TORNADO

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This book is devoted to the fundamental problems of investigation of free concentrated vortices. The possibilities of mathematical modeling of whirlwinds (tornados) are discussed. It states and solves, for the first time in domestic and global practice, the problem of physical (laboratory) modeling of whirlwinds without using mechanical whirling devices. The issues of generation and stability of free vortices and methods for controlling their characteristics are analyzed. The possibilities for affecting atmospheric whirling formations of various scales are described.

The book is designed for scientists investigating hydrodynamics and heat and mass transfer of vortex flows, as well as for university teachers, students, and post-graduate students.

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CHAPTER 5

FOREWORD

This book is devoted to investigation of free concentrated air vortices (whirlwinds), which are common in the environment and in technologies. Vortex or eddy motion is a common form of air motion. There exist many types of vortex motion of the atmospheric air, differing in sizes, typical speeds, and lifetimes. We should note specifically vortex motions that have catastrophic effects, such as whirlwinds (tornados), vortex storms, and hurricanes.

Examples of technical devices using vortex flows include: cyclone separators and vortex tubes, centrifugal burners, vortex furnace chambers, and burners (Piralishvili et al., 2000), various vortex generators, and many others. The use of vortex effects provides broad opportunities for intensification of different processes (mixing and combustion) and control of their stability.

Vortex structures often generate along surfaces of different aircraft and space rocket facilities, as well as in their aerodynamic wakes (Ginevskii and Zhelannikov, 2008). Controlling the flow around bodies with the aid of vortex cells is a promising and significant line of the modern fluid and gas dynamics (Baranov et al., 2003).

Investigations of free (not bounded by walls) concentrated (vorticity localized in space) vortices are difficult for a number of reasons, such as their spontaneous generation, space and time instability, impossibility of controlling characteristics, etc.

Whirlwinds (or tornados) represent one of the particular, but very intriguing and mysterious manifestations of natural free vortices. Therefore, the authors of this book decided to use this term in the book title.

The first, introductory, chapter gives brief data on the basic forms of air motion. It includes the definitions of cyclones (tropical and extratropical), hurricanes, storms, whirlwinds, hurricane whirlwinds, and vortices. It describes the 12-level Beaufort wind force scale. The next section describes the Saffir–Simpson hurricane scale, which includes 5 categories and is the extended Beaufort scale for winds of hurricane force. Then, some characteristics of hurricanes are discussed, based on the review of Atlantic hurricanes of 2005, which was the year of the greatest in history cyclonic activity. It should be noted that the paths of Atlantic hurricanes coincide with the regions of the most active whirlwinds (tornados). The development of hurricanes is discussed using the example of Katrina hurricane, which takes a special place in terms of damage force and the number of casualties among all hurricanes ever occurring over USA. At the end of the section, data on hurricane whirlwinds that often accompany Atlantic hurricanes are provided.

Further on, the first chapter provides the initial data on whirlwinds (tornados). It describes the classical Fujita tornado scale. This scale includes six categories and is an enhanced scale of winds and hurricanes for very strong winds, characterizing tornados. It describes the enhanced Fujita tornado scale, containing evaluation of wind speeds, causing specific damage by different indicators (construction sites, structures, and elements of the landscape).

The final section of the first chapter makes some conclusions on hydrodynamic similarity of different forms of atmospheric air vortex motion.

The second chapter includes brief information on the largest vortices existing in the Earth atmosphere, such as cyclones and anticyclones. The authors are strongly convinced that the knowledge and use of long-lasting cyclone and anticyclone research in order to analyze small-scale atmospheric vortices, such as whirlwinds (tornados), can be most expedient, since their hydrodynamic nature is similar.

A great part of material, used on the second chapter, was taken from the classical monograph of Pogosyan (1976), not claiming to be original. At the beginning of the chapter, the composition and structure of the Earth atmosphere as well as elementary data on the atmospheric pressure field are given. Important notions on dry and moist adiabatic air temperature gradients are introduced; they are used to define stable and unstable atmosphere equilibrium. The conditions of formation of front areas and different atmospheric fronts, greatly affecting the weather, are described. Data on the extratropical cyclones and anticyclones, including the stages of their development, specific features of air motion, the frequency and places of development and typical pressure values are given. Atmospheric precipitations in the system of cyclones and hurricane winds in the system of anticyclones are described. At the end of the chapter, brief data on tropical cyclones are provided. A comparative analysis of the conditions of generation and the properties of cyclones in tropical and extratropical latitudes is made.

The third chapter provides a brief review of whirlwinds (tornados) and vertical vortices. A significant part of the materials, used in this chapter, is taken from the monograph by Nalivkin (1969), which is a bibliographic rarity since long ago. It includes detailed data on the issues discussed and cannot be claimed as original. The available factual material on the meteorological phenomenon, such as whirlwinds (tornados), is provided in this chapter so as to try a qualitative transition from the collection of descriptive data on whirlwinds (tornados) to their modeling and analysis in the subsequent chapters.

At the beginning of the third chapter, whirlwind (vortex) clouds are described. The part of the cloud, possessing an intense vortex motion, is an integral part of the whirlwind (tornados). Horizontal and towering whirlwind clouds are discussed. Data on the whirlwind structure are provided. In addition to vortex formations in the mother (whirlwind) cloud, the whirlwind includes a funnel and a cascade. The basic types of funnels and cascades of atmospheric whirlwinds are described. Data on possible shapes of whirlwinds are provided, and the main features of dense and blurred whirlwinds are discussed. The basic features of whirlwinds, such as development stages, motion speed, lifetime, path length, typical sizes and their frequency, are described. Data on different types of whirlwinds and vortices, such as invisible, dusty, water, fire, and snow vortices, are provided. By their structure, the availability, and the type of the carried substances, the invisible (dusty, water, etc.) vortices are similar to invisible (dusty, water, etc.) whirlwinds. The most known whirlwinds which occurred in the last 100–200 years in Russia (Moscow Whirlwind, Moscow Region Whirlwind), Western Europe (Monville Whirlwind, etc.) and USA (Irving Tornado, Delphos Tornado, and Three State Tornado) are described. An array of statistical data, concerning the prevalence of tornados in USA, is discussed. At the end of the chapter, data on the investigations of tornados, their damage and protection methods are provided.

The fourth chapter presents elementary data on vortex flows. The material of the chapter was taken from different sources and is auxiliary by its character, since the chapter is designed to help better understand the material of the subsequent chapters. The basic notions, used for describing the kinematics of vortex flows as well as basic characteristics of such flows, are described. Data on very simple vortices — free, forced, and combined (Rankine vortex) — are provided. The main hydrodynamics equations, such as the continuity equation, Navier–Stokes equation, and vorticity equation, are written in detail. The vorticity equation plays a very important role in understanding the complex physics of vortex flows; therefore, it is given a special attention. Solutions of elementary hydrostatic problems, such as the problem of the dropping liquid equilibrium in a rotating vessel and the problem of gas equilibrium, are provided. The dry adiabatic gradient, a key notion of geophysical hydrodynamics, is defined. The final section of the fourth chapter discusses in detail the causes of the Coriolis force, responsible for the formation of the overwhelming majority of devastating vortex structures in the Earth atmosphere. The solutions of classical problems of vertical motion of material point and of motion of heavy material point in the horizontal plane due to the Coriolis force are discussed.

The fifth chapter describes some mathematical models of whirlwinds. Unfortunately, the use of the methods of direct numerical simulation, intensively developed in the recent years, is difficult in tornado studies, primarily, because of serious problems related to correct formulation of boundary and initial conditions. Today, the simplified analytical and semi-empirical models of whirlwinds, described in this chapter, are very important.

Models of tornados of different complexities are discussed. At the beginning of the chapter, a simple analytical model of tornados, based on the Bernoulli equation for motionless air (tornado's funnel) and moving (rotating) air, is provided. A very simple solution for incompressible air, an accurate solution for compressible air, and a solution for a stratified tornado are obtained. It is demonstrated that even a simple model describes adequately the properties of real whirlwinds. An analytical model, describing the initial stage of tornado development, is described. This model is based on the vorticity equation, taking into account the impact of the Coriolis force and the presence of solid (or liquid) particles. The process of development of vortex atmospheric formations due to instability, caused by the growing vertical velocity component towards the ground or the increasing concentration of suspended particles, is analyzed.

The next section of the chapter gives a new class of analytical solutions of the Navier–Stokes equations, which make it possible to predict characteristics of complex vortex flows, including tornados. The known very simple solution of the Euler (or Navier–Stokes) equations for a flat vortex sink (vortex source) is generalized to the case, when an axial flow is superimposed on axisymmetric vortex sinks. A new solution (exactly, a family of solutions) for a viscous incompressible fluid allows construction of patterns of various vortex flows. In particular, it can be used to study the formation of tornados near the surface as well as to interpret the effect of a sharp expansion of the funnel at some elevation above the ground. The last model described is the analytical model, based on the system of hydrodynamics equations within the model of an ideal incompressible fluid with due account for the Coriolis force. The appearance of twist (swirl) in the positive direction (anticlockwise in the Northern Hemisphere) in the part of the ascending twisted vortex near the ground due to a substantial role of the Coriolis force in the development of tornados is justified. Accurate and approximate solutions, describing the steady-state flow in the bottom part of the ascending twisted vortex are built. The produced solutions make it possible to construct a physical pattern of the flow, contradicting the common ideas of the tornado development and stability, which, however, agrees very well with multiple full-scale observations.

The final section of the fifth chapter describes the results of some research, devoted to numerical simulation of tornados.

The sixth chapter provides the results of original experimental research of free concentrated vortices, being analogs of whirlwinds (tornados). The principal opportunity for physical modeling of whirlwinds under laboratory conditions without using mechanical twisting devices is demonstrated.

At the beginning of the sixth chapter, a simple experimental device for controlled heating of the underlying surface (metal sheet) from beneath in order to create unstable air stratification is described. Unstable air stratification under specific conditions leads to the generation of free concentrated vortices which are the subject of our investigation. The basic parameters of thermal conditions, used for the generation and study of whirlwind characteristics, are provided. Thermal modes of heating (cooling) of the underlying surface, as well as the space–time field of air temperatures, in which unstable stratification results in free vortices, are studied. The obtained data allow evaluating the air heating rates and the horizontal and vertical temperature gradients, required for generating vortex structures. Some integral parameters of concentrated vortices (geometric dimensions, lifetime, motion velocity, etc.) using video filming are evaluated. Different types of trajectories of motion of the vortex structure basis are identified. The efficiency of different methods of visualization of free concentrated vortices is shown. The use of a flat light knife (laser knife), together with visualization by means of magnesium and smoke particles enabled the study of whirlwind funnel formation and evolution. The results of measurement of the instantaneous velocity field in free concentrated vortices are presented.

The seventh chapter includes the results of physical modeling of free vortices in order to identify methods for their monitoring. The results of experiments on the generation and study of stability of an unsteady-state vortex, described in the previous chapter, allowed a qualitatively new level of modeling and formulating, for the first time, the problem of study of different methods of impact on vortex structures.

The seventh chapter begins with brief information on passive and active methods of controlling vortex atmospheric formations. It is noted that, despite numerous attempts made by scientists from different countries in order to propose different methods of impact on the above vortex atmospheric formations, no efficient methods for controlling natural phenomena exist so far. Further in the chapter, the results of experimental studies of the possibilities for controlling air vortices are provided. The chapter describes the proposed and tested method of impact on whirlwinds (tornados), i.e., the placement of barriers in the form of vertical and horizontal meshes along the paths of vortex structures. The efficiency of this method was verified under laboratory conditions by studying the impact of such barriers on the dynamics of a free vortex with the structure similar to real tornados. A comparative analysis of mechanisms and efficiency of vertical and horizontal meshes was made. It is noted that such protection structures, due to their simple fabrication and low costs, are unrivaled among the currently proposed methods of control in terms of cost effectiveness.

The final section of the seventh chapter gives a brief analysis of the basic physical mechanisms of impact of the proposed passive-active method on tornados, which precondition its advantages.

The annexes include the description of the methods for estimating the tornado hazardousness of the area. These data are taken from the official guidelines of the Russian State Committee on Nuclear and Radiation Safety. The guidelines include recommendations on calculating the whirlwind characteristics on the sites of location and construction of nuclear power facilities and describe all stages of evaluation of the tornado hazardousness of the area, including whirlwind parameters, needed to specify loads on buildings and structures important in terms of safety. These methods can be used to develop measures for protection of especially important facilities, located in areas with low tornado hazardousness.

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NOMENCLATURE

Dimensional quantities

a	rate of gravitational settling of solid (liquid) particles; sound velocity, m/s; thermal diffusivity of gas, m^2/s
A	region (zone) surface area, m^2
c_p	isobaric heat capacity of gas, J/kg·K
c_v	isochoric heat capacity of gas, J/kg·K
d	diameter of the streamlined body, m
f_1	first Coriolis parameter, s^{-1}
f_2	second Coriolis parameter, s^{-1}
$\vec{F}$	vector of the total mass force, N
$\vec{F}_c$	Coriolis force vector, N
F_x, F_y, F_z	projections of the vector of the total mass force in the Cartesian system of coordinates, N
g	acceleration of gravity, m/s^2
h	typical vertical size; model screen height; protected facility height, m
h_1	mesh structure height, m
h_2	height of the surface flow generating a vortex, m
H	vortex height, m
l	laboratory vortex height, m
l_1	fixed barrier height, m
l_2	mesh barrier height, m
l_c	Coriolis circle length, m
L	space scale, tornado height, m
L_k	propagation path length of the k intensity tornado, m
m	material point mass, kg
p	gas pressure, Pa
R	the Earth radius, m; the universal gas constant, J/(kg·K)

R_c	Coriolis circle radius, m
r, φ, z	radial, azimuthal (tangential), and axial coordinates in the cylindrical system of coordinates, m, rad., m
S	entropy, J/K; total damage area, m^2
T	temperature of gas and underlying surface, K; effective period of observations, s
T_a	air temperature over the underlying surface, K
T_c	temperature at the center of the underlying surface, K
U	forward velocity of tornado, m/s
U_k	forward velocity of the k intensity tornado, m/s
U_p	forward velocity of the probable tornado, m/s
$\vec{U}$	gas velocity vector, m/s
U_r, U_φ, U_z	projections of the gas velocity vector in the cylindrical system of coordinates, m/s
U_x, U_y, U_z	projections of the gas velocity vector in the Cartesian system of coordinates, m/s
V	rotational velocity of the tornado funnel wall, m/s
V_k	rotational velocity of the k intensity tornado funnel wall, m/s
V_p	rotational velocity of the probable tornado funnel wall, m/s
$\vec{V}$	vector of material particle velocity, m/s
V_x, V_y, V_z	vector of material particle velocity projection in the Cartesian system of coordinates, m/s
W_k	propagation path width of the k intensity tornado, m
x, y, z	longitudinal, lateral, and vertical coordinates in the Cartesian system of coordinates, m

Greek symbols

β	coefficient of volumetric expansion, K^{-1}
Γ	circulation, m^2/s; temperature gradient, K/m
Δp_p	pressure difference between the center of the funnel and the periphery of the probable tornado, Pa
μ	coefficient of dynamic viscosity, $N \cdot s/m^2$
ν	kinematic viscosity coefficient, m^2/s
ρ	gas density, kg/m^3
ρ_p	density of solid (liquid) particles, kg/m^3
φ	geographical latitude, rad.
τ	time, s

τ_c	time of cooling of the underlying surface; time of motion along the Coriolis circle, s
τ_h	time of heating of the underlying surface, s
Ψ	stream function, m^3/s
$\vec{\omega}$	gas vorticity vector, s^{-1}
ω_r, ω_φ, ω_z	projection of the gas vorticity vector in the cylindrical system of coordinates, s^{-1}
ω_x, ω_y, ω_z	projection of the gas vorticity vector in the Cartesian system of coordinates, s^{-1}
Ω	vector magnitude of the angular velocity; angular rotational velocity of the Earth, s^{-1}
$\vec{\Omega}$	vector of angular rotational velocity, s^{-1}
Ω_x, Ω_y, Ω_z	projections of the angular velocity vector in the Cartesian system of coordinates, s^{-1}

Dimensionless quantities

a	ratio of the actual number of tornados to the recorded number
k	adiabatic index; tornado intensity class
k_p	calculated intensity class of probable tornado
m_k	the highest class of recorded tornados of the class in the area
n	polytropic index; number of tornados recorded in the area
n_k	number of tornados recorded in the area, class k
N	total number of tornados crossing the area
P	annual probability of a tornado of the specific intensity class
P_0	annual probability of a tornado-like event
P_s	annual probability of a tornado-like event in the area
Ra	Rayleigh number
$\mathrm{Re_d}$	Reynolds number for flow past a body
$\mathrm{Re_r}$	radial Reynolds number
Re_φ	vortex Reynolds number
Ro	Rossby number
S	parameter of twisting

Greek symbols

Φ	volume concentration of solid (liquid) particles
ψ	stream function

Subscripts

∞	value at infinity
0	value at the initial instant of time; on the ground surface; on the core boundary
c	value at the center of the underlying surface
f	value on the funnel surface
k	value for the k intensity tornado
max	maximum value
min	minimum value
p	value for the probable tornado.

CHAPTER 1

INTRODUCTORY CHAPTER

1.1 Preliminary Remarks

The goal of this introductory chapter is to present brief data on the basic forms of air vortex movement and discuss some of their characteristics.

Section 1.2 provides definitions of the basic forms of atmospheric air vortex movement: cyclones (tropical and extratropical), hurricanes, storms, tornados, hurricane tornados, and vortices. This simplifies the material understanding, since these definitions (terms) are used throughout the book.

The following three sections of Chapter 1 provide the basic data on winds, hurricanes, and tornados.

Section 1.3 presents the 12-level Beaufort wind force scale. The minimum wind force, correspondent to the maximum level 12 of the Beaufort scale, is 32.7 m/s. The wind is called hurricane at this level.

Section 1.4 is devoted to hurricanes. First, the section presents the Saffir–Simpson hurricane wind scale, which classifies hurricanes into five categories, extending the wind force scale to hurricane force winds. Thus, the above wind force of 33 m/s corresponds to a weak hurricane of the lowest category 1. It further discusses some hurricane characteristics using the review of the 2005 Atlantic hurricanes. The paths of Atlantic hurricanes coincide with regions of maximum whirlwind (tornado) activity. The year 2005 was very indicative, because it was characterized by the record cyclone activity. The section also uses hurricane Katrina to discuss the dynamics of hurricane development. This hurricane was especially devastating by its force and the number of casualties of all hurricanes ever occurring over the USA. At the end of the section, data on the hurricane-type tornados in Atlantic hurricanes are analyzed. The information on tornados sheds some light on the complex dynamics and hydrodynamic similarity of vortical atmospheric formations of different scales.

Section 1.5 presents data on whirlwinds (tornados). At the beginning, it presents the Fujita scale of tornados, including six categories, which extends the wind and hurricane scale to the strongest winds characterizing tornados. Indeed, the wind speed 33 m/s (level 12 by the wind scale) corresponds only to the lower level of a weak tornado F1, whereas the wind speed 70 m/s (category 5 by the hurricane scale) does not reach the lower level of a strong tornado F3. Violent tornados of the top category F5 are characterized by the wind speed 117 m/s or more. It is noted that the classical Fujita scale does not correlate the wind speed with the damage. The enhanced Fujita scale for tornados, described further in this section, has no such drawback and contains the assessment of the wind speed with a specific level of damage by different indicators (construction sites, landscape elements and structures).

The final Section 1.6 provides some conclusions concerning the entire diversity of atmospheric air movement forms.

1.2 Basic Definitions

Definitions of the basic forms of vortical movement of atmospheric air, including the description of their characteristics (sizes, wind speed, etc.), are given below.

Cyclone is a giant atmospheric vortex, characterized by a reduced air pressure in the center and the anti-clockwise air rotation in the Northern Hemisphere and the clockwise air rotation in the Southern Hemisphere.

Cyclones are divided into tropical and extratropical.

A ***tropical cyclone*** is a cyclone that originates and develops in tropical latitudes. The normal width of a tropical cyclone makes several hundreds of kilometers, with the height from 6 to 15 km. The central part, *the eye of the storm*, has the lowest pressure, weak winds, and low clouds. The eye of the storm is surrounded by a ring of the cyclone walls, constituted by dense clouds and characterized by hurricane rotational speeds. The cyclone walls evolve into the peripheral part, where the wind speed gradually falls to no-wind condition.

An ***extratropical cyclone*** is a cyclone that emerges and develops in extratropical latitudes. Its lateral dimensions exceed the dimensions of a tropical cyclone, making from one thousand kilometers (at the stage of development) to several thousands of kilometers (at the stage of the so-called central cyclone). Extratropical cyclones are characterized by relatively small wind speeds, although, in some cases, they may reach storm or even hurricane wind speeds.

A ***hurricane*** is a tropical cyclone, characterized by an extremely reduced pressure in the center and the wind speed reaching very high values. A hur-

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