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Project Summary

Wake of a Block Vehicle in a Shear-Free Boundary Flow—An Experimental and Theoretical Study

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The wake of a moving vehicle was simulated using a specially-constructed wind tunnel with a moving floor. A "block-shaped" model vehicle was fixed in position over the test-section floor, while the floor moved at the freestream air speed to produce a uniform, shear-free, approach flow. This simulates an automobile traveling along a straight highway under calm atmospheric conditions.

Vertical and lateral profiles of mean and fluctuating velocities and Reynolds stresses in the wake of the vehicle were obtained using a hot-film anemometer with an X-probe. Profiles were taken at distances of 10 to 80 model heights downwind.

A momentum-type wake was observed behind the block-shaped vehicle. The wake does not have a simple self-preserving form. However, it is possible to collapse the velocity deficit with one length and one velocity scale.

Two new theories for the velocity deficit are compared to the theory of Eskridge and Hunt. A theory that considered a height-dependent eddy viscosity was found to fit the data best.

Length and velocity scales were found for the longitudinal variations of the turbulent kinetic energy. The lateral variation is described by a two-dimensional numerical fit of the crosswind variation of the data.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The dispersion of automobile exhaust near highways is of much current interest. Mathematical models are needed that will accurately predict concentration fields. This study on the structure of the wakes of vehicles was undertaken at the U.S. Environmental Protection Agency's Fluid Modeling Facility to provide information to be used in numerical models of automobile exhaust dispersion.

A wind tunnel with a test-section floor that moves at the freestream air speed was constructed to generate a uniform (constant speed with height) approach flow. Scale model vehicles with rotating wheels were held in position in the test section by guys attached to the test-section walls. A vehicle fixed in a uniform flow over a moving floor is aerodynamically equivalent to a vehicle moving down a straight highway through a calm atmosphere.

Automobiles and scale model vehicles have wakes that can be characterized as momentum wakes, which contain an organized vortex pair aligned with the axis of the wake. In this paper we are interested in only the momentum wake, and therefore, generally discuss only those data and theories applicable to momentum wakes. To create a "pure" (no mean swirl) momentum wake, block-shaped vehicles of appropriate heights and widths have been used. It should be noted that momentum wakes contain vortices, but the vortices disappear when the flow is time-averaged.

A momentum wake's character is determined mainly by the flow field in which it is embedded. Flows that are free of limiting walls and flows that are influenced by a boundary are important cases. Free flows may be subdivided further into shear flows and shear-free flows. In addition, wakes in the flows can be subdivided into laminar and turbulent wakes. J. C. R. Hunt's theory and work showed that the strength of the wake for surface-mounted objects is determined by the couple, rather than by the drag.

Hunt's work was extended by other researchers. They have described wakes of two-dimensional objects in a turbulent boundary layer and have shown that Hunt's theory is inapplicable when the wake height approaches that of the boundary layer. However, the wakes of very small two-dimensional objects did not agree with Hunt's theory as well as those behind large two-dimensional blocks. Some investigators conclude that a constant eddy viscosity model will not likely describe the complex flow in this type of wake.

Theories for wakes behind three-dimensional objects in turbulent boundary layers have been developed by various workers recently. Eskridge and Hunt have developed a model of a three-dimensional wake near a moving surface (no shear in the approach flow).

There is an additional complexity in wake flows not yet mentioned. The Townsend hypothesis states that a wake flow becomes self-preserving (i.e., one length and one velocity scale will be adequate to describe the velocity, stresses, and higher turbulence moments) because the turbulence attains an equilibrium state which depends only on the type of flow and momentum integral, or, in the present case, the couple.

However, other researchers have shown that wake strength depends not only on the drag (momentum integral) but also on the structure of the dominant eddies. The flow behind a block-shaped vehicle will shed vortices into the wake like a sphere. The resulting "memory" effect implies that in a block vehicle wake, the turbulent kinetic energy terms (u'^2, v'^2, w'^2) will not be self-preserving in the Townsend sense.

Apparatus

A wind tunnel was constructed especially for this study. A commercially available conveyor-belt assembly was used for the test-section floor, and for supporting framework for the entrance, test, and exit sections of the wind tunnel. The test section was 4.75 m long (4.15 m of which was moving floor), with a cross-section 0.82 m wide x 0.71 m high.

The entrance section had the same cross-section dimensions as the test section. A bellmouth (diameter of 0.22 m) around the perimeter of the entrance directed room air into a section of Verticel™ (Verticel Co., Englewood, CO; a paper triangular-cell honeycomb with a cell length of 0.15 m and a hydraulic diameter of 0.01 m). Two fiberglass screens (16 x 18 mesh) were placed downwind of the honeycomb to further lower the freestream turbulence.

The moving portion of the test-section floor was the rubber conveyor belt (0.75 m wide). A notched overlapped joint and large end rollers produced a smoothly running belt. Rails along the tops of the walls were installed to support an instrument-traversing mechanism. The longitudinal position of a probe was set manually; vertical and lateral positions were remotely set and read from an operator's desk.

The exit section contained a section of Verticel and a lateral contraction to a 0.71 m wide x 0.71 m high cross-section. A cast aluminum fan with three blades (diameter of 0.61 m) was powered by a two-speed (1140/1725 RPM) 250 W electric motor (115 V, 60 Hz). The fan was mounted in a metal "venturi panel" (i.e., shroud) for efficient operation. Baffle plates of different porosities were inserted into a slot just upwind of the fan to fine tune the air speed or to obtain a variety of air speeds for velocity probe calibrations. The maximum air speed, obtained with no baffle plate and with the fan motor on high speed, was 4.0 m/s.

The operating speed of the tunnel during all experiments was 1.9 m/s; the turbulence intensity (root mean square of the velocity fluctuation divided by the mean speed) was less than 1%.

Two additional wind tunnels of a more conventional nature were used to perform additional tests to determine possible Reynolds number effects and the extent of the blockage effects resulting from the size of the models; the Fluid Modeling Facility's Meteorological Wind Tunnel, and the Air Pollution Training Wind Tunnel with test sections of 3.7 m wide x 2.1 m high x 38 m long and 1 m wide x 1 m high x 3 m long, respectively.

Velocities were measured with Thermo-Systems (St. Paul, MN) hot-film anemometers. X-configured probes (model 1243-20) were used to obtain transverse velocity components as well as the streamwise component. The bridge outputs of the anemometers (model 1054-A) were suppressed with signal conditioners (model 1057), attenuated, and sent to the laboratory's Digital Equipment Corporation PDP 11/40 minicomputer. Software in the computer controlled the analog to digital conversion or sampling rate, linearized the signal, and provided real-time displays of results. The probes were calibrated in position on the instrument-traversing mechanism against a pitot tube located nearby for determining mean test section velocities obtained with the various baffle plates. The X-probe was oriented to measure either the streamwise and lateral components or the streamwise and vertical components. Calculated values were mean streamwise speed, fluctuating streamwise and transverse components, and the associated Reynolds stress. Most measurements were made at 100 samples/s for 30 s. A few ten-minute samples at 500 samples/s were taken at 30 heights downwind of the vehicle at various vertical positions, to calculate turbulence spectra. From these, an eddy viscosity formulation was derived for use in a theory presented below.

Simple block-shaped models were constructed of wood, with the dimensional proportions of a typical automobile. Each model was mounted on a baseplate with wheels and rubber tires. Approximate scale ratios of 1/32 and 1/8 were used.

The 1/32-scale block-shaped vehicle was patterned on the dimensions of an intermediate size American automobile: height = .043 m, width = .055 m, length =

.145 m, ground clearance = .009 m, and wheel diameter = .024 m. The 1/8-scale vehicle was four times as large in all respects.

Summary and Conclusions

An experimental study of the wake of a moving vehicle was made using a specially-constructed wind tunnel with a moving floor. A block-shaped model vehicle was fixed in position over the test-section floor, while the floor moved at the freestream air speed to produce a uniform, shear-free, approach flow. This simulates an automobile traveling along a straight highway under calm atmospheric conditions.

Vertical and lateral profiles of mean and fluctuating velocities and Reynolds stresses in the wake of the vehicle were obtained, using a hot-film anemometer with an X-probe. Profiles were taken at distances of 10 to 80 model heights downwind of the vehicle.

A momentum wake was observed for the block-shaped vehicle. The wake does not have a simple self-preserving form. However, it is possible to collapse the velocity deficit with one length growth rate and one velocity scale, and the turbulence with different length growth rate and velocity scales.

The velocity deficit behind the vehicle decayed as $(x/h)^{-3/4}$, and the length scale grew as $(x/h)^{1/4}$, confirming the earlier predictions of Eskeridge and Hunt. However, the turbulent kinetic energy components decayed as $(x/h)^{-1.2}$, and the turbulent length scale grew as $(x/h)^{0.4}$, instead of the self-preserving solutions of $(x/h)^{-3/2}$ and $(x/h)^{1/4}$ that were predicted.

Velocity deficit solutions were found for the equations of motion in three cases: first, when scale-lengths differed for the lateral and axial directions with constant viscosity (two scale lengths); second, when viscosity varied continuously in the vertical; and finally, a matched solution where viscosity varied linearly near the surface and then was held constant above a given height.

None of the above solutions matched the data in all respects, but the two-scale-length, variable-viscosity solution was the best.

The turbulence decayed longitudinally as $(x/h)^{-1.2}$. To describe the behavior in the lateral and vertical direction, a two-dimensional fit of the data was found by least-squares-fit, using "orthogonal" polynominals. Appropriate constants were determined from the data which allow a complete description of the wake turbulence.

Numerical models that predict pollutant concentrations along roadways can be enhanced by including the physical properties of wakes found in this study.

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The complete report, entitled "Wake of a Block Vehicle in a Shear-Free Boundary Flow—An Experimental and Theoretical Study," (Order No. PB 82-196 528; Cost: $12.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
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Telephone: 703-487-4650

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