in the general case, $\nu_T = \nu_T(x, z)$. The Coriolis force $\vec{f_g} = k\cdot\{V, U_g - U\}$ linearly depends on the local velocity but needs to be accounted for only in tall forest canopies.

The drag force $\vec{f_*} = \{f_U, f_V\}$ on the right-hand side of equations (1.4) or (1.5) parameterizes the influence of the canopy: it equals zero outside it but depends on the local velocity and on the density within the canopy. All the individual obstructions that produce drag forces $\vec{F_i}$ onto the flow in a unit volume Ω, “smeared” into an average

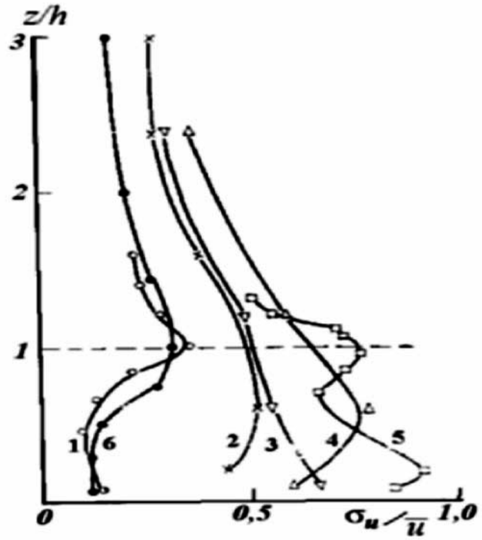

Figure 1.3: Turbulence intensity in various canopies: 1 – spruce and 2 – pine forests [155], 3 – deciduous forest in winter and 4 – in summer [124], 5 – jungle [124], 6 – in a wind tunnel forest model [410]. Cited from [155].

local mass force to the flow by means of the procedure

$$\vec{f} = \{f_U, f_V\} = -\lim_{\Omega\to 0} \frac{\sum_{i=1}^{N} \vec{F}_i}{\rho_1 \Omega}. \tag{1.6}$$

The relations for individual body forces have been well known for a number of body shapes and various circumstances (like turbulence level, body' tandems, etc.) in aerodynamics and in hydraulics [273, 304] and can be explored here. From the general empirical relation for the drag to a body $\vec{F}_i = \frac{1}{2} c_F \rho_1 |\vec{V} - \vec{W}| S$, where S is the cross section area, ρ_1 is the density of the carrying medium (air in this case), $\vec{V} - \vec{W}$ is the relative local velocity of the obstructions with regard to the medium, and $c_F = c_F(\mathrm{Re})$ is the empirical drag coefficient that accounts both for body's form and viscous drag, one obtains the following final parametrization of the mass force *to the medium*:

$$\vec{f}_*(z) = \begin{cases} k_d\left(U\vec{i} + V\vec{j}\right), & z \in [0, h] \\ 0, & z > h \end{cases} \tag{1.7}$$

where h is the canopy height. This force is in the same direction as the local flow velocity $\{U, V\}$, and its magnitude is determined by the drag coefficient k_d. Really, we deem that it is worth to investigate the models discussed below with this coefficient kept constant, i.e. for the linear force law (1.7). However, the force law should be taken quadratic for most practical calculations, because

$$k_d = 0.5 c_F s \sqrt{U^2 + V^2}, \tag{1.8}$$

where

$$s = \lim \frac{\sum_{i=1}^{N} S_i}{\Omega},$$

$1/m$, represents the specific drag area, thus characterizing the canopy density (stiffness) provided $\Omega \to 0$. More generally, Raupach and Thom [522] declare that the distributed force f within forests may be parameterized in the form $f \propto (U - u)^k$ with the exponent $\frac{3}{2} \leq k \leq 2$.

Boundary conditions for the one-dimensional (1.4) and two-dimensional (1.5) models are evident. They are the no-slip condition on the surface and a prescribed velocity value (often, the geostrophic wind velocity U_g) sufficiently far away of the surface:

$$z = o \qquad U = 0, \quad V = 0, \qquad\qquad z \to \infty \qquad U = U_g, \quad V = 0. \tag{1.9}$$

The velocity vector $\vec{V}(z) = U\vec{i} + V\vec{j}$ is known from the general meteorology to rotate by an angle with z, the Eckman arc. The main reason for the rotation is still the Coriolis force, but vegetative resistance favours it, [155].

Three-dimensional performances have been realized by some authors for a few practical arrangements, for example for the forests on hilly terrains, or for a few fundamental investigations like the large-eddy simulation of turbulence structures. This chapter is restricted to only $1d$ or $2d$ problems.

Vegetation that constitutes the forest or agricultural canopy reveals living activities that are vitally important for its influence on the environment or for practical needs of the mankind. This activity manifests itself in the thermal and mass exchange with the air flowing through. The last is the carrier and the mediator in this exchange. The typical vertical distributions of the air temperature and its humidity expressed through the water vapour partial pressure are displayed in Fig. 1.1. For mathematical modelling, the corresponding equations for the relevant quantities should be written down. Similarly to the force parameterizations (1.6)–(1.7), the discontinuous source terms for heat and mass should be included in the form

$$i_H = \begin{cases} \alpha_H S_0 (T - t), & z \in [0, h] \\ 0, & z > h \end{cases}$$

and

$$i_E = \begin{cases} \alpha_H S_0 (E - e), & z \in [0, h] \\ 0, & z > h \end{cases}$$

where i_H (in Wt/m^2) and i_E (in $kg/(s \cdot m^2)$) are the rates of heat and mass sources, correspondingly, T (in grad) and E (in kg/m^3) are the temperature and the admixture

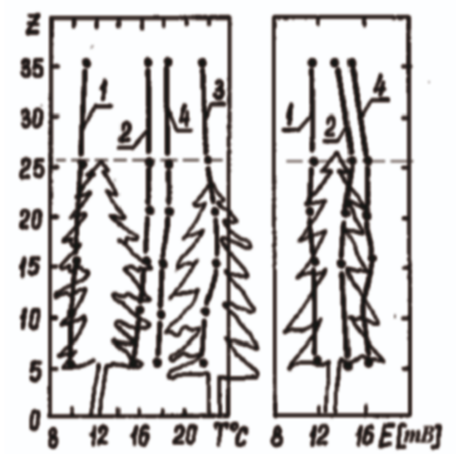

Figure 1.4: Daily course of time-averaged air temperature (A) and aqueous tension (B) within and over a spruce forest for several day moments: 1 – 1 a.m., 2 – 7 a.m. 3 – 1 p.m. and 4 – 7 p.m. [343].

concentration in the flow passing through. The exchange coefficients α_H and α_E should account for the kind of obstructions; biophysics of leaves should be applied in the case of the forest or crop canopies [544, 631].

Most works took the canopy elements rigid and did not consider their motion under the action of a wind. However, when the wind blows over a vegetation stand, the leaves, branches, and stems significantly bend and wave. The motion of agricultural or forest plants and the wind velocity distribution are evidently coupled mutually. A few experiments were carried out however by Finnigan and Raupach, Stacey and Wood e.a. [530, 652]. The early theoretical paper of the Russian scientist Menzhulin [408] introduced the additional equation for tree's stem bending. The resulting mathematical model turned out to be extremely difficult for the investigation. A set of models was suggested by Wood [652], but, again, it hasn't obtained any wide development and application. A much wider attention was given to a closer practically applicable problem of the forests on hills and on the other really complex orography, see chapter 5.

The most important parameter of the models is the turbulent viscosity ν_T that varies over the whole boundary layer, $\nu_T = \nu_T\left(z, \frac{\partial U}{\partial z}, ...\right)$. It should account evidently for the mechanism of mixing processes running in the canopy layer and thus for the regularities of vortices produced there. As in the general turbulence theory, several turbulence models are in use. They vary from relatively simple algebraic closures to the models including several additional differential equations. Some more information will be provided later.

The results obtained by meteorologists for forest canopies are the most advanced. They are widely applied now by other scientists who deal with canopies of other kinds. The theoretical investigations of the forest canopy flows stimulated their laboratory investigations, to which a special paragraph has been devoted.

1.2 Vegetated river beds

Hydraulics and hydrology are another field of study, where we meet structures interacting with a flow. Water flows in natural or artificial conduits with vegetation or with artificial obstructions have obtained a considerable attention of researchers over past 50 years. The main question arisen initially was a reduction in the water discharge associated with vegetation that was estimated to be from 20% to 70%. Prof. V.N. Goncharov stated in his book of 1962 that there were no tools, at that time, to perform such calculations of flows.

Whilst researchers were interested in estimating only the hydraulic discharge capacity of vegetated conduits, the empirical solution of the problem in terms of hydraulic resistance coefficients was quite sufficient in the opinion of Kouwen, Petryk, Knight and Macdonalds and other early authors [338, 350, 492]. During the last 20 years, ecologists require to prohibit the cutting off the vegetation in natural conduits. Its preservation was a new stimulus to understand the problem in more details. From the other side, another practical applications have appeared. For example, the Ukrainian authors Sherenkov and Bennovitsky suggested that water reservoirs vegetated by selected species should be able to absorb biological and chemical impurities in the water stream; the invention was named the "biological plateaus", [55]. For designing this system, one needs to know the mean velocity and the turbulence of flows within vegetation. The investigations of diurnal periodic flows over the aquatic vegetation in coastal regions published in [172] also required to know better of the detailed flow behaviour. The German researchers Rouve, Pasche, Nuding [470, 483, 553] and, later, the Japanese researchers Naot and Nezu [453, 454], Tsujimoto [617, 618, 619] focused on the flows over wetlands and flood plains obstructed by trees, bushes, and buildings during flood events [48, 453, 454, 470, 483, 540, 553, 617]. Some other applications of the fluid dynamics involved the design of passageways that allow fishes to bypass dams. Typically, passageways include artificial obstructions that were penetrable for the flow and fishes, but changed the water stream structure and created the regions with definite levels of the current and the turbidity, that fishes can take advantage of. So, in hydraulics, there are many applications of the studies of the flows in obstructed geometries. The transport of contaminants, nutrients, and sediments will be omitted in this book; a person interested in could be referred to the publication [658].

The fluid mechanics of the water flows through obstructed geometries may be divided into two groups of problems with respect to open surface flows, vertical-plane and horizontal-plane problems.

1.2.1 The problem in a vertical plane

The problem in a vertical plane is formulated for a wide channel, ideally for an infinitely wide one, of a constant depth assuming that the flow pattern is approximately the same in each vertical plane along the flow direction, as it has been depicted in Fig. 1.5. A usual vertical velocity distribution that follows formula (1.1) takes place only above the vegetation submerged in the water flow. This distribution becomes complex and uncommon within the vegetation layer where a significant motion of the water still takes place. A number of experimental data given in [69, 172, 347, 370, 617] confirms

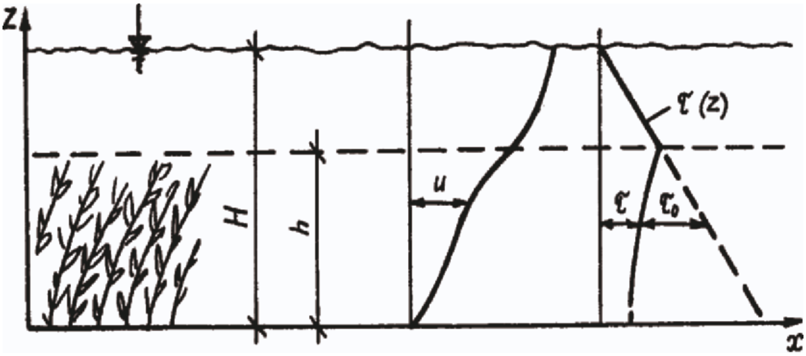

Figure 1.5: Schematic of the vertical-plane hydraulics problem.

this conclusion. Shear stress is distributed linearly (or closely to the linearity) over the vegetating grass, but its profile needs the sophisticated calculations within obstructed layers, as seen from measurements by Lopez and Garcia [377], Fig. 1.6.

Kouwen seemed to be the first among hydraulicians who doubted yet in 1969 the ability of traditional resistance formulas to correctly represent the role of vegetation, its possible features (solidity or flexibility) and characteristics like its height and spacing (density) [86]. In his experimental work, he introduced an empirical "slip velocity" taken proportionally to the velocity gradient outside the "penetrable block". Later, he carried out the experiment with a flexible artificial grass in a laboratory flume [350].

The formulation of the theoretical problem was firstly suggested by Kosorin in 1977 [344]. He suggested that the vertical mean velocity profile should account for a distributed force acting within the vegetated layer. Because of the longitudinal homogeneity, an equilibrium takes place between the shear stress τ and two forces, the pressure gradient because of the hydraulic slope J and a quadratic force representing the vegetation:

$$\frac{1}{\rho}\frac{d\tau}{dz} = KU^2 - gJ \tag{1.10}$$

with the coefficient K which represents the stiffness of the vegetation [344] and vanishes above it, $K = 0$. Similar approaches were used later on by other authors, [147, 462, 463]. The up-to-date calculations involve even three-dimensional versions of the same vertical-plane problem with the $k - \epsilon$ turbulence closures, [581, 658]. One could evidently see numerous similarities in the phenomenology and its theoretical description between the aquatic and terrestrial vegetation. Terrestrial flows are unconfined, but this hasn't been important. The main mechanisms to account for is the retarding influence of obstructions. Initially, hydrologists carried out their experiments and developed theoretical models independently. But later on, they began intensively use the extended experience of meteorologists.

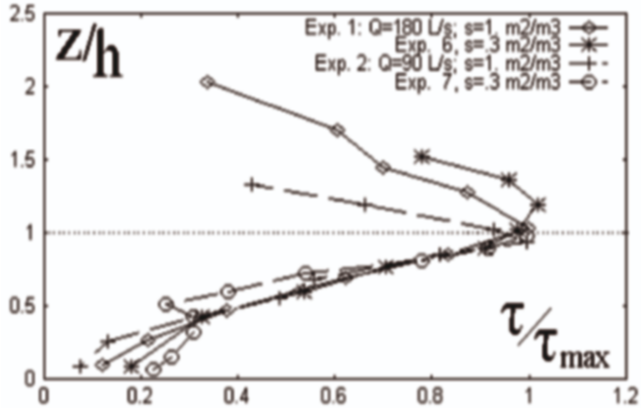

Figure 1.6: Distribution of the shear stress $\rho u'v'$ across the water flow over a tall grass as dense as $s = 1.09\ m^2/m^3$ accordingly to [377, 378].

The significant contribution to the field under study was also done by Rouve, Pasche, Nuding [470, 553], Tsujimoto and Kitamura [581, 617, 618, 619] (both experiment and theory), by Garcia [377] and Ginsberg [231] (mainly experiment).

As for the terrestrial vegetation, the difficulty appeared here concerns to the problem of the estimate of the vegetation stiffness that may be also called *the density* of the obstruction layer (the canopy). In the field measurements of Bennovitsky [53, 54], the natural vegetation (the reed) provided the blockage 7, 40, and 120 plants on m^2. In the measurements of Nepf [463], the blockage of plants was 330 $plants/m^2$. Another measure for the canopy density, the frontal area per unit volume s, $1/m$, has been more universal. Its typical vertical distribution is shown in Fig. 1.7, [463].

This brief overview of the vertical-plane hydraulics problem may be accomplished with references to non-stationary problems. It is important for oceanography problems that the flow evolves in time because of the seagrass-current periodicity. In article [172], the one-dimensional problem (1.10) accounted also for the time- and space-periodicity of the sea water surface, $\zeta(x,t) = A\sin(\omega_x x - \omega_t t)$. The final motion equation was written as

$$\frac{\partial U}{\partial t} - \frac{\partial U}{\partial z}\left(\nu_T \frac{\partial U}{\partial z}\right) = -g\frac{\partial \zeta}{\partial x} - c_f U|U|. \qquad (1.11)$$

The problem in a similar formulation will be considered in the section 3.1.1.

Another important feature of aquatic obstructions consists in their significant flexibility. Experiments of many authors show that water plants exhibit a grate range of motion with increase in the flow speed, i.e. erect state, gentle swaying, strong coherent swaying (monami), and almost prone state, [463]. None of models (1.10) or (1.11) accounts for the above feature. Hence, other new elements should be introduced into models. The Russian author Sokolov [585] included the obstruction inclination into the force expression (1.7) and supplemented the model by an additional equation of console static equilibrium. Other work was done also by Kouwen, [350].

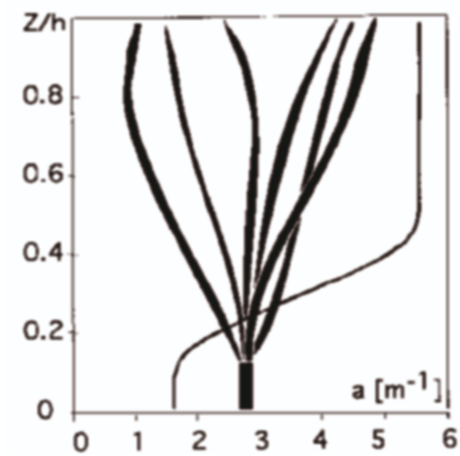

Figure 1.7: Typical vertical canopy density distribution within the aquatic vegetation after Nepf [463].

1.2.2 The problem in a horizontal plane

The problem in a horizontal plane expresses flow parameter distributions across the water conduit width which is vegetated near one or both banks like the situation shown in Fig. 1.8. It was assumed there that the "local mean velocity" was averaged over all the flow depth $0 \le z \le \zeta(x, y)$. In fact, the flow field in such a geometry, even in the simplest configurations, is completely three-dimensional and is varied in the flow direction Ox, across the conduit Oy, and in the vertical direction Oz, i.e., $U = U(x, y, z)$. It is natural, however, to average the velocities over the whole flow depth ζ, [540]:

$$\overline{U}(x, y) = \frac{1}{\zeta} \int\limits_0^{\zeta} U(x, y, z)dz, \qquad \overline{V}(x, y) = \frac{1}{\zeta} \int\limits_0^{\zeta} V(x, y, z)dz. \tag{1.12}$$

Therefore the velocity vector $\{\overline{U}, \overline{V}\}$ is related to every point (x, y) of the flow plan.

The problem under consideration was experimentally investigated by Bennovitsky both in natural streams and on laboratory scale [52]–[56] and compared with the above vertical-plane problem. He reported that the closeness of vegetation varied from $N = 40$ till 500 stems per meter squared in the nature. Usual stem diameters $2r$ were between 0.5 and 1 cm, so that the relative distance between neighboring stems $l/2r$ varied from 4.5 to 30. The flow was decelerated in the area of vegetation and became faster in the free stream. The flow was reproduced in a laboratory modeling, the results of which have been presented in Fig. 1.9. Cylindrical obstructions were "planted" on berms symmetricly, as it has been shown in the insert. The depth-averaged velocity distribution depended on the relative obstructed cross section area ω_{veg}/ω_0. Only symmetric halves for two measurements have been shown. If the vegetated section was relatively narrow, ω_{veg}/ω_0=0.19, the flow in the middle was almost uniform, and the

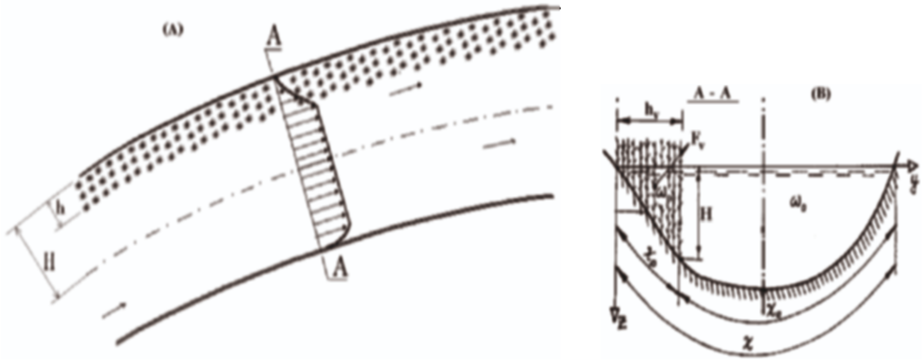

Figure 1.8: Schematic of the horizontal-plane hydraulics problem: (A) plane view of the flow with vegetation near left bank; (B) typical flow cross-section.

latter had a jet-like form in the case of a wider vegetation ω_{veg}/ω_0=0.45. Other data for horizontal plane problem were published by Nuding [470], Tsujimoto, Kitamura e.a. [581, 618, 619] and a few other authors.

Bennovitsky suggested and validated the experimental evidence that velocity profiles followed the logarithmic law just over the vegetation in the free stream [56]. So the approximation (1.1) may be employed in this problem again. Three empirical parameters required were adopted from the theory of atmospheric canopy flows [155]. For instance, the relation $d = 0.65h$ was found [56].

No approaches were known however for the velocity distribution within the vegetated layer. Bennovitsky stated that formulas (1.3) may be approximately applied. So both kinds of hydraulic problems turned out to be similar to the forest canopy problem.

Theoretical approaches to the horizontal-plane hydraulic problem are often based upon momentum equations derived from the Navier—Stokes equations being averaged over the flow depth. This approach was developed by Rodi, Emtsev, Sherenkov, Beffa, and other authors [48, 171, 540]. In the case where the vegetation is present, the resulting two-dimensional shallow-water equations for a time-dependent flow read as follows [540]:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial\left(\zeta \overline{U}\right)}{\partial x} + \frac{\partial\left(\zeta \overline{V}\right)}{\partial x} = 0,$$

$$\begin{aligned}
\frac{\partial \overline{U}}{\partial t} + \overline{U}\frac{\partial \overline{U}}{\partial x} + \overline{U}\frac{\partial \overline{V}}{\partial y} &= -g\frac{\partial \zeta}{\partial x} + \frac{1}{\rho\zeta}\frac{\partial}{\partial x}\left(\zeta\tau_{xx}\right) + \frac{1}{\rho\zeta}\frac{\partial}{\partial y}\left(\zeta\tau_{xy}\right) - \frac{\overline{\tau}_{bx}}{\rho\zeta} - f_{*x}, \\
\frac{\partial \overline{V}}{\partial t} + \overline{U}\frac{\partial \overline{V}}{\partial x} + \overline{V}\frac{\partial \overline{V}}{\partial y} &= -g\frac{\partial \zeta}{\partial y} + \frac{1}{\rho\zeta}\frac{\partial}{\partial x}\left(\zeta\tau_{xy}\right) + \frac{1}{\rho\zeta}\frac{\partial}{\partial y}\left(\zeta\tau_{yy}\right) - \frac{\overline{\tau}_{by}}{\rho\zeta} - f_{*y}.
\end{aligned} \tag{1.13}$$

Here ζ is the actual water depth at the location (x, y). A characteristic feature of the water flows is the presence of the free water surface which varies at different points of the flow plan. It is higher in the zones of flow deceleration and lower in the free

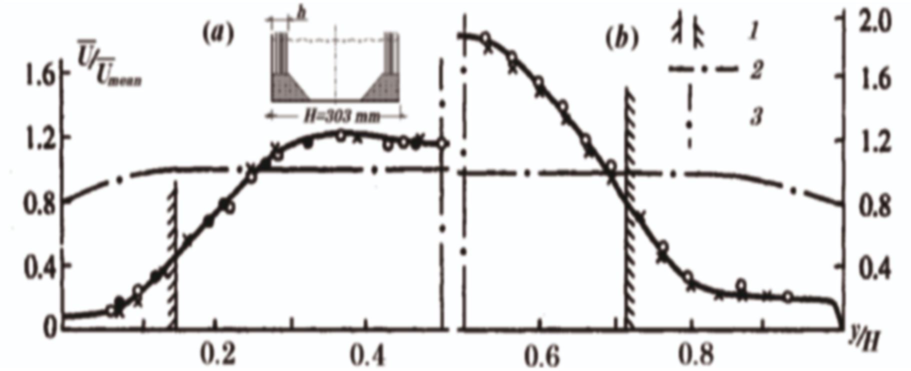

Figure 1.9: Typical velocity distributions measured in the horizontal-plane problem by Bennovitsky [56]: (a) relative obstructed cross section ω_{veg}/ω_0 = 0.19, and (b) ω_{veg}/ω_0 = 0.45. Line markings: *1* - border of the vegetated area; *2* - velocity distribution if vegetation is absent; *3* - flume symmetry line.

stream zone. This characteristic may be important in the performance of the flow plan and is thus included as an unknown variable $\zeta(x, y)$ in the equations. $\overline{\tau}_{xx}, \overline{\tau}_{xy}, \overline{\tau}_{yy}$ are the depth-averaged shear stresses being often neglected, and $\{\overline{\tau}_{bx}, \overline{\tau}_{by}\}$ is the shear stress vector usually linked, due to the bottom influence, with a bottom inclination Θ and the local velocity vector $\vec{U} = \{\overline{U}, \overline{V}\}$ as

$$\{\overline{\tau}_{bx}, \overline{\tau}_{by} = (\cos\Theta)^{-1}\rho C_b|\vec{U}|\vec{U}.$$

The force vector $\{f_{*x}, f_{*y}\}$ should represent the discontinuous influence of the vegetation in a form like (1.7). The model closed by boundary conditions and hypotheses as for turbulent viscosity allows the numerical performance of a practical importance, [453, 658].

Natural water vegetation waves very easily under the action of a flow. In turn, the velocity of the flow and the turbulence in it depend upon the waving motion of obstructions. There are few works that investigated the mutual behavior of the flow and the canopy, [305]. Sokolov [585] suggested that the flow-governing equations (1.11) or (1.13) should be supplemented with an additional one to express the shape of a strained thread. An equation was derived for the inclination of a vegetation plant in terms of the angle to the horizontal direction. On the other hand, the force (1.6) or (1.7) should also depend on it. The model becomes more complex as the flowing medium and the medium of bending grass are linked with each other.

It has been few years only since hydraulics began the implementation of methods used by meteorologists for modeling the flows obstructed by vegetation. A more close exchange between both sciences seems to be very useful.

1.3 Urban canopies

The investigation of air flows, turbulence, heat exchange, and pollutant transport within residential urban areas have become important in recent years because of the ecological reasons and the elaboration of measures for a better urban comfort and countermeasures to possible terrorist's attacks. There are several scientific programs running by the USA and European Union towards a better understanding of relevant physical mechanisms and forecasts for the urban climate of some test cities, see Chapters 2 and 9.

On a certain scale, the wind flow well over an urban settlement may by considered as distributed conventionally in the logarithmic form $U = \frac{U_*}{k} \ln \frac{z}{z_0}$ for the neutrally stratified atmospheric boundary layer with a certain roughness coefficient z_0 depending on the particular properties of the underlying urban surface, or in the form (1.1) more close to the rough surface. These assumptions that did not account for the motion within an obstructed layer were accepted in many early studies on urban climatology [356] but turned out insufficient for modern requirements. One of the first systematic instrumental measurements within a real urban surrounding was carried out by Rotach [545]. He confirmed that most time the horizontal wind within the urban structure has been considerably reduced as compared with its above-roof value. Basing on this fact, some authors suggested a scheme of the wind distribution within and over the urban canopy h shown in Figure 1.10, [425]. The canopy height can be usually determined only approximately as the mean height of buildings. The flow beneath the inertial sublayer 1 regularly departs from the above logarithmic law because it is constantly influenced by particular urban obstructions. The most decelerated, distorted, and variable velocity profile takes place in the layer between buildings called *urban canopy*.

The real structure of an urban canopy consists of individual buildings, clusters of buildings, and various city objects such as squares, street intersections, parks, boulevards, etc. The wind causes the shedding of vortices around buildings that are of many scales. The interaction of vortices produces various flow patterns. Therefore, researchers classify them into typical patterns that can be reproduced in wind tunnels or modeled theoretically. For instance, the model of a wind canyon is developed in [71, 425]. A phenomenon of wind channeling causing the wind to move even faster that the external wind over roofs is known for city canyons. Generally, a variety of urban flow features suggested by Britter and Hanna [81] can be divided into four ranges of spatial scales: the regional scale with an extension up to 100 or 200 *km*, city scale extended for an averaged city diameter up to 10 or even 20 *km*, neighborhood scale up to 1 or 2 *km*, and street scale with an extension less than 100 or 200 *m*. The internal motion within an urban canopy is important for the city and neighborhood scale phenomena, and it can be treated in a statistical way. Several mathematical models that interpreted an urban canopy as a penetrable layer exerting a distributed force to the flow were independently suggested by Sorbjan and Uliasz [589], Bykova [96] and Jerram, Belcher and Hunt [319] and led to some practically used results. The theory gave a base for some idealized laboratory simulations where relatively homogeneous urban settlements were modeled with an array of cubes, [386]. The photo of a cubic array and two their possible arrangements are presented in Fig. 1.11. The exponential

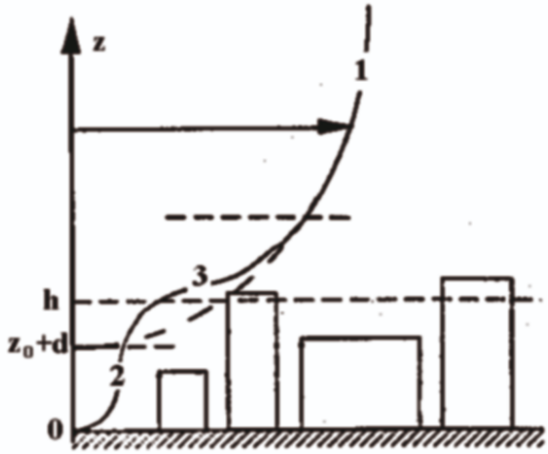

Figure 1.10: Schematic wind distribution over an urban territory after Bottema, 1993 [71] and Fisher et al., 2005 [193]: 1 – logarithmic portion high enough over the city; 2 – decelerated and distorted velocity profile within the urban canopy; 3 – transition layer (roughness sublayer).

formula (1.3) for the internal velocity distribution treated in a statistical way has been experimentally confirmed for the urban canopies, [81].

It is natural that equations like (1.4) and (1.5) can be considered as correct for only forest or riparian structures but only as approximate for urban canopies. The fundamental difference between two canopy types lies in the fact that trees in a forest and grass in a water stream displace a negligibly small amount of air and so the volume of all obstructions $\Omega_{obstructions}$ divided to the whole volume Ω is very small,

$$\varepsilon = \frac{\Omega_{obstructions}}{\Omega} << 1.$$

However, his fraction was estimated approximately as $\varepsilon \approx 0.6$ for the urban canopy [394]. Maruyama suggested to introduce the coefficient G meaning the residuary volume ratio to be equal to 1 outside the urban roughness and to 1-ε within it [394] into governing equations in the form like that in (1.5). It is not our aim to analyze this suggestion which must lead to some conjugation problem on the canopy height level $z = h$. The conclusion we would like to infer sounds that the concept of a penetrable canopy or a penetrable roughness expressed in equations (1.4) and (1.5) can be successfully employed in a number of applications.

1.4 Spraying coolers

Landscapes of our planet become more and more artificial today. Canopies of an artificial kind have replaced forests in some places. One of the examples gives a wind farm consisted of a cluster of wind turbines [168]. Each wind turbine takes out some momentum from the passing wind, thus causing a reduction in the wind speed at the

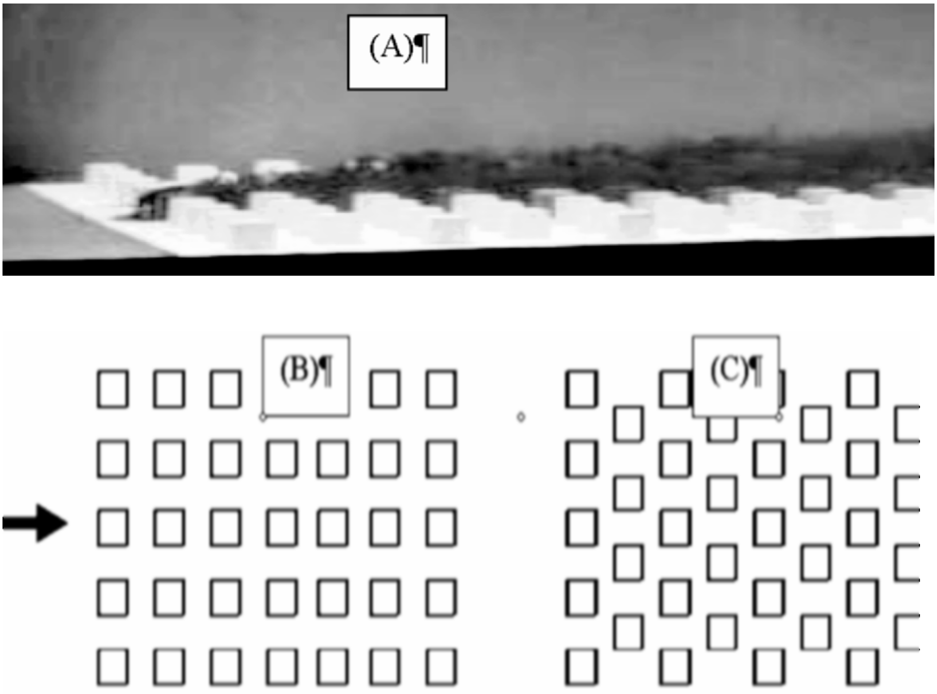

Figure 1.11: Cubic array in a wind tunnel as the simulation of a homogeneous urban settlement (A); two types of experimental setups: aligned (B) and staggered (C) arrays, Macdonald [386].

height of a wind hub. This means also a reduction in the energy production by consequent turbines. Despite the “wind mill forest” is very sparse, its influence on the wind structure is remarkable, and so engineers need to know it exactly, [168].

Another example of an artificial landscape is given by extended spraying cooling systems (SCS) like that displayed in Fig. 1.12 which can be often meet near electric power plants. To know how they interact with the atmosphere is necessary both for the project designers, SCS engineering exploitation, and for preventing their enormous ecological impact. Spraying coolers are very rarely considered as a kind of “canopy.” Therefore, a greater attention is given to them in the present work.

To obtain the effective heat dissipation in circular water supply systems, cooling ponds, cooling towers, “dry” cooling towers, and spraying coolers are used in the energy producing industry. It is known, for example, that the power station capacity can be increased by 1% provided the cooling system ensures the cooling by 2^oC deeper. Particularly, spraying coolers have been widely used for a long time on thermal and nuclear power electric plants especially in the USA and in countries of the former Soviet Union. Up-to-date Spraying Cooling Systems give the example of a human-made artificial terrain that is formed by a number of tall fountains. Getting a big output of warm water from a power plant, fountains divide it into a plenty of droplets sized from several microns to $6 - 10$ *mm*, thus ensuring a developed heat and mass exchange surface. In this way, the SCSs ensure the cooling of water $\Delta t = 7 - 10^oC$ under summer