

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

Date: 1 April 1970

RESEARCH PROJECT INITIATION

Project Title: Research Initiation - Turbulent Boundary Layer in a Rotating Fluid

Project No: B-1116 (E-25-611)

Project Director: Dr. Wolfgang Wulff

Sponsor: National Science Foundation

Agreement Period: From 1 April 1970 until 30 September 1971

Type Agreement: Grant No. GK-5525

Amount: \$15,000 NSF Funds (B-1116)
10,828 GIT Contribution (E-1106)

\$25,828 Total Budget

Grant Administrator

Dr. Michael P. Gaus
Program Director
Engineering Mechanics Program
Division of Engineering
National Science Foundation
Washington, D.C. 20550

Reports Required

Annual - 1 April 1971; short, informal,
letter technical report.
Final - Upon completion of project. See
Appendix V to NSF 69-23 for items to be
included.

Assigned to: School of Mechanical Engineering

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A-344

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION
RESEARCH PROJECT TERMINATION

Date: June 2, 1972

Project Title: Research Initiation - Turbulent Boundary Layer in a Rotating Fluid

Project No: E-25-611 (Old B-1116)

Principal Investigator: Dr. W. Wulff

Sponsor: National Science Foundation

Effective Termination Date: March 31, 1972

Clearance of Accounting Charges: by March 31, 1972

Grant/Contract Closeout Actions Remaining:

Final Fiscal Report by June 30, 1972

Assigned to: School of Mechanical Engineering

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B-1116

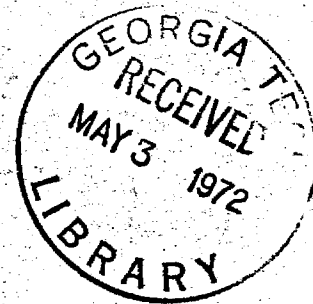
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

Wolfgang Wulff
Principal Investigator

March 30, 1971

Dr. Michael P. Gaus
Program Director
Engineering Mechanics Program
Division of Engineering
National Science Foundation
Washington, D. C. 20550



Subject: Annual Report, Grant No. GK-5525
Research Initiation - Turbulent Boundary Layer
in a Rotating Fluid over a Flat Plate at Rest.

Dear Dr. Gauss:

This is the letter report covering the progress during the first twelve months' period of research carried out under the above grant. The total contract period is approximately eighteen months and started on April 1, 1970.

Purpose

The objective of the experimental and analytical research program is to measure both the radial and the tangential, time-mean average velocity profiles in the turbulent boundary layer of a rotating flow over a flat plate at rest and to predict, from the experimental results, the mass flow rate of air supplied by the ground boundary layer to the vertical column of atmospheric vortices such as hurricanes, tornadoes and fire whirls. Early during the research program limited velocity measurements were published by S. J. Ying and C. C. Chang of The Catholic University, Washington, D. C. While it was deemed prudent to verify and supplement the published data the scope of the program was also widened, as a result of the publication, to include the measurement of the wall shear stress in the ground boundary layer.

This study is necessary for the understanding of buoyancy-driven, atmospheric vortices because the ground boundary layer furnishes not only the bulk of rising air masses but also its vertical angular momentum component. Moreover, in the case of mass fires, such as forest and brush fires, most of the oxygen is supplied to the fuel by the intruding air in the ground boundary layer. This controls the burning rate and the driving buoyancy forces. Ultimately, the understanding of the growth and decay of atmospheric vortices will serve to relate the probability for the occurrence of natural wind disasters to atmospheric conditions such as lapse rate and circulation.

Experimental and Analytical Techniques Employed

Hot wire anemometry and the Preston tube are used, respectively, to investigate the two-dimensional velocity field and the wall shear stress in the boundary layer. A three-dimensional Pitot device (five-hole sphere, for instance) will be used to establish the flow field outside the boundary layer. Analytical techniques to be employed are based on the integral forms of the boundary layer equations of continuity and momentum balance and local or global similarity of the velocity profiles.

Accomplishments

1. Vortex Generator. A fan-driven vortex generator was designed, constructed and is nearly assembled. The vortex generator consists of a cylindrical array of twenty-four vertical vanes, each 10 inches wide and 12 feet long, whose trailing edges form a cylinder of 48 inches in diameter. The vanes are hung from the ceiling by means of a 55 inch-diameter ball bearing which permits the synchronous rotation of each vane about a vertical axis near its trailing edge, through the angle of $\pm 75^\circ$ from the radius. The vanes are presently being mounted.

The vortex is driven by a 12,600 scfm capacity attic fan mounted above a 44 inch-diameter, circular hole in the ceiling and fastened to the joists above the ceiling. The fan is mounted.

The working surface, representing the stationary ground below the vortex, consists of a horizontal circular, 48 inch-diameter plexiglass plate mounted, as a table, approximately four feet above the floor. The plexiglass plate permits visual observation of the vortex from below. This base plate is completed.

The air is drawn in radially through two wire mesh cylinders surrounding the vanes, then through the vanes at a prescribed angle and upward through an orifice through the opening in the ceiling. The orifice serves to control the radial distribution of the upward velocity component.

The expected operating conditions of the vortex generator are characterized by

- i) range of Reynolds numbers, based on the average radial free-stream velocity component and the ground plate diameter

$$0 < (N_{Re})_{rad} < 18,300$$

- ii) angular momentum variation corresponding to the directional change of the intake velocity from -75° to $+75^\circ$, measured from the radius.

2. Hotwire Anemometer. A two-dimensional hot wire V-probe has been designed and constructed and is presently being calibrated on a specially

designed calibration rig capable to move the probe, in a circular path, at velocities from 0.10 ft/sec to 12.0 ft/sec. The performance characteristics of the probe were first predicted and the electrical circuitry designed to sense the magnitude of the velocity to an accuracy of 0.02 ft/sec, and the direction of the velocity to within $\pm 0.5^\circ$.

3. The Preston Tube for the measurement of the wall shear stress has been designed and its construction is nearly completed. The probe was designed in accordance with the specifications published by V. C. Patel* whose calibrations will be employed.

Publications

No publication has been prepared as yet. An M.S. thesis is forthcoming, titled "An Experimental Study of Skin Friction On A Stationary Flat Surface In Contact With Vortex Flow", by J. R. Huntley.

Students and Professional Staff Involvement

Besides the Principal Investigator there is one Master of Science candidate, Mr. James Richard Huntley involved in this study. Interest in future continuations of the project has been expressed by other graduate students.

The project director and the graduate student involved in this program wish to express their gratitude toward the National Science Foundation for its interest in, and its support of this research endeavor.

Respectfully submitted



Wolfgang Wulff
Associate Professor and
Principal Investigator

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V. C. Patel, Calibration of the Preston Tube and Limitations on its Use in Pressure Gradients, J. Fluid Mech. (1965) Vol. 23, part 1, pp. 185-208.

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

Wolfgang Wulff
Principal Investigator

March 28, 1972

Dr. Michael P. Gaus
Program Director
Engineering Mechanics Program
Division of Engineering
National Science Foundation
Washington, D. C. 20550



Subject: Final Report, Grant No. GK-5525
Research Initiation - Turbulent Boundary
Layer in a Rotating Fluid Over a Flat Plate
at Rest.

Dear Dr. Gaus:

This is the final letter report covering the research carried out during the original grant period of approximately eighteen months, starting on April 1, 1970, and ending on September 30, 1971, and during the automatically granted, unfunded extension through March 30, 1972.

Purpose

The objective of the experimental and analytical research program is to measure both the radial and the tangential, time-mean average velocity profiles in the turbulent boundary layer of a rotating flow over a flat plate at rest and to predict, from the experimental results, the mass flow rate of air supplied by the ground boundary layer to the vertical column of atmospheric vortices such as hurricanes, tornadoes and fire whirls. Early during the research program limited velocity measurements were published by S. J. Ying and C. C. Chang of The Catholic University, Washington, D. C. While it was deemed prudent to verify and supplement the published data the scope of the program was also widened, as a result of the publication, to include the measurement of the wall shear stress in the ground boundary layer.

Experimental and Analytical Techniques Employed

A fan-driven vortex generator served to produce the ground boundary layer. Hot wire anemometry and the Preston tube were used, respectively, to investigate the two-dimensional velocity field and the wall shear stress in the boundary layer. Analytical techniques employed are based on the integral forms of the boundary layer equations of continuity and momentum balance and local or global similarity of the velocity profiles.

Accomplishments

1. Vortex Generator

A fan-driven vortex generator was designed, constructed and assembled. The vortex generator consists of a cylindrical array of twenty-four vertical vanes, each 10 inches wide and 12 feet long, whose trailing edges form a cylinder of 48 inches in diameter. The vanes are hung from the ceiling by means of a 55 inch-diameter ball bearing which permits the synchronous rotation of each vane about a vertical axis near its trailing edge, through the angle of $\pm 75^\circ$ from the radius.

The vortex is driven by a 12,600 scfm capacity attic fan mounted above a 44 inch-diameter, circular hole in the ceiling and fastened to the joists above the ceiling.

The working surface, representing the stationary ground below the vortex, consists of a horizontal circular, 48 inch-diameter plexiglass plate mounted, as a table, approximately four feet above the floor. The plexiglass plate permits visual observation of the vortex from below.

The air is drawn in radially through two wire mesh cylinders surrounding the vanes, then through the vanes at a prescribed angle and upward through an orifice through the opening in the ceiling. The orifice serves to control the radial distribution of the upward velocity component.

The stable operating conditions of the vortex generator, in its present state of design, are characterized by

- i) range of Reynolds numbers, based on the average radial free-stream velocity component and the ground plate diameter

$$9,200 < (N_{Re})_{rad} < 16,000$$

- ii) angular momentum variation corresponding to the directional change of the intake velocity from -75° to $+75^\circ$, measured from the radius. Stable vortices were obtained for the range of tangential free stream Reynolds numbers from

$$16,000 < (N_{Re})_{\text{tang}} = \Gamma/v < 47,000$$

where $\Gamma = vr$ represents the free stream circulation and ν stands for the kinematic viscosity.

2. Hotwire Anemometer

A two-dimensional hot wire V-probe has been designed and constructed and calibrated on a specially designed calibration rig capable to move the probe, in a circular path, at velocities from 0.10 ft/sec to 12.0 ft/sec. The performance characteristics of the probe were first predicted and the electrical circuitry designed to sense the magnitude of the velocity to an accuracy of 0.02 ft/sec, and the direction of the velocity to within $\pm 0.5^\circ$.

3. The Preston Tube

A Preston tube for the measurement of the wall shear stress has been designed and constructed. The probe was designed in accordance with the specifications published by V. C. Patel* whose calibrations were employed, in part, for the shear stress evaluation.

4. Results

a. Experimental Results. Velocity profiles and the wall shear stress in the ground boundary layer were measured at five discrete stations located at the radii of 6, 9, 12, 15 and 18 inches. The plate radius is 24 inches large. Measurements were taken at three different tangential Reynolds numbers, each at three vane positions of 60° , 67.5° and 75° , the vane angles at which reasonably stable vortices could be maintained. Radial mass flow rates, boundary layer and displacement thicknesses were evaluated as functions of radius.

b. Analysis of the test results revealed that tangential velocity profiles are self-similar and follow the $1/7$ -power law. Radial velocity profiles are not self-similar; however the parameters representing the integrals of normalized momentum in the boundary layer were found to remain constant over portions of the plate, between the outer starting sections and the inner core.

A Master thesis entitled, "An Experimental Study of Skin Friction and Boundary Layer Velocity Profiles in a Vortex Over a Stationary Flat Surface," by James Richard Huntley, Jr. will be completed by June 1972 and contain the complete description of experiments and analysis.

Publications

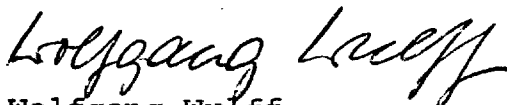
No publication has been prepared as yet. An M.S. thesis will be prepared by June 1972 entitled, "An Experimental Study of Skin Friction and Boundary Layer Velocity Profiles in a Vortex Over a Stationary Flat Plate," by J. R. Huntley. A publication will be prepared to be submitted to the Journal of Applied Mechanics of ASME.**

Students and Professional Staff Involvement

Besides the Principal Investigator there was one Master of Science candidate, Mr. James Richard Huntley, involved in this study. Future research will be devoted to the buoyancy-driven vortex and the effect of surface roughness.

The project director and the graduate student involved in this program wish to express their gratitude toward the National Science Foundation for its interest in, and its support of this research endeavor.

Respectfully submitted,



Wolfgang Wulff
Associate Professor and
Principal Investigator

WW:skb

* V. C. Patel, Calibration of the Preston Tube and Limitations on its Use in Pressure Gradients, Journal of Fluid Mechanics, (1965) Vol. 23, Part 1, pp. 185-208.

** Preprints will be sent to NSF after they become available.