FINAL REPORT

Numerical and Physical Models of Urban Heat Islands

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ABSTRACT

The response in the atmosphere of stratified shear layers to nonhomogeneous surface features is the subject of this report. Many interesting atmospheric circulations such as the sea breeze, the urban heat island, and flow over a heated island in the ocean (heat mountain) are induced by unbalanced bouyancy forces as a result of differential surface temperature.

Such phenomena are very complex since the motion is coupled with several dominant features such as thermal stratification, high roughness elements, nonuniformity of surface roughness and/or surface temperature, nonplanar boundaries, and unsteadiness of boundary conditions. These problems may be successfully examined, however, by a coordinated laboratory-analytical research effort.

This report summarizes a numerical and experimental research program which examined such a complicated airflow over nonhomogeneous surface complexities in two- and three-dimensional space.

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I. INTRODUCTION

On the smaller mesoscale the vagrancies of sea-land breezes, the effects of inversions on pollution in cities, or the flow over a heated island or a city represent examples of two- and three-dimensional interaction of a thermal boundary with the lower atmospheric shear flow. Specifically, the interaction of a metropolitan area as a heat source of finite extent on wind patterns and the potential penetration of heat plumes through inversion layers resulting in fumigation are relevant research topics.

Sabersky (1970) in his review "Heat Transfer Research in the 70's" emphasized the consensus that the application of heat transfer methodology to urban or agricultural heating appears fruitful. In their review titled "Meteorological Effects of the Heat and Moisture Produced by Man," Hanna and Swisher (1971) concluded that "there is clearly a need for numerical models and observations of air flow over mesoscale areas where surface momentum, heat and moisture fluxes vary." They suggested such studies will contribute to estimation of moisture losses from ponds and reservoirs, impact of space heating, and air conditioning over urban areas.

In another report (Yamada and Meroney, 1971) some simple nonhomogeneous boundary configurations in temperature have been investigated. The flow was assumed to be two-dimensional and a single disturbance was placed perpendicular to the flow field. The results obtained both by numerical and wind tunnel experiments agree closely. They reproduced the primary characteristics of the urban heat island and the heated island phenomena.

However, an urban area generally does not develop a uniform surface temperature distribution in both lateral and longitudinal directions. It is composed of several areas such as business districts, residential areas, parks, highways, etc., which have different thermal characteristics resulting in nonuniform temperature variation. Therefore it is desirable to incorporate three-dimensional features of the atmospheric boundary in laboratory and numerical models which are more similar to prototype phenomena. Experimental results for a three-dimensional heated island in the laboratory display many interesting phenomena which cannot be obtained by two-dimensional models (Yamada and Meroney, 1971).

A strictly analytical approach to the problem discussed herein is very difficult even in two-dimensional space. Fortunately, the recent development of numerical techniques associated with large capacity digital computers, provides a powerful mathematical language; hence the development of a three-dimensional numerical model may soon be possible.

Review of Literature

a) Field Evidence of the Effects of Nonhomogeneous Surface Heating

That certain cities have warmer temperature than their surroundings has been known since as early as the beginning of the eighteenth century, "but it was not until the relationships between the cities' heat island and the pathogenic and pernicious effects of air pollution were made evident that the study of this urban phenomenon was stimulated and accelerated" (Kopec 1970, p. 602). A comprehensive review of recent works on the matter is available in Peterson (1969) and in a W.M.O. technical note (1968).

Since urban heat island effects are most pronounced at night almost all past observers described the nocturnal heat island. Daytime temperature differences have also been observed (Ludwig and Kealoha, 1968; Preston-Whyte, 1970)., but their magnitudes are generally small. Furthermore, measurements difficulties arise since (Kopec, 1970); "daytime attempts to record temperature patterns were frustrated by constant sun-shade changes along the roads traveled, caused by trees, buildings, and other roadside obstructions".

Most prominent field experiments were conducted by Duckworth and Sandberg (1954), DeMarrais (1961), Bornstein (1968), and Ludwig and Kealoha (1968). They examined wind and temperature fields over San Francisco, California; Louisville, Kentucky; New York, N.Y.; and Dallas, Texas, respectively. Commonly observed heat island characteristics are listed as follows:

1. Very regular variation of daily temperature over flat unpopulated areas, whereas no generalizations of variation are obtained over urban region;
2. Less frequent occurrence of nocturnal inversion over a city;
3. One or more elevated inversion layers are formed over cities, whereas less frequently over rural regions;
4. Stronger nocturnal urban heat islands are observed in a calm, clear atmosphere;
5. Daytime urban heat islands are less intense than the night counterpart;
6. Intensity of urban heat islands depends on meteorological (wind, stability) and physical (city size) factors;
7. Formation of "cross over" phenomena over cities;
8. Displacement of heat island center windward and
9. Upper limit of a direct effect of urban heat islands extends occasionally up to 1000 m but average height ranges 50~400 m.

b) Theoretical Models of Nonhomogeneous Surface Heating

Only a few attempts are recorded which try to quantitatively explain the phenomena above (Myrup, 1969; Tag, 1969; Olfe and Lee, 1971; Vukovich, 1971). However, similar phenomena to that of urban heat islands have been observed in oceanographic fields. Malkus and Bunker (1952) observed periodically-spaced rows of small cumuli leeward of small islands on sunny summer days. This phenomenon is now known as a "heated island" phenomenon (Malkus and Stern, 1953). Wavy air motion at the lee side of an island in a strongly stably stratified airflow is the result of unbalanced buoyancy forces as a result of the temperature difference between the island and over the surrounding ocean. This is a "lee wave" phenomenon as described previously by other authors. Malkus and Stern (1953) noted the similarity between the heated island convection and airflow over a physical mountain. The heated island was replaced by an "equivalent mountain" whose shape is a function of the temperature excess of the island over the ocean, stability of the air, wind speed, and eddy diffusivity.

Several numerical studies have been conducted to obtain the solutions of the equation which retained both diffusion and convection terms (Tanouye, 1966; Estoque and Bhumralkar, 1968, 1970; Spelman, 1969; Magata, 1967; Delage and Taylor, 1970; Yamada and Meroney, 1971; Meroney and Yamada, 1971). Yamada and Meroney (1971) used a vorticity and stream function in their two-dimensional numerical models. During the development of the finite-difference scheme a wind tunnel was used as a diagnostic tool. This was in addition to the primary purpose of the collection of distinctive experimental data. It was found that the upstream finite difference approximation widely used was not appropriate to simulate lee wave phenomena of airflow over an obstacle. Since many authors are currently using this scheme even where a strong gravity wave is expected (Tanouye, 1966; Estoque, 1968; Lin and Apelt, 1970; Orville, 1967), the above finding suggests to us careful interpretation of their results as has also been suggested by Molenkamp (1968) and Crowley (1968). The failure of simulation is due to the strong numerical damping effects introduced by the first order finite difference approximation of nonlinear terms. A second order scheme successfully reproduced lee waves behind a rectangular obstacle observed in wind tunnel experiments.

c) Wind Tunnel Modeling

Meroney and Yamada (1971) reported model experiments of airflow over a heated island in two- and three-dimensional space. It is apparently the first systematic gravity wave research conducted in air. Their wind tunnel test section has dimensions of 2 x 2 ft cross section and 15 ft length. To provide a conditioned stratification in the test section, a series of heaters and cooling panels were added to the entrance section, ceiling and floor of the tunnel. Sixteen electric heaters of 6 x 24 in. were arranged in a grid accross the entrance section. Four larger heaters of 2 x 3 ft were adhered to the adjustable ceiling. The floor was constructed from a series of water cooled aluminum ducts. Final tunnel provided thermal gradients as large as 1.50°C/cm and wind speeds from 5 to 200 cm/sec.

Copper-constantan thermocouples of 30 gage were utilized to monitor temperature variations. Nine thermocouples mounted on a rake were used for vertical temperature distribution measurements. A smoke wire method has been utilized to investigate flow field during thermal stratification. It has been perfected for a practical use at the Engineering Research Center, Colorado State University. The advantage of the smoke wire method is an instantaneous visualization of the velocity profile.

Numerical results obtained by Meroney and Yamada showed close agreement with their wind tunnel experiments. Some characteristic features of urban heat island effects were simulated qualitatively both in a wind tunnel and by numerical computation. Both results displayed the less frequent surface and the more frequent elevated inversion layers over a city as obtained in previous field observations. A phenomena called "temperature cross over" (cooler temperature at certain height over a city), a downward wind and an acceleration of a horizontal velocity in the surface layer of the approaching flow to a city were also reproduced.

An experimental result on a three-dimensional airflow over a rectangular heated island was reported by Yamada and Meroney. A rectangular area of 30 x 8 cm on the wind tunnel floor was heated and the rest of the area was kept cooler. Temperature excess over the island was 64° C. The results indicated several different features from those observed in two-dimensional cases. Among them, the following are significant;

1. Horizontal convergence of wind directions;
2. Development of longitudinal vortexes along the lateral boundaries;
3. Stronger gradients of isotherms in the approaching flow, and;
4. A pair of vertical vortexes at both lee side corners of the island.

The horizontal convergence of wind into an urban area are commonly observed phenomena (Okita, 1960; Pooler, 1965). Air over a city is moved upward as heated below and continuity requires supply of air from the surroundings. The second observation simulates a situation where a large scale synoptic wind is blowing parallel to a sea coast. An immediate explanation of the isotherms' behavior stated in feature 3) is not apparent; however, an example in the atmosphere is provided by comparing Fig. 10 with Fig. 19 in Malkus and Bunker (1952). The latter figure displays less horizontal gradients in temperature than the former which was observed in a more three-dimensional flow situation. The natural occurence of a vertical vortex motion in the atmosphere such, as a fire whirl (corresponding the observation (4)), is the result of the simultaneous presence of ambient vorticity and rising air (Emmous and Ying, 1966).

d) Three-dimensional Numerical Models

Three-dimensional numerical models have been restricted by several factors:

1. Limited or finite physical capacity of a digital computer (even some current two-dimensional geophysical models need all available computer core for adequate accuracy).

2. Computational stability and convergence analysis. Mathematical proof of the above for a given numerical model is not yet available for such nonlinear problems as are described herein. Linear analyses have been performed, however, which suggest necessary conditions for stability in most cases. At the present moment, the

most reliable test of a numerical scheme is by comparison with the results obtained by other independent analog methods such as model experiments or field observations.

Recent three-dimensional numerical analyses include those by:

1. Chorin (1968), Miller (1970),
2. Estoque and Bhumralkar (1970), McPherson (1970),
3. Williams (1969),
4. Aziz and Hellumes (1967).

(Authors in the same numbered group have used a similar numerical scheme.)

Analyses differ primarily in terms of decisions concerning the following points:

i. Primitive equation versus vorticity-stream function system

It is interesting to note that in attacks on the three-dimensional problem all authors expect one (Aziz and Hellumes) used primitive equations. The situation is completely reversed for two-dimensional analysis where more than 90 percent of reviewed papers utilized a vorticity-stream function concept. The reason for this is that a vorticity-stream function system can eliminate the appearance of pressure terms from the governing equations in an incompressible fluid, i.e., one dependent variable is removed. Since a stream function can replace two velocity components u, and w in two dimensional case as $u=-\frac{\partial\psi}{\partial z}$ and $w=\frac{\partial\psi}{\partial x}$, finally two dependent variables, a vorticity and a stream function replace u, w, and p in the primitive equation. Application of this vorticity-stream function system to a three-dimensional problem is not straightforward since a streamline is changed to a stream surface (Vector-Potential in Aziz and Hellumes) and vorticity has three components instead of only one in the two-dimensional case. Now velocity (u, v, w)--Pressure in the primitive equation will be replaced by a vorticity and a stream surface both of which have three components. However, the elimination of pressure terms greatly simplify the computational effort, since the difficulty arises from the calculation of pressure equation expressed by the Poisson equation in three-dimensional space. Treatments of boundary conditions on the vorticity are not straightforward for general in--and outflow problems. Aziz and Hellumes argue that their method is free from the instability associated with treatment of boundary conditions for solid boundaries.

ii. Explicit versus Implicit Schemes

If new variables at all grid points in a finite-difference expression are computed explicitly from the known values in a previous time step then the scheme is called explicit. While an implicit scheme requires a simultaneous replacement of all new values from the old one. The former has the advantage in a simpler programming and the latter can utilize a larger time increment which saves computational time. It requires an optimization over such choices to decide to select either an explicit or an implicit scheme. In the previous investigations the former was used by Miller, Estoque and Bhumralker, McPherson, and Williams. As an implicit scheme the "Alternating Direction Implicit" (A. D. I.) method is most popular since the matrix used to express the finite difference scheme can be reduced to a tridiagonal form which may be solved easily by a Gaussian elimination technique.

iii. Constant versus Nonconstant grid systems

A three-dimensional numerical model requires a great number of grid points which may require more storage capacity than is available by current digital computers or result in a very expensive computation. Therefore, it is necessary to utilize an effective grid system: Finer meshes in the regions where abrupt changes of variables are anticipated and coarser ones far away from sources.

Very few studies are available which compare the advantages and disadvantages of utilizing a nonconstant grid system (Round et al., 1962).

iv. Optimum Finite-Difference schemes for solving the Poisson Equation

In either system discussed in (i), the set of primitive equations or the vorticity-vector potential system, it is necessary to solve the Poisson equation to advance one time increment in a numerical integration. Since this is expected to be the most time consuming single process in any numerical model an effective method is desirable. The most popular method for this purpose is a successive over relaxation (S. O. R.) method. However, the A. D. I. method has been proven to have a faster convergence rate than S. O. R. in a rectangular computational domain with a square mesh. Recent investigations also suggest a Fast Fourier Transform (F.F.T.) technique may be very powerful to solve the Poisson equation.

II. OBJECTIVES

The discussions in the previous sections summarize briefly the current status of understanding of the effects of shear flows over nonhomogeneous surface features. It was apparent there is a need for further theoretical and experimental work in this field. It has been shown in the previous remarks that a wind tunnel is an excellent facility not only for collecting experimental data but also as a diagnostic tool for development of an appropriate numerical model. Results obtained by parallel numerical and wind tunnel experiments may help to eliminate erroneous conclusions associated with errors in inadequacies of the independent techniques. The research summarized herein was designed to speak to those questions raised above. The specific objectives chosen were to consider:

1. Two dimensional greenbelt model--examine the effects of spacing and intensity of temperature differentiation of the fluid motion over a sequence of heated and cooled "islands."

2. Three-dimensional heat island model--examine the effect of thermal plume penetration over a simulated urban area for neutral, ground based inversion, and elevated inversion stratification.

3. Three-dimensional heat island incorporating surface roughness--investigate the combined effects on airflow by heating and roughness.

III. RESEARCH RESULTS AND REPORT ABSTRACTS

NUMERICAL AND PHYSICAL SIMULATION OF A STRATIFIED AIRFLOW OVER A SERIES OF HEATED ISLANDS, Meroney, R. N. and Yamada, T., CSU CEP71-72RNM-TY64, 1972.

Abstract

Perturbations of a stratified shear flow by two identical heated boundaries are investigated both numerically and experimentally. These heated islands may represent a simplified two-dimensional urban complex. A numerical model was constructed by solving a set of two-dimensional, time dependent, and nonlinear governing equations.

The results obtained by wind tunnel and numerical simulations agree. They both simulated the mutual interaction between the islands: The height of the upstream "thermal mountain" was reduced by half as a result of a strong approach wind induced by the downstream heat island, or the downstream one was intensified because of the existence of the upstream one. Commonly noted modifications of meteorological factors by urbanization are also reproduced--such as a temperature cross-over and a downward acceleration of vertical velocity in the surface layer over the upper half of a city. Maximum streamline displacement observed was about 5 cm both in the numerical and in the wind tunnel models. A linearized theory predicted as high as 15 cm.

All computer outputs are demonstrated in a 16 mm movie film. They include the contour line plottings of stream function, vorticity, and temperature. Wind tunnel flow is presented through streamline tracers of smoke.

Published in Open Literature as:

Meroney, R. N. and T. Yamada, "Numerical and Physical Simulation of a Stratified Airflow over a Series of Heated Islands," Summer Simulation Conference, Proceedings of June 13-16, 1972, 12 p.

(The programs developed by Yamada and Meroney (1971) have been completely rewritten by Meroney to examine the influence of different differencing schemes, solution algorithms, and grid arrangements. In the process of preparing these programs for application to atmospheric scale problems it became apparent adequate and simple turbulence models did not exist to handle the influence of stratification which is dominant in these problems. An effort directed toward finding some simple but adequate solution resulted in the following report.)

BUOYANCY EFFECTS ON A TURBULENT SHEAR FLOW, Meroney, R. N., CER73-74RNM38, 95 p., 1974.

Abstract:

It has long been recognized that the buoyancy force due to density stratification has pronounced effects on the turbulence structure. A number of investigations have utilized stability corrections based on the assumption of the existence of an eddy viscosity or eddy diffusivity. Unfortunately such models are incapable of physically behaving as the measurements in the presence of strong stable or unstable stratifications suggest. Recently Donaldson et al. (1972), Lumley (1972), Daly (1972) and Lee (1974) have proposed closures of the equations of motion in the presence of buoyancy forces which require equations for all Reynold's stresses and heat fluxes. Unfortunately even for a one-dimensional model one must at a minimum then solve simultaneously nine partial differential equations and one algebraic equation. Other theories suggest an even higher total.

Utilizing a simple time dependent one-dimensional example as a test case this report discusses a solution which represents the important characteristics of a buoyancy dominated shear flow by solving four partial differential equations in addition to the mean equations of motion. This suggested model solves equations for total turbulent kinetic energy, k, total turbulent temperature fluctuations, k_t, eddy dissipation, ε, and thermal eddy dissipation, ε_t. Three separate versions of this model are discussed--an algebraic length scale version, a Prandtl-Kolmogorov eddy viscosity version, and an algebraic stress and heat flux model. The final version (requiring six partial differential equations) manages to replicate results for a much more complicated version (requiring ten partial differential equation). The advantages for two- and three-dimensional problems are even greater.

Conclusions:

Of course one of the most interesting aspects of these results is the duplication of Donaldson et al. (1972) conclusion that there is a radically different behavior of the heat flux correlation $\overline{w'T'}$ depending on whether $\partial T/\partial z$ is greater or less than zero. In fact, the ASM equations indicate that for small values of $\partial T/\partial z$ and $\partial u/\partial z$ there may be transport of heat and momentum up the gradients due to finite values of k_T or $\overline{u'T'}$! This effect has often been observed by experimentalists in atmospheric transport. In addition if one considers only production terms and neglects pressure scrambling and dissipation terms in equations for k, k_T and $\overline{w'T'}$ it is not difficult to show that when $\partial T/\partial z < 0$, there is an exponential development of $\overline{w'T'}$. However when the atmosphere is stable, i.e., when $\partial T/\partial z > 0$, the heat flux correlation $\overline{w'T'}$ is oscillatory about the Bront-Vassala frequency.

Utilizing a simple, time-dependent, one-dimensional example as a test case this report has discussed a solution which represents the important characteristics of a buoyancy dominated shear flow by solving four partial differential equations in addition to the mean equations of motion. This suggested model solves equations for total turbulent kinetic energy, k, total turbulent temperature fluctuations, k_t, eddy dissipation, ε, and thermal eddy dissipation, ε_t. Three separate versions of this model were discussed--an algebraic length scale version, a Prandtl-Kolmogorov eddy viscosity version, and an algebraic stress and heat flux model. The final version (requiring six partial differential equations) manages to replicate results for a much more complicated version (requiring ten partial differential equations). The advantages for two- and three-dimensional problems are even greater.

One must conclude on the basis of these results that:

1. An algebraic length scale version of a MTE model closure is not able to replicate the behavior of thermally stratified flow, especially in regions where production and dissipation of turbulence are not in equilibrium. A single dissipation length scale does not appear sufficient here to develop the expected degree of damping in stable regions.

2. Addition of transport equations for length scales does not suffice to solve the above problem. Such MTE models are still inadequate.

3. Addition of algebraic relations for stress and heat flux which incorporate the influence of stability do appear to incorporate the physics of the phenomena to the extent that results are similar to the MRS test case.

Published in Open Literature as:

Meroney, R. N., "Buoyancy Effects on a Turbulent Shear Flow," AMS/WMO Symposium on Atmospheric Diffusion and Air Pollution, Proceedings of, Santa Barbara, California, September 9-13, 1974, pp. 25-30.

Meroney, R. N., "An Algebraic Stress Model for Stratified Turbulent Shear Flows," Submitted to Computers and Fluids, 1974, 33 p.

(In addition to the work accomplished directly by the principal investigator be served as advisor to two projects directly related to the objectives of this grant. As a result of this interaction the objectives of the grant were persued without additional financial committment from the National Science Foundation the results of these studies are found in the following reports.)

STRATIFIED SHEAR FLOWS OVER A SIMULATED THREE DIMENSIONAL URBAN HEAT ISLAND. SethuRaman, S., Ph.D. Dissertation, Civil Engineering Department, Colorado State University, August, 1973.

Abstract:

Three dimensional airflow over a rectangular heat island was studied for various conditions of approach flow in a wind tunnel. Three different thermal stratifications of the approach flow were selected for the study--neutral, ground based and elevated inversions. For each

of these flows studies were conducted with and without roughness over the heat island for the conditions with and without heating of the island. Approach flow temperature profiles were modeled according to atmospheric data available in the literature.

For each of the twelve cases mentioned above, measurements of mean wind velocity, longitudinal velocity fluctuations, mean temperature and temperature fluctuations were made. In addition, mean concentration measurements of a radioactive gas released from a two-dimensional, ground-level line source upwind of the heat island were also made. Flow patterns were visualized for different cases with the help of a passive smoke source. Comparisons of data from the wind-tunnel measurements with the field data were made. Three-dimensional measurements of the mean wind velocity, temperature and turbulence have yielded valuable information concerning the flow of air around a typical urban heat island.

The mechanisms of the heat island observed in the wind-tunnel for different stratified flows were very similar to those observed in the field. The urban heat island plume that passes aloft downwind causes an appreciable reverse flow onto the heat-island. The helical vortices at the edge of the heat island cause a reduction in the turbulence level resulting in high concentrations of the mass released from a continuous line source upwind of the heat island.

A theoretical model based on linearized equations of motions incorporating a boundary layer type velocity profile has been developed to predict the urban excess temperatures and velocities. Theroetical results compare fairly well with data obtained in the laboratory and in the field.

Conclusions:

In the light of the foregoing discussions the following conclusions can be made:

1. Simulation of a three-dimensional flow over an idealized urban heat island in a wind tunnel with stratified approach flows gives results very similar to those observed in the field.

2. The orders of magnitude of the depth of the heat island representing the maximum effect on the airflow and the roughness length are the same as found over "typical" cities.

3. Flow visualization and quantitative measurements of mean and turbulent velocities, mean temperatures and diffusion for different conditions (of stratification) of the approach flow and the heat island reveal the following significant flow characteristics of the flow pattern:

   Cool air from the surrounding area near the surface moves across the periphery of the heat island towards the center due to the circulation caused by the adjoining hot and cool areas (similar to urban-rural complex). This circulation causes inflow of air near the upwind edge of the heat island and reverse (counter-gradient) flow near the downwind edge. The convergence at the surface and the buoyancy forces set up by the heat source causes air to raise and move above the cool floor (similar to rural area) downwind of the heat island as a massive plume. This plume is well defined and narrow for a stable approach flow. For an elevated inversion approach flow it becomes more diffused. The reverse flow near the downwind edge of a smooth heat island is persistent and stronger than if the surface is rough.

4. Longitudinal vortices are seen to exist near the fringes of the heat island as noted by flow visualization. Measurements indicate a region of low turbulence over the edge which may be the core of the vortex.

5. Similarity of z/L' where z is the height above the surface and L' is Monin-Obukhob's length ensured a reasonably good simulation of the heat source for the urban heat island.

6. A linear model incorporating a boundary layer type velocity profile predicts the perturbed temperatures near the surface of the heat island fairly well for laboratory and field experiments. Variable stability factor for the approach flow in line with the actual conditions may improve the capability of the linear model to predict the urban excess temperatures at higher levels equally well.

Published in the Open Literature as:

SethuRaman, S. and J. E. Cermak, "Physical Modeling of Flow and Diffusion over an Urban Heat Island," Proceedings of the Second IUTAM-IUGG Symposium on Turbulent Diffusion in Environmental Pollution, 8-14 April 1973, Advances in Geophysics, Vol. 18, 1973.

SethuRaman, S. and J. E. Cermak, "Mean Temperature Distributions over a Physically Modeled Three-Dimensional Heat Island for Different Stability Conditions, Symposium on Atmospheric Diffusion and Air Pollution, Proceedings of, Santa Barbara, 9-13 September 1974, pp. 381-386.

THREE-DIMENSIONAL TURBULENT BOUNDARY LAYER FLOW ON ROUGHNESS STRIP OF FINITE WIDTH, Edling, W., Ph.D. Dissertation, Civil Engineering Department, Colorado State University, April 1974.

Abstract:

Described are the results of an experimental study of a well developed, turbulent boundary layer on a smooth, flat surface encountering an area of much rougher surface. The roughened area is a strip with its length extending in the direction of the mean flow but of finite width in the surface direction normal to the flow. The resulting three-dimensional flow differs significantly from previously studied cases involving step changes in roughness of infinite extent in the direction normal to the flow.

Extensive experiments were carried out in a wind tunnel having a length of nearly 100 ft (30.5 m) with a boundary layer thickness of the order of 18-20 in. (0.5 m). Pitot tube and hot-wire anemometer measurements were made of mean velocity and Reynolds stress quantities in great detail throughout the flow field. Secondary flow components were measured by a new x-wire technique permitting quick resolution of very small deflections of the mean flow vector. Considerable effort was expended to reduce and examine sources of error. The data obtained is presented both graphically and in tabular form.

Analysis of the three-dimensional, turbulent boundary layer equations is carried out using the experimental results to identify significant terms. Several conclusions are reached regarding the driving mechanism of the flow, the significant flow parameters, and the effects of the three-dimensionality upon the flow as compared to the analagous two-dimensional case.

Conclusions:

The objective of this study was to attempt to penetrate the complexities of a common type of three-dimensional, turbulent boundary-layer flow. Following is a summary of the pertinent observations and conclusions resulting from this study:

1. The three-dimensional effects resulting from having an edge or line parallel to the mean flow separating regions of differing roughness are confined largely to the immediate neighborhood of that edge.

2. More specifically, that neighborhood may be thought of as a shear plane extending upward from the edge to the outer limit of the inner boundary layer.

3. The flow in the region away from the roughness is nearly two-dimensional and for first-order analyses may be regarded as two-dimensional.

4. The flow in the region over the roughness but away from the edge is also two-dimensional to first order analysis. Furthermore, this flow shows a definite trend toward similarity after an initial adjustment region following the roughness change.

5. The flow in the shear plane over the edge is highly three-dimensional even to first order analysis. However these strong three-dimensional effects are confined to the narrow shear plane, the width of which does not increase beyond a certain point.

6. Within the shear plane are generated turbulence levels and Reynolds stresses which are significantly larger than those seen anywhere else over the roughness.

7. The effects of the shear plane diffuse into the flow in proportion to the square root of the distance downstream. This diffusive effect is much more noticeable over the smooth surface where turbulence is of lower intensity than it is over the rougher surface where turbulence levels are higher.

8. In the cases examined, the penetration of the edge effect into the region above the roughness was limited to a distance nearly an order of magnitude smaller than the inner layer thickness. This penetration shows no sign of increasing with increasing x.

9. There is additional production of turbulent energy in the edge region in excess of that produced by the roughness itself.

10. The edge shear region gives rise to nonzero values of the $\overline{uw}$ Reynolds stress, which is zero in two-dimensional flow. The quantity $\overline{uw}$ attains values which are comparable in magnitude to local values of $\overline{uv}$.

11. No significant effects of the $\overline{vw}$ stress term were detected in this study; however the difficulties associated with attempting to measure this quantity preculde ruling it out entirely.

12. Values of $\overline{vw}$ inferred from cross flow velocity components assuming an eddy-viscosity model suggest that $\overline{vw}$ is a negligible quantity.

13. The edge region contains lateral (z direction) gradients which are of the same order of magnitude as the vertical (y direction) gradients. The lateral gradients of $\overline{uv}$, $\overline{uw}$, u^2, $\overline{v^2}$, and $\overline{w^2}$ exhibit this characteristic.

14. The terms $\partial\overline{uw}/\partial z$, $\partial\overline{v^2}/\partial z$, and $\partial\overline{w^2}/\partial z$, which are not significant in two-dimensional flow, arise through the balance in the edge regions.

15. Viscous effects in the edge region arise from curvature of the velocity profiles in the z direction as well as in the y direction. Locally, these curvatures may be of comparable magnitude.

16. The lateral gradients in the edge region give rise to a cross flow component which in turn leads to an eventual downflow in the boundary layer over the roughness.

17. Analysis of the equations of motion leads to the conclusion that the primary driving force for the cross flow is the lateral gradient of the quantity $(\overline{w^2} - \overline{v^2})$ in the edge region.

18. It appears that the presence of an edge has little direct effect upon the velocity and turbulence profiles over the roughness. Instead, the detectable effects appear to be a direct result of the downflow over the roughness.

19. Cross flow velocity components were seen over the roughness with a maximum magnitude of about 1.5 percent of the free stream velocity.

20. The vertical downward flow over the roughness is opposite in direction to the usual upward component seen in two-dimensional boundary layers.

21. The maximum vertical flow component seen in less than one percent of the free stream velocity.

22. The maximum deflection of the flow vector due to these secondary flow components is less than two degrees.

23. The limited data available suggest that the cross flows decrease very rapidly with decreasing Reynolds number. (A 25 percent reduction in Reynolds number produced an order of magnitude decrease in the cross flow component.)

24. The secondary flow components influence the flow over the roughness by transporting high-momentum fluid downward in the boundary layer. The effect is of second order, however it is most noticeable in its effect upon the shape factor, which grows with increasing distance downstream.

25. The parameters which characterize the cross flow and therefore its influence on the remainder of the flow field cannot be verified from the present tests. However the most likely parameters are predicted to be those identified in the dimensionless ratios given in Eq. (5-36).

26. The rate of growth of the internal layer in the x direction is decreased slightly by the vertical downflow. The effect is just noticeable, with an observed decrease of about 15 percent in the exponent of the power law describing the growth of the internal layer.

27. Determination of the inner layer thickness is subject to variations depending on which velocity or turbulence quantity is examined for this purpose. The most distinct and consistent indication is obtained from the $\sqrt{v^2}$ data profiles.

28. The technique suggested by Antonia and Luxton (36,37) using half-power plots in y does not define the inner layer clearly at large distances downstream.

29. The ratio δ/D may be conveniently used to categorize flows over various sizes of roughness areas. Values of this ratio of unit order or smaller will characterize a flow which is essentially two-dimensional with local perturbations near the edges of the roughness area.

IV. FINAL RECOMMENDATIONS

It is expected of course, that the new information developed by this research will be incorporated into design and health safety practices when considering the environmental impact of urban areas. Additional problems which warrant consideration in this area remain. They are:

1. Analysis of the dispersion of scale tracers in the vicinity of urban modified flow fields.

2. Analysis and prediction of the dispersion of atmospheric pollutants during the breakup of an inversion situation; i.e., fumigation.

3. The influence of a heated city center on the local environment when the city is located in rugged terrain; in simple valley complexes, or near large bodies of water.

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