PROJECT ADMINISTRATION DATA SHEET

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Project No. E-16-651 GTRI/~~GIT~~ DATE 10 / 13 / 83

Project Director: Warren Strahle School/~~Lab~~ AE

Sponsor: U. S. Army Research Office

Research Triangle Park, N.C. 27709

Type Agreement: Contract No. DAAG29-83-K-0143

Award Period: From 10/1/83 To ~~9/30/85~~ ~~86~~ ~~10-31-87~~ 11-30-87 (Performance) 11/30/84 (Reports)

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Estimated: $ ______ $ 51,099

Funded: $ ______ $ 51,099

Cost Sharing Amount: $ 4,476 Cost Sharing No: E-16-333

Title: Stagnating Turbulent Reacting Flows

ADMINISTRATIVE DATA OCA Contact John W. Burdette x4820

1) Sponsor Technical Contact:

Dr. David A. Mann
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, N.C. 27709

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Mr. Abram J. VanHall - all matters
except as covered by ONR RR below
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, N.C. 27709
ONR-property,patent,invoice & closing mtrs

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See Attached SFRC Supplemental Information Sheet for Additional Requirements.

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Date 2/24/88

Project No. E-16-651   School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) W. ~~Strahel~~ Strahle   GTRC/~~GIT~~

Sponsor Army/ARO, Res Triangle Park, NC

Title Stagnating Turbulent Reacting Flows

Effective Completion Date: 11/30/87 (Performance) 1/31/88 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Copy of Last Invoice Serving as Final
- [x] Release and Assignment
- [x] Final Report of Inventions and/or Subcontract:
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PROGRESS REPORT

(TWENTY COPIES REQUIRED)

1. ARO PROPOSAL NUMBER: 20658 - EG

2. PERIOD COVERED BY REPORT: October 1, 1983 - June 30, 1984

3. TITLE OF PROPOSAL: Stagnating Turbulent Reacting Flows

4. CONTRACT OR GRANT NUMBER: DAAG29-83-K-0143

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

C. S. Murali, Graduate Research Assistant

Warren C. Strahle, Principal Investigator

No degrees awarded

BRIEF OUTLINE OF RESEARCH FINDINGS

The program was initiated during the period to investigate the effects of freestream turbulence on the behavior of stagnating flows. The initial two problems investigated have been planar and axially symmetric, incompressible stagnating flows (Hiementz and Hohmann flows with imbedded turbulence).

The Tam-Bremhorst approach to turbulence modelling with the k-ϵ equations has been adopted for both convenience and because of some experimental support. Some data bases have been located for later comparison with experiment when the compressible case with heat transfer is attempted.

Some numerical difficulties have been discovered with this problem. Because of a disparity in orders of magnitude between the mean flow equations and the turbulence quantities equations, exceptionally small step sizes are required in the integration to achieve step size independence of the results. For the solutions gained to date it has been found that two compensating effects serve to change the wall shear stress very little from the laminar value. The turbulence tends to thicken the sublayer while increasing mixing rates, and the net effect is a slight <u>lowering</u> of the shear stress, as compared with the laminar value.

Two unexpected findings have been made. First, in contrast to the laminar stagnation point problem, solutions do not exist for all values of the parameters controlling the turbulence level and scale. In brief, below a critical value of the turbulence Reynolds number solutions to the stagnation point ordinary differential equations are nonexistent. Secondly, for a given turbulence situation near the wall, a wide variety of freestream turbulence situations exist. The solutions are thereby nearly degenerate and insensitive to the freestream. Current work is centering about understanding this degeneracy, before proceeding to more complex problems involving heat transfer.

PROGRESS REPORT

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1. ARO PROPOSAL NUMBER: 20658-EG

2. PERIOD COVERED BY REPORT: 1 July 1984 - 31 December 1984

3. TITLE OF PROPOSAL: Stagnating Turbulent Reacting Flows

4. CONTRACT OR GRANT NUMBER: DAAG29-83-K-0143

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHORS OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Warren C. Strahle	Principal Investigator
C. S. Murali	Graduate Research Assistant

W. C. Strahle
Department of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

The equations for stagnation point flows with imbedded freestream turbulence are being investigated using the Lam-Bremhorst k-ϵ turbulence model. The practical applications lie in ability to compute stagnating turbulent flows such as at the leading edge of nozzle guide vanes in gas turbines, for example, and to provide analytical boundary conditions for numerical computations near stagnation points, such as near a reattachment point is recirculatory flows.

Serious difficulties have been found in finding a proper match between the outer inviscid (but turbulent) flow and the viscous layer. Integrating outward from the body, any edge condition can be met that is desired. The question is, what is the proper edge condition? Little guidance is given by the outer flow since it is found that, integrating toward the body from the far field along the stagnation line, an improper balance between diffusion, convection, dissipation and production takes place. Specifically, diffusion should be weak in the outer stream and it is not. Resolution of this difficulty will have to be made for further progress to be made.

The compressible variable density formulation is complete and awaits resolution of the above difficulty with incompressible flow.

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4. CONTRACT OR GRANT NUMBER: DAAG29-83-K-0143

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHORS OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

"Stagnating Turbulent Flows" abstract submitted for 24th AIAA Aerospace Sciences Meeting.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Warren C. Strahle	Principal Investigator
William Meyer	Research Engineer
Robert K. Sigman	Research Engineer

W. C. Strahle
Department of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

The equations for stagnation point flows with imbedded freestream turbulence are being investigated using a variable density modification to the Lam-Bremhorst k-ϵ turbulence model. The practical applications lie in being able to compute stagnating turbulent flows such as at the leading edge of nozzle guide vanes in gas turbines, as one example.

Past theoretical deficiencies which have been addressed in this program are:

a) Past work did not recognize a strong alteration in the turbulence from the freestream value during the inviscid part of the stagnation process.

b) Past work has the turbulence quantities behaving improperly near the wall.

c) Past theories do not account for the possibility of temperature fluctuations in the freestream flow.

These deficiencies have been corrected with the current theory.

The problem has been found to be a two layer problem consisting of an outer non-diffusive flow followed by a laminar-turbulent viscous stagnation region. It has been demonstrated that the joining condition is that dissipation and production are in balance at the junction of the two regions. Theoretically it has been found that the dissipation of the turbulence dissipation rate does increase over values typically found in shear layers. This is the first theoretical demonstration of an experimental fact that this must occur in flows where normal stresses are dominant over shear stresses.

Current calculations are being performed in the heat transfer case to compare with the stagnation point data of Smith and Kuethe. Initial calculations are favorable with no adjustment of model constants.

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5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHORS OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

   a) Strahle, W. C., "Stagnation Point Flows with Freestream Turbulence - The Matching Condition," AIAA Journal, 23, pp 1822-23 (1985).

   b) Strahle, W. C., Sigman, R. K. and Meyer, W. L., "Stagnating Turbulent Flows," AIAA Paper No. 86-0437 (1986).

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

   Warren C. Strahle - Principal Investigator
   Robert K. Sigman - Senior Research Engineer

W. C. Strahle
Department of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Brief Outline of Research Findings

The equations for stagnation point flows with imbedded freestream turbulence are being investigated using a variable density modification to the Lam-Bremhorst k-ε turbulence model. The practical applications lie in being able to compute such things as heat transfer at the leading edge of nozzle guide vanes in gas turbines, as one example.

Extensive comparisons with experiment have been completed during the report period, the primary standard of comparison being the Smith and Kuethe weak heat transfer experiments. At low Laminar Reynolds number the agreement is excellent. At the higher Reynolds number (> 100,000 based on cylinder diameter) a rather severe discrepancy has been found and it is one which has not been properly addressed insofar as data gathering is concerned. It is theoretically found that a strong effect of the ratio of turbulence length scale to body diameter appears at high Reynolds number, but there are no experiments to test this effect in the literature. Consequently, a strong research finding is that some systematic experiments are required at high Reynolds number.

Previous numerical difficulties with "shooting" methods for the present two point boundary value problem have become compounded in integration for the highly variable density case, because of the large number of dependent variables. Consequently, the problem is being reformulated to use quasi-linearization as the numerical method.

The deceleration process of the flow external to the viscous zone has a strong effect upon the turbulence, as previously reported. An analytical solution to the full stress transport equations has been found in this region to check the anisotropy induced in the turbulence during the inviscid deceleration process. This could have an effect upon the solution since k-ε methods are basically near-isotropic methods. While the development of anisotropy is predicted, the effect is not believed sufficiently strong to negate the use of the current analytical method in calculation of heat transfer.

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4. CONTRACT OR GRANT NUMBER: DAAG29-83-K-0143

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHORS OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

Strahle, W. C., Sigman, R. K. and Meyer, W. L., "Stagnating Turbulent Flows," accepted by AIAA Journal, October, 1986.

Strahle, W. C. "Anisotropy Development in Stagnating Turbulent Flows," submitted to AIAA Journal, August, 1986

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Warren C. Strahle - Principal Investigator
Robert K. Sigman - Senior Research Engineer

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Atlanta, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

The equations for stagnation point flow with imbedded freestream turbulence are being investigated using a variable density modification to the Lam-Bremhorst k-ε turbulence model. Decisions on an experimental program to be conducted at NASA/Lewis have been made and windtunnel modifications have been submitted to NASA.

A prior analytical difficulty in the nearly inviscid stagnation equations has been overcome by use of a modified dissipation rate equation. In the modification, with prior justification for flows where normal stresses dominate shear stresses, production increases relative to dissipation in the dissipation equation. A singular behavior is removed which limits the growth of turbulence quantities as the viscous zone of the stagnation point is approached. The results, however, are not substantially changed when compared with experiment - there is a divergence of results of analysis and experiment at high Reynolds number.

The initial planning trip to NASA/Lewis has been completed and drawings for windtunnel modifications have been submitted to NASA. The experimental program, to be conducted in the Summer, will concentrate on a) the effects of scale/body size ratio on stagnation point heat transfer and b) anisotropy development during the stagnation process. These effects will have been computed prior to the experimental program and the objective is to compare theory and experiment.

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1. ARO PROPOSAL NUMBER: 20658-EG

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5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHORS OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

None

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Warren C. Strahle - Principal Investigator
Robert K. Sigman - Senior Research Engineer

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Atlanta, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

Experiments are being conducted upon and the balance equations are being investigated for stagnation point flows with imbedded freestream turbulence. The analytical formulation uses a variable density formulation and the experiments use a heated wall configuration with grid generated turbulence in a two-dimensional windtunnel. The experiments are being conducted at NASA/Lewis in a unique Georgia Tech/NASA collaboration.

It has been analytically found that a) there is strong anisotropy development from an initial isotropic turbulence state as the stagnation point is approached, b) there is heat transfer disagreement between theory and prior experiment at high Reynolds number and c) there is only a small effect of freestream temperature fluctuations on wall heat transfer. These analytical results are being checked in the experiments at NASA, and the results will be used to reformulate the theory, if necessary, in future work.

The current major conclusion is that quasi-isotropic analytical methods, such as the Lam-Bremhorst k-ε model currently in use, may have to be abandoned in favor of second order closure methods for this strongly decelerating flow in which normal stresses, as opposed to shear stresses, are dominant.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulence, Stagnation Point, Reacting Flows, Heat Transfer

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Theoretical and experimental results are reported concerning the problem of heat transfer to bodies when there is turbulence imbedded in the freestream. Both velocity and temperature turbulence are considered and a fully variable density theory is developed. Experiments were conducted in collaboration with NASA/Lewis. Excellent closure of theory and experiment was achieved for the case of no freestream temperature fluctuations. With no data

available for comparison, no closure could be achieved for the case of temperature fluctuations, but the theory indicates that the heat transfer effect of this phenomenon is strong.

Final Report

STAGNATING TURBULENT REACTING FLOWS

School of Aerospace Engineering
Georgia Institute of Technology
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prepared for

U. S. Army Research Office
Research Triangle Park, NC 27709

Contract No. DAAG29-83-K-0143

Warren C. Strahle
Principal Investigator

Problem Statement

Stagnating flows of a turbulent fluid occur in many reacting flow applications. Included are turbine stagnation regions in gas turbines, several regions in diesel engines and near reattachment points in ramjets. Prior to this program, however, there was no good analytical method for prediction of heat transfer in such regions and there certainly were no adequate data for comparison with prediction.

The problem studied, both theoretically and experimentally, was the problem of stagnation point heat transfer for a flow that contained imbedded free stream turbulence. The goals were a) construction of an analytical model of the stagnation process b) comparison of the model with available experiments, c) experimentation to fill voids in the experimental data, and d) determination of voids of understanding for future work.

All goals of the program were achieved.

Summary of Results

Analytical

1. A new model of turbulent stagnating flows was constructed which matched, in a manner superior to prior theories, prior experimental results and experimental results attained under this program. These results were obtained for heat transfer under conditions of arbitrary free stream turbulence intensity and scale for low Mach number, constant mean density flows.
2. A unique discovery was made that a two parameter (intensity and scale) freestream turbulence degenerates into a one-parameter (intensity becomes related to scale) turbulence problem during the inviscid stagnation process, before flow entry into the viscous stagnation zone.

3. This flow was found to have unique properties of normal stress domination over shear stresses that required a new viscous - inviscid matching procedure to be developed.
4. Anisotropy development during the inviscid part of the stagnation process was found to not be large, justifying the use of a two equation (k-ε) model of turbulence to be employed in the analysis.
5. The general model developed was for the variable mean and fluctuating density case, although no tests could be made against experiment because no data were available. Calculations show, however, that the effect of temperature (density) fluctuations in the freestream have an important effect upon heat transfer and experiments are required to verify this effect.

Experimental

1. In cooperation with NASA/Lewis, experiments were conducted to specifically isolate a) anisotropy development during stagnation and b) the independent effects of freestream intensity and scale on heat transfer to cylinders.
2. The experiments were matched by theory in all respects and showed small anisotropy development and clear evidence that both scale and intensity are important variables in stagnation point heat transfer.

General

The two most important summary graphs are shown in Figs. 1 and 2. In Fig. 1, comparison of theory and experiment is shown for the data of this program and some older data (Ref. [4] from Smith and Kuethe). Reynolds numbers are shown based on cylinder diameter, and only high Reynolds number results are shown since both theory and experiment show little effect of turbulence at low Reynolds number ($Re_D < 100{,}000$).

The solid lines and closed dots on Fig. 1 show the agreement between theory and experiment for the older data. The squares and triangles show agreement between theory and experiment for the data of this program. In general, it may be stated that the agreement is for superior to any prior theory and that the essential physics are contained in the theory.

Figure 2 shows a theoretical output of the program which does not, however, have any experimental data as back-up. Figure 2 shows an extraordinary effect of freestream turbulence levels in temperature, for fixed velocity turbulence, on stagnation point heat transfer. These calculations were done for a cooled wall case typical of turbine cooling (T_{wall} / T_∞ = 0.67). It is strongly recommended that an experimental program be initiated to verify this effect.

Publications

Refereed

1. Strahle, W. C., "Stagnation Point Flows with Freestream Turbulence - The Matching Condition," AIAA Journal, 23, 1822 (1985).

2. Strahle, W. C., Sigman, R. K. and Meyer, W. A., "Stagnating Turbulent Flows," AIAA Journal, 25, 1071 (1987).

Conference Proceedings

1. Strahle, W. C., Sigman, R. K. and Meyer, W. A., "Stagnating Turbulent Flows," AIAA Paper No. 86-0437, Reno, NV, January 1986.

Submitted to Conference (Refereed)

1. Huval, D. J., Van Fossen, G. J., Sigman, R. K. and Strahle, W. C., "Heat Transfer in Stagnating Turbulent Flows," submitted to 1st National Fluid Dynamics Conference sponsored by AIAA, ASME, SIAM.

Scientific Personnel and Degrees Awarded

Warren C. Strahle, Principal Investigator and Regents' Professor

C. S. Murali, Graduate Research Assistant - Master of Science, 1984

William A. Meyer, Research Engineer

Robert K. Sigman, Senior Research Engineer

Danny J. Huval, Graduate Research Assistant

Note to Program Manager

This program has shown unique cooperation between Georgia Tech. and NASA/Lewis. A follow-on proposal has been submitted to continue this collaboration on the important problem of temperature fluctuation effects upon heat transfer.

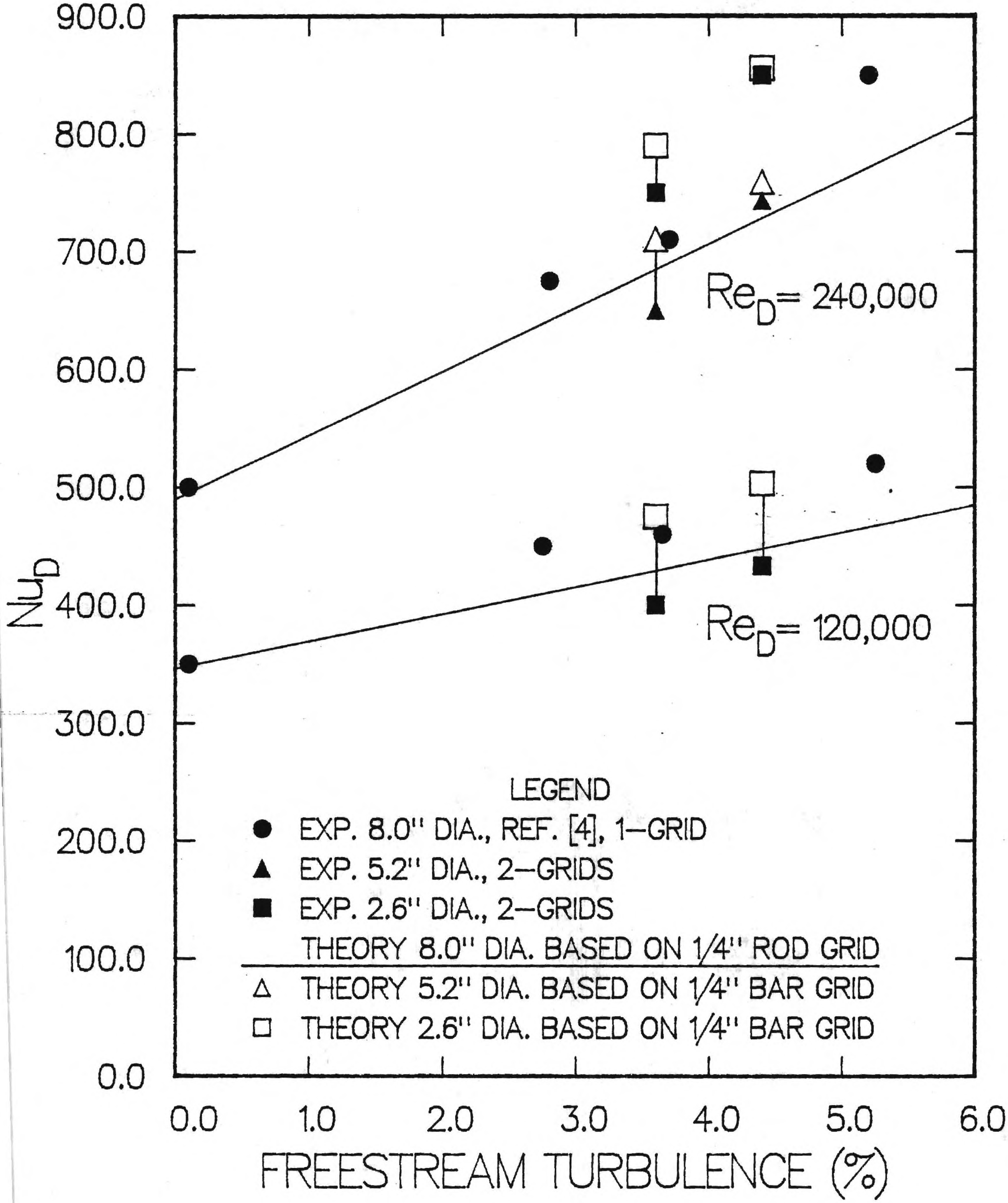

Figure 1. Nusselt number for stagnating turbulent flows as a function of laminar Reynolds for cylinders as a function of freestream turbulence level and turbulence generating grid.

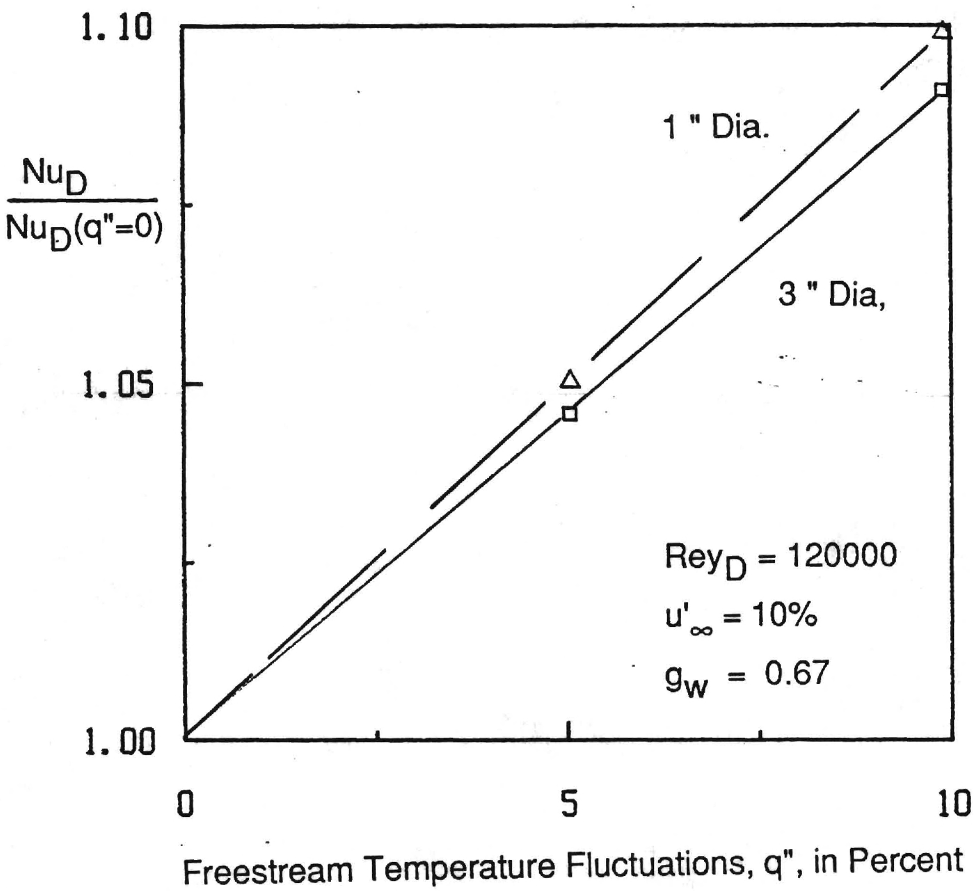

Figure 2. Rates of heat transfer to heat transfer without temperature fluctuations as a function of freestream temperature fluctuation level.