OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/19/90
Original Closeout Started ********

Project No. E-16-679 Center No. R6651-0A0

Project Director STRAHLE W C School/Lab AE

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. CBT-8901292 Contract Entity GTRC

Prime Contract No. ______

Title PROOF OF CONCEPT IN PRESSURE CORRELATION MEASUREMENT IN TURBULENT FLOWS

Effective Completion Date 891231 (Performance) 900331 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other ______	N	

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:	
Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
OCA/CSD	N
Other ______	N
______	N

NOTE: Final Questionnaire sent to PDPI.

15:26:04 OCA PAD INITIATION - PROJECT HEADER INFORMATION 12/14/88

Active

Project #: E-16-679 Cost share #: E-16-337 Rev #: 0
Center # : R6651-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: CBT-8901292 Mod #: Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

Project unit: AE Unit code: 02.010.110
Project director(s):
STRAHLE W C AE (404)894-3032

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 890101 to 891231 (performance) 900331 (reports)

Sponsor amount	New this change	Total to date
Contract value	29,237.00	29,237.00
Funded	29,237.00	29,237.00
Cost sharing amount		293.00

Does subcontracting plan apply ?: N

Title: PROOF OF CONCEPT IN PRESSURE CORRELATION MEASUREMENT IN TURBULENT FLOWS

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U
Defense priority rating : N/A
Equipment title vests with: Sponsor GIT X
NONE PROPOSED

ONR resident rep. is ACO (Y/N): N
NSF supplemental sheet

Administrative comments -
PROJECT INITIATION

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
SCHOOL OF AEROSPACE ENGINEERING GEORGIA INSTITUTE OF TECHNOLOGY ATLANTA, GEORGIA 30332	ENGINEERING	CBT 890 1292
	4. Award Period From 89-01-01 To 90-03-31	5. Cumulative Award Amount 29,237

6. Project Title

PROOF OF CONCEPT IN PRESSURE CORRELATION MEASUREMENT IN TURBULENT FLOWS

PART II—SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

This program set out to prove that pressure velocity correlations in turbulent flows could be measured nonintrusively, needing no intrusive pressure measurement. A device was developed to rotate and translate the probe volume of one component of a two component laser velocimeter to allow arbitrary two point space separated velocity correlations. With these correlations, an exact solution to the Poisson equation for pressure could be used for calculation of the pressure velocity correlations. The program was successful - remarkably so. In the course of the program, it also became evident that new models could be constructed for the pressure velocity correlation and these results have been now tested on several flows. The result is that the course of two-equation and stress transport modelling of turbulent flows should be changed to explicitly include the pressure velocity correlations. Another feature of the results is that the use of intrusive dynamic Pitot barometry for pressure measurement has been verified to be accurate. Future work necessary is to use the measurement method in hot flows, including density fluctuation measurements.

PART III—TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (✓)	Approx. Date
a. Abstracts of Theses	X				
b. Publication Citations	X				
c. Data on Scientific Collaborators	X				
d. Information on Inventions				X	90-03-15
e. Technical Description of Project and Results				X	90-03-15
f. Other *(specify)* PAPER ON COMBUSTION SYMPOSIUM				X	90-03-15

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
WARREN C. STRAHLE		12/12/89

FIINAL REPORT

to

The National Science Foundation

PROOF OF CONCEPT IN PRESSURE CORRELATION MEASUREMENT IN TURBULENT FLOWS

by

School of Aerospace Engineering

Georgia Institute of Technology

Atlanta, GA 30332

Grant No. CBT-8901292

Warren C. Strahle
Principal Investigator

INTRODUCTION

Under a prior NSF program (CBT-8414906) measurements were attempted of two troublesome turbulence correlations by a combined use of Rayleigh scattering, laser velocimetry (LV) and dynamic Pitot tube baraometry. These correlations are the pressure-strain and pressure-scalar gradient correlations. They enter in a description of turbulent stress transport and scalar transport when calculating turbulence fields at the level of second order closure. While the PI was able to show some time ago that pressure-velocity and pressure-scalar correlations could be measured directly by such techniques, the rate of strain field and scalar gradient field require the measurement of a spatial derivative. It was found that the accuracy of measurement in the gradient was simply not great enough to extract the desired information.

The pressure fluctuation, however, exactly obeys a Poisson equation which may be solved in terms of the density and velocity fluctuations and the mean flow field quantities. In principle, therefore, only velocity and density measurements are required to determine the pressure and its correlation against any quantity of interest. The fundamental problem, however, is that the solution comes out as an integral of a Green's function times space-separated correlations of density against itself, density against velocity and velocity against itself; the integral is over all of space. The questions of a) time required to conduct the necessary measurements, b) convergence of the integral in light of the fact that it contains a singularity, and c) accuracy of the result needed to be addressed in order to proceed with an ambitious program.

Another issue concerned usual commercial laser equipment. These laser velocimeters always want the probe volumes of two independent velocity components to intersect. Consequently, a device had to be invented to space separate the beams and still retrieve the signals. The development of such a device was started on the prior program and completed on this program.

RESULTS

All objectives were achieved on the program. Appended to this report is a paper submitted to the 23rd Symposium (International) on Combustion which contains all the results of the program. The following results were achieved:

(1) A device to space-saparate and arbitrarily rotate any component of the LV was developed and demonstrated;

(2) Using a cold turbulent round jet, it was demonstrated that, in fact, only a few space-separated correlations of the velocity measurement were needed for acceptable accuracy;

(3) No convergence problems of the integral occured, and, in fact, the fact that it is a singular integral actually helped in extracting results;

(4) Unexpectedly, new, powerful models for the pressure-velocity correlation emerged;

(5) The role of the density fluctuation in forcing a pressure fluctuation became clarified.

The appended paper is intended as the final report. The results suggest that the pressure-strain and pressure-scalar gradient correlations in hot flow can now be attacked.

FORM 98A HAS ALREADY BEEN SUBMITTED UNDER SEPARATE COVER

PART IV - SUMMARY DATA ON PROJECT PERSONNEL

NSF Division Engineering

The data requested below will be used to develop a statistical profile on the personnel supported through NSF grants. The information on this part is solicited under the authority of the National Science Foundation Act of 1950, as amended. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. NSF requires that a single copy of this part be submitted with each Final Project Report (NSF Form 98A); however, submission of the requested information is not mandatory and is not a precondition of future awards. If you do not wish to submit this information, please check this box ☐

Please enter the numbers of individuals supported under this NSF grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

*U.S. Citizens/ Permanent Visa	PI's/PD's		Post-doctorals		Graduate Students		Under-graduates		Precollege Teachers		Others	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
American Indian or Alaskan Native												
Asian or Pacific Islander												
Black, Not of Hispanic Origin												
Hispanic												
White, Not of Hispanic Origin	1				1						1	
Total U.S. Citizens	1				1						1	
Non U.S. Citizens												
Total U.S. & Non-U.S. ..	1				1						1	
Number of individuals who have a handicap that limits a major life activity.	0				0						0	

*Use the category that best describes person's ethnic/racial status. (If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN OR PACIFIC ISLANDER: A person having origins in any of the original peoples of the Far East, Southeast Asia, the Indian subcontinent, or the Pacific Islands. This area includes, for example, China, India, Japan, Korea, the Philippine Islands and Samoa.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

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THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.

ATTACHMENT

Submitted to 23rd Symposium (International) on Combustion

PRESSURE-VELOCITY CORRELATION IN TURBULENT REACTING FLOWS

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ABSTRACT

Examination is made of the correlation between pressure and velocity fluctuations in both cold and reacting turbulent flows. This correlation which accounts for pressure diffusion in turbulence transport equations, is shown to be extremely important physically and not well treated in the past. Experiments on confined and unconfined cold flows and unbounded premixed flames are examined and found to suggest new modeling approaches to this correlation. These suggestions are completely borne out by analytical examination of the Poisson equation for pressure which exactly describes the pressure fluctuation. Under certain restrictions on the flow type, new models are developed for the correlation of interest. These models are shown to compare favorably with experiment and a new experimental technique for nonintrusive pressure measurement is presented.

Subject Matter: (27) Turbulent Reacting Flows
(5) Diagnostic Methods
(19) Modeling and Simulation

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INTRODUCTION

In the analysis of turbulent flows at the level of two equation closure or stress transport modeling, there always appear correlations between pressure and velocity and their gradients which give modeling difficulty[1]. The most primitive form of the correlation and its most often seen expansion into three terms is

$$\overline{v_i'' \frac{\partial p}{\partial x_j}} = \frac{\partial}{\partial x_j}\left(\overline{v_i'' p'}\right) + \overline{v_i''}\frac{\partial \bar{p}}{\partial x_j} - \overline{p'\frac{\partial v_i''}{\partial x_j}} \tag{1}$$

The first term on the right side of Eq. (1), the gradient of the pressure velocity correlation, often suffers outright neglect in modeling; however, it has long been known in free shear flows[2,3] and has been shown in recent years in premixed flames[4,5], that this term cannot be neglected. Moreover, in direct numerical simulation, albeit at relatively low Reynolds numbers, it has been shown that this term can play a dominant role in energy transport in reacting flows[6,7]. The quantity $\overline{p'v_i''}$, the pressure velocity correlation, is the item of interest in this paper. While the correlation has been known to be important there appear to be no reliable models for it in the literature, and its measurement has been difficult.

In variable density flows an exact Poisson equation for the pressure fluctuation may be developed from the continuity and momentum equations[1,8]. It is

$$\frac{\partial^2 p'}{\partial x_j \partial x_j} = \frac{\partial^2 \rho'}{\partial t^2} - 2\frac{\partial^2 \left(\rho'\tilde{v}_j v_i''\right)}{\partial x_i \partial x_j} - \frac{\partial^2 \left(\rho'\tilde{v}_i\tilde{v}_j\right)}{\partial x_i \partial x_j}$$

$$- \frac{\partial^2 \left(\rho v_i'' v_j'' - \overline{\rho v_i'' v_j''}\right)}{\partial x_i \partial x_j} - 2\frac{\partial^2 \left(\bar{\rho}\tilde{v}_j v_i''\right)}{\partial x_i \partial x_j} \tag{2}$$

The only approximation in Eq. (2) is that viscous terms have been neglected for good cause; pressure is primarily influenced by the large energy containing eddies of a turbulent flow whereas viscous action occurs at small scales.

Equation (2) is formidable, and working with it has been avoided by modelers because of its complexity[1]. However, recent experience by the authors in evaluation of past data and in the generation of new data suggests a return to use of Eq. (2), because in some flows it appears that only a few terms (in fact, one term) are important. The use of Eq. (2) to generate new models for the pressure velocity correlation is one purpose of this paper. The second purpose is to verify these models by examination of past and new experimental results. Along the way a new nonintrusive method of measuring the pressure velocity correlation will have been demonstrated.

ANALYSIS

Flows far away from boundaries will be considered such that a solution to Eq.(2) may be written in terms of the free space Green's function

$$G(x_i,y_i)=1/(4\pi R), \qquad R=[(x_i-y_i)(x_i-y_i)]^{1/2}$$

with the summation convention employed. The solution for p' is then multiplied by v_i'' and averaged to yield the pressure velocity correlation

$$\overline{p'v_i''} = \int dV(y_i)\ G(x_i,y_i)\ \overline{\left[F_\rho(y_i) + F_v(y_i)\right]\ v_i''(x_i)} \qquad (3)$$

with F_ρ being the first three terms on the right of Eq. (2) and F_v being the last two terms. This generally separates the correlation into parts involving the density fluctuation and velocity correlations, although, for completeness, the fourth term should also be split because ρ stands alone and is equal to $\bar{\rho}$ + ρ'.

$$\overline{p'^2}(x_i) = \overline{\left[\int dV(y_i)\ G(x_i,y_i)\ [F_\rho(y_i)+F_v(y_i)]\right]^2} \qquad (4)$$

With the x_i values specified, y_i are the variables over which the integration is being taken, so space separated two point correlations of density-velocity, velocity and density are required to evaluate Eqs. (3) and (4). Double and triple correlations are required.

In general, for a variable density flow, Eqs. (3) and (4) are very complicated. However, because they will apply to the experimental flows to follow, consider a flow with the following restrictions:

a. The correlation terms involving density fluctuations against the velocity are small compared with terms involving only velocity correlations.

b. The turbulence intensity is sufficiently small (say 10%) so that triple correlations of velocity are small compared with the product of a mean velocity and a double velocity correlation.

c. The flow has a dominant single flow direction (say, a jet). This direction is direction 1.

In such a case, Eq. (3) reduces to a single term, where the position point x_i will be taken as the origin without loss of generality. After noting a fortuitous property of Favre averaging that $\overline{p'v_i''} = \overline{p'v_i'}$ and $\overline{v_i''v_i'} = \overline{v_i'v_i'}$, the result is

$$\overline{p'v_i'}(o) = 2 \int dV(y_i)\, G(o,y_i) \frac{\partial}{\partial y_j}\left[\bar{\rho}\tilde{v}_1 \frac{\partial}{\partial y_1}\left(\overline{v_j'(y_i)v_i'(o)}\right)\right] \qquad (5)$$

In the above, use has been made of the fact that continuity makes $\bar{\rho}v_i$ divergence-free. The mean square pressure equation will only so simplify if, in addition, the density fluctuation is small, in which case

$$\overline{p'^2}(o) = \overline{\left[2 \int dV(y_i)\, G(o,y_i) \frac{\partial}{\partial y_j}\left[\bar{\rho}\tilde{v}_1 \frac{\partial}{\partial y_1} v_j'(y_i)\right]\right]^2} \qquad (6)$$

These expressions can be evaluated if the shape of the correlation curves are known. Notice immediately, however, that the expressions are dimensionally homogeneous with respect to length. The result can depend on shape but not on any turbulent length scale, <u>per se</u>.

Now concentrate on the case where the velocity fluctuation is in the same direction as the primary flow velocity, $v_i'=v_1'=u'$. Make the following two restrictions in addition to those above:

d. Shear stresses are small compared with normal stresses either because one is near an axis of symmetry or in a low shear region of the flow.

e. The mean density and velocity product varies only weakly over the distance required for the integral to converge.

The integrand of Eq. (5) will now only have one important term involving the velocity correlation, it is

$$\frac{\partial}{\partial y_m} \bar{\rho}\tilde{v}_1 \frac{\partial}{\partial y_1} \overline{v_m'(y_i)u'(o)}$$

A crucial move is to apply the divergence theorem once and move the y_m derivative to the Green's function and pull the mean density-velocity product out from under the derivative. The mean density-velocity product may then be pulled out of the integral under restriction e above. Now make the assumption of an axially symmetric flow, measurement near the axis of symmetry, and a two-scale Gaussian correlation function

$$\overline{u'(y_i)u'(o)} = \upsilon^2(o)\, e^{-\alpha y_1^2}\, e^{-\beta(y_2^2+ y_3^2)} \qquad (7)$$

experimentally realizable, as will be seen below. Using Eq. (7) in Eqs. (5), the result for the axial velocity-pressure correlation is

$$\overline{p'u'} = -2\bar{\rho}\tilde{v}_1\, \upsilon^2\, SK_u \qquad (8)$$

where the shape factor is, for $\beta/\alpha > 1$, which is the usual case

$$S = \frac{1}{1-\beta/\alpha}\left[1 + 1/2\sqrt{\frac{1}{1-\alpha/\beta}}\ \ln \frac{1-\sqrt{1-\alpha/\beta}}{1+\sqrt{1-\alpha/\beta}}\right]$$

This is remarkable in its simplicity. The constant K_u, supposedly around unity, is intended as a calibration constant to be obtained experimentally and to account for errors introduced if Eq. (7) is not obeyed precisely.

A remark is necessary concerning Eq. (8). While the left side is invariant to a Galilean transformation, the right side does not appear to be so, containing the mean velocity. In the flows to be considered, a Galilean transformation on the flow will require that the hardware also undergo the uniform translation that the fluid does. That is, for example, for a flame anchored on the end of a burner tube, the tube must be moved if the fluid is translated. Consequently, the mean velocity is a <u>relative</u> velocity measured with reference to hardware causing the flow.

Although the manipulations are somewhat different for the transverse velocity-pressure correlation, similar calculations yield

$$\overline{p'v'} = -K_v \bar{\rho} \tilde{V}_1 \, \overline{u'v'} \tag{9}$$

so that this correlation should track the shear stress. It was, in fact, this observation from experimental data[2,3] that led the authors to pursue the above line of reasoning. Since the shear stress is not appreciable until one is substantially off the axis of symmetry, however, the assumptions made in deriving Eq. (9) are not as well satisfied as those made in deriving Eq. (8). Therefore, some greater error as compared with experiment can be expected.

Equation (6) is very cumbersome to carry out in the same detail as with the pressure velocity correlations. However, if $\alpha = \beta$, a tedious calculation yields for the mean square pressure in a constant density flow

$$\overline{p'^2} = \frac{8}{3} \bar{\rho}^2 \tilde{V}_1^2 \, \upsilon^2 \tag{10}$$

Since this manipulation started out as an equation for pressure, it is reasonable that the shape factor and the correction constant in Eq. (8) belong to the pressure, and an ad hoc correction to Eq. (10) to account for $\alpha \neq \beta$ and possible inaccuracies in the approach is postulated as

$$\overline{p'^2} = (K_u S)^2 \ \frac{8}{3} \ \bar{\rho}^2 \tilde{V}_1^2 \ \upsilon^2 \qquad (11)$$

Under the constant density conditions necessary for both Eqs.(8) and (11) to be valid, a correlation coefficient may be calculated for the axial velocity-pressure correlation. Remarkably, and in accord with experiment below, it is a constant

$$r_{pu} = \frac{\overline{p'u'}}{(\overline{p'^2})^{1/2} \ \upsilon} = -.625$$

EXPERIMENTAL

Four experimental flows will be considered - two cold and two hot. They are:

#1. A fully developed turbulent pipe flow of air at nearly one atmosphere, the details of which are located in Refs. (9) and (10). Velocity and its fluctuation were measured by hot film anemometry and pressure and its fluctuation were measured by frequency-compensated dynamic Pitot barometry. Conditions for the above equations to be valid existed from the pipe centerline to the three-quarter radius point.

#2. A premixed propane-air turbulent flame stabilized on a 2.54 cm diameter burner tube. The configuration is as shown in Fig. 1 and the equivalence ratio was 0.8. This flow is documented in Refs. (5) and (11). Velocity was measured by laser velocimetry (LV) and temperature was measured by frequency-compensated thermocouple thermometry as calibrated against Rayleigh scattering measurements. Pressure was measured by dynamic Pitot barometry, but here also compensated for probe tip temperature effects. The adiabatic flame temperature was 2000K, the tube (cold) exit plane velocity was 6.18 m/s and the surroundings were open still air. This and the #1 flow provide the dominant information on the pressure velocity correlation.

#3. The same burner as in flow #2, but with stoichiometric methane-air. The adiabatic flame temperature was 2250K and the exit plane velocity was 4.67 m/s. While velocity and pressure were measured as with flow #2, temperature (density) was measured by Rayleigh scattering. Reference (12) contains the details of measurement. This flow served primarily as a check flow on a conclusion below as to the weakness of the correlation between velocity and density, although some conclusions concerning pressure velocity correlation will be drawn from this flow.

#4. The same burner hardware as in flows #1 and #2, but operated in cold flow. The mirror apparatus shown in Fig. 2 was built in order to rotate and space-separate the two LV probe volumes to measure the necessary space-separated correlations in Eq. (2). One component of the 5w Argon-ion laser was unmolested and velocity was measured in the backscatter mode while the molested component used forward scattering. This technique was to verify that a nonintrusive velocity correlation measurement could be substituted for the usual intrusive Pitot pressure measurement. The measurements were carried out about a volume centered on the axis at z/D=4 where the mean axial velocity was 3.69 m/s and the mean square axial velocity fluctuation was .119 $(m/s)^2$.

Fig 2

Consider first flow #1, where in Ref. (10), with a more rudimentary theory, a formula similar to Eq. (8) was derived. For a pipe flow the ratio of longitudinal to transverse integral length scales is about 4, so that the ratio of β to α is about 16 leading to a shape factor of about .07. Excellent agreement of theory and experiment is achieved with both Eqs. (8) and (11) for K_u about 2. This agreement extends over three fourths of the tube radius, after which wall effects become important. In these experiments $\overline{p'v'}$ was not measured. The correlation coefficient for $\overline{p'u'}$ was a remarkable constant of -0.6 (see the theoretical value above). One reason for the excellent agreement between theory and experiment for this flow is that it closely satisfies all restrictions in the development of the theory, and the axial velocity profile is quite flat over the transverse dimensions of agreement.

Considering next hot flows #2 and #3, the profiles on the centerline for the mean axial velocity and mean density are shown in Fig. 3. For both flows most of the heat release on the centerline takes place for z/D between 2 and 4. Both flames have the unconfined flame characteristic that the mean velocity on the centerline is almost a constant, because there is no strong axial pressure gradient. The density is highly variable, however. Using a result to be obtained later on flow #4, the longitudinal to lateral length scale is roughly about 2, yielding a shape factor of about .17. With K_u=2 a comparison of $\overline{p'u'}$ computed from Eq. (8) is made with the experimental values in Fig. 4. The agreement is quite good, even through the flame zone.

The agreement is somewhat surprising and probably arises because of one peculiar fact for these two flames. For these unconfined flames the correlation between density and velocity is exceptionally low[5,11,12]. While the density fluctuation itself may be of the order of 40% of the cold density, the correlation coefficient against velocity is only of the order of 0.1. This feature of the unconfined flame does not usually hold up in confined flames because there are strong mean velocity gradients. But here the correlation is so low that the theoretical assumptions made in throwing out the density fluctuation terms appear valid.

It is not true, however, that $\overline{p'^2}$ can be computed from Eq. (11) for these flames. The density fluctuation effect does not disappear for this quantity, as mentioned above. To illustrate this fact experimental and theoretical (computed from Eq. (11)) rms pressure fluctuation results are shown on Fig. 5. While the agreement is good upstream and downstream of the flame zone, there is a dramatic rise in p' in the flame zone. This can only occur because of the density fluctuation effects. Also shown in Fig. 5 is the density fluctuation for both flames (notice the scale change for the hottest flame which has substantially higher fluctuation in density than does the colder flame). There is a substantial displacement of the peak in density fluctuation from the peak in pressure fluctuation which is somewhat unexpected. However, this may arise from some peculiarity in the theory, if it could be carried out including the density fluctuation effects. This will be left for future work.

In Fig. 6 is shown a theoretical-experimental comparison for the transverse velocity-pressure correlation. The theory uses Eq. (9) with K_v=1 and the experimental result is from flow #2. The agreement is quite good, but the comparison is made at z/D=6, which is quite far downstream from the flame zone. Although not shown, the p'v' correlation in the flame zone also tracks the shear stress, as demanded by Eq. (9), but K_v would have to be about 6. There must be some problem in the theoretical assumptions in the flame zone concerning the p'v' correlation, although at least the shape of the radial variation in this quantity appears to be correctly predicted.

A problem in usual turbulence modelling[1] is now clear. The diffusion of pressure energy is at least as large as the usual modelling of the diffusion of turbulence kinetic energy and should be so considered. While the current results are gained under certain restrictions on the flow type and cannot be considered completely general, the fact remains that typical k-ε modelling has to be modified. This conclusion is also drawn in Refs. (6) and (7).

A final demonstration considers Flow #4, where a nonintrusive indirect measurement of the pressure velocity correlation is concerned. As demanded by Eq. (5), after simplification, what is required is a space separated two point correlation of the axial velocity fluctuation, if the p'u' correlation is required. Shown in Fig. 7 are the measurement points and general nomenclature for the measurements on the axis of Flow #4. The mean velocity, as seen in Fig. 3, has a very weak axial gradient, measurements are made on an axis of symmetry, the transverse velocity is very small, shear stresses are negligible, and, in general, all restrictions on the theory are met. Typical measurements of the radially separated axial velocity are shown in Fig. 8. A composite graph of axial and radial separations, as well as some points skewed to the radial and axial directions is shown in Fig. 9. The correlations are quite symmetric about the origin point, justifying the bi-directional Gaussian approximation to the correlation function used above. The primary contribution to the integral in Eq. (5) comes near the singularity (integrable) of the Green's function and the maximum in the correlation function. Consequently, a Gaussian is fitted to best match the experiments in this region. The result is that $\beta/\alpha = 4$, which is a value used above in determination of K_u. It should be cautioned, however, that this flow is cold.

The results from Eq. (8), using the space separated measurements, and those from use of the Pitot probe with LV are as follows, with $K_u=2$:

	Space separated	Pitot-LV
$p'u'$	-.34 Pa m/s	-.35 Pa m/s
$r_{p'u'}$	-.6 Pa m/s	-.48 Pa m/s

These results give a renewed confidence in the use of intrusive Pitot barometry. The space separated measurements are extremely time consuming, but act as a check on the intrusive measurements. For the general case in which density fluctuations play a strong role, velocity and density measurements and their correlation would be required by the indirect method, giving strong motivation to use of the intrusive method of measurement.

CONCLUSIONS

1. The pressure velocity correlation in both hot and cold turbulent flows is as strong as any other turbulence energy transport term in the physics of energy transport and cannot be neglected.

2. Contrary to popular opinion, the pressure velocity correlations are of the order of the mean velocity times either a normal or shear stress, depending on the direction of the velocity of interest.

3. An indirect, nonintrusive method of measurement of the pressure velocity correlations has been developed as an adjunct method to check the results of Pitot barometry, LV and Rayleigh scattering. The method rests upon space separated measurements of velocity fluctuations, and, in the general case, space separated measurements of density fluctuations and density-velocity correlations.

4. Under several restrictions on the flows, simple models for the pressure-velocity correlation have been theoretically developed and experimentally verified. While the models are not completely general, they should be applicable to several simple flows, and, in particular, reacting turbulent flows.

NOMENCLATURE

D	burner diameter
F_ρ, F_v	grouping of density and velocity terms in Eq. (3)
G	free space Green's function
K_u, K_v	constants in pressure velocity correlations
p	pressure
r	correlation coefficient
R	distance between x_i and y_i
S	shape factor
u	axial velocity
V	volume
v_i	velocity in ith direction
v,w	transverse velocities
x_i, y_i	Cartesian coordinates
z	axial direction coordinate
α,β	length scale constants in Gaussian correlation
ρ	density
υ	rms axial velocity turbulence intensity
ν	rms transverse velocity turbulence intensity

Superscripts

'	ordinary fluctuation
"	Favre fluctuation
_	average
~	Favre average

ACKNOWLEDGEMENTS

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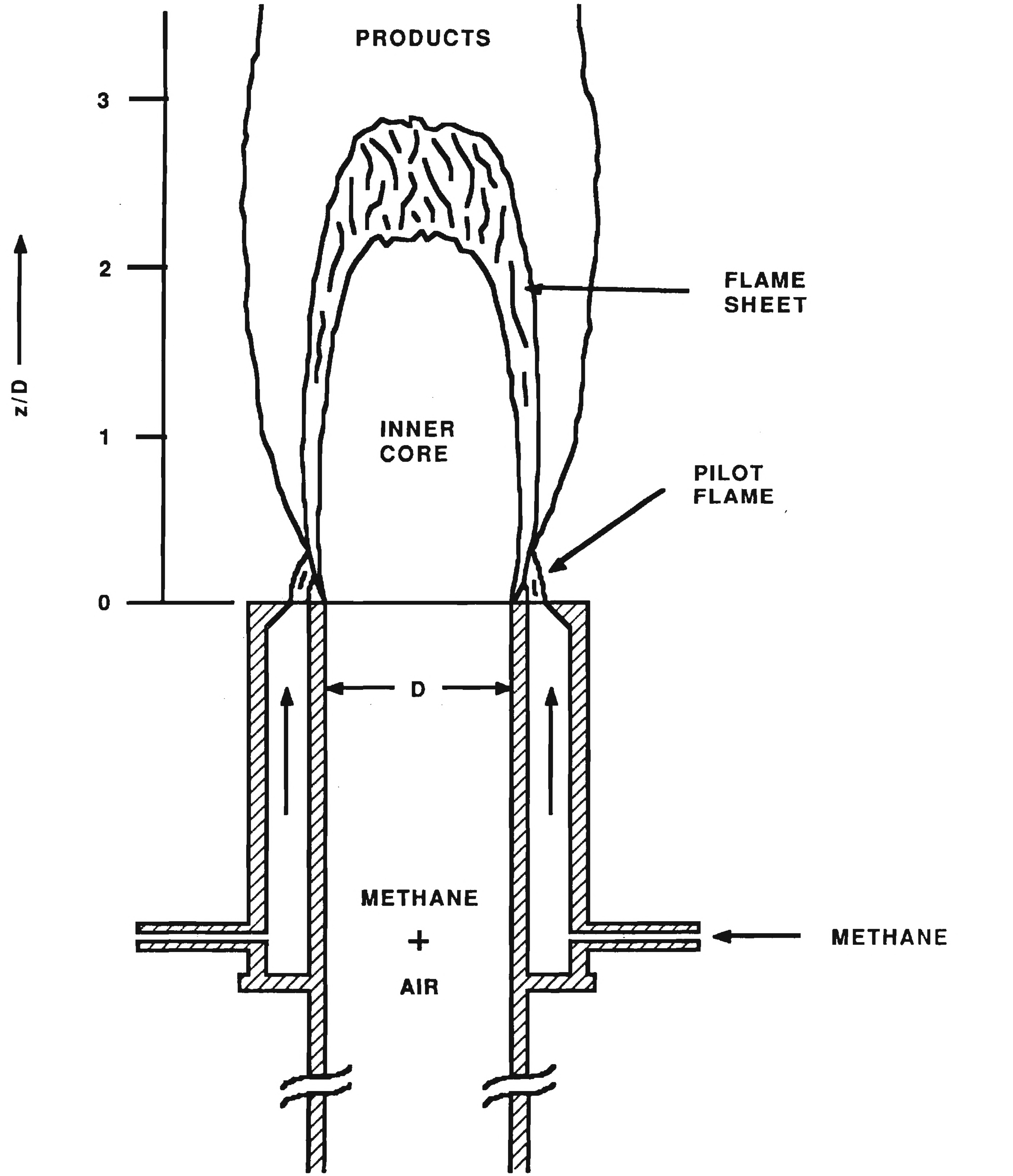
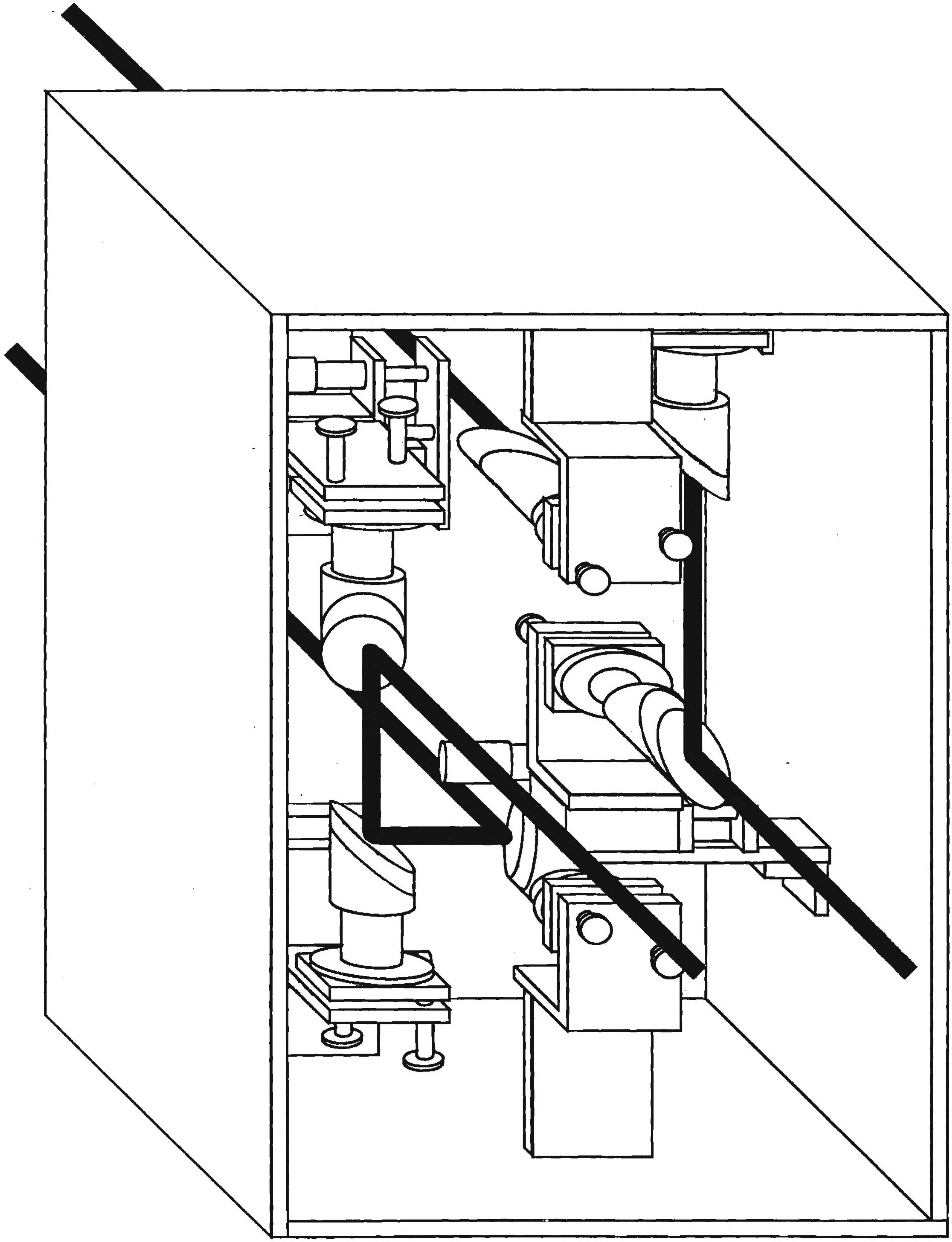
REFERENCES

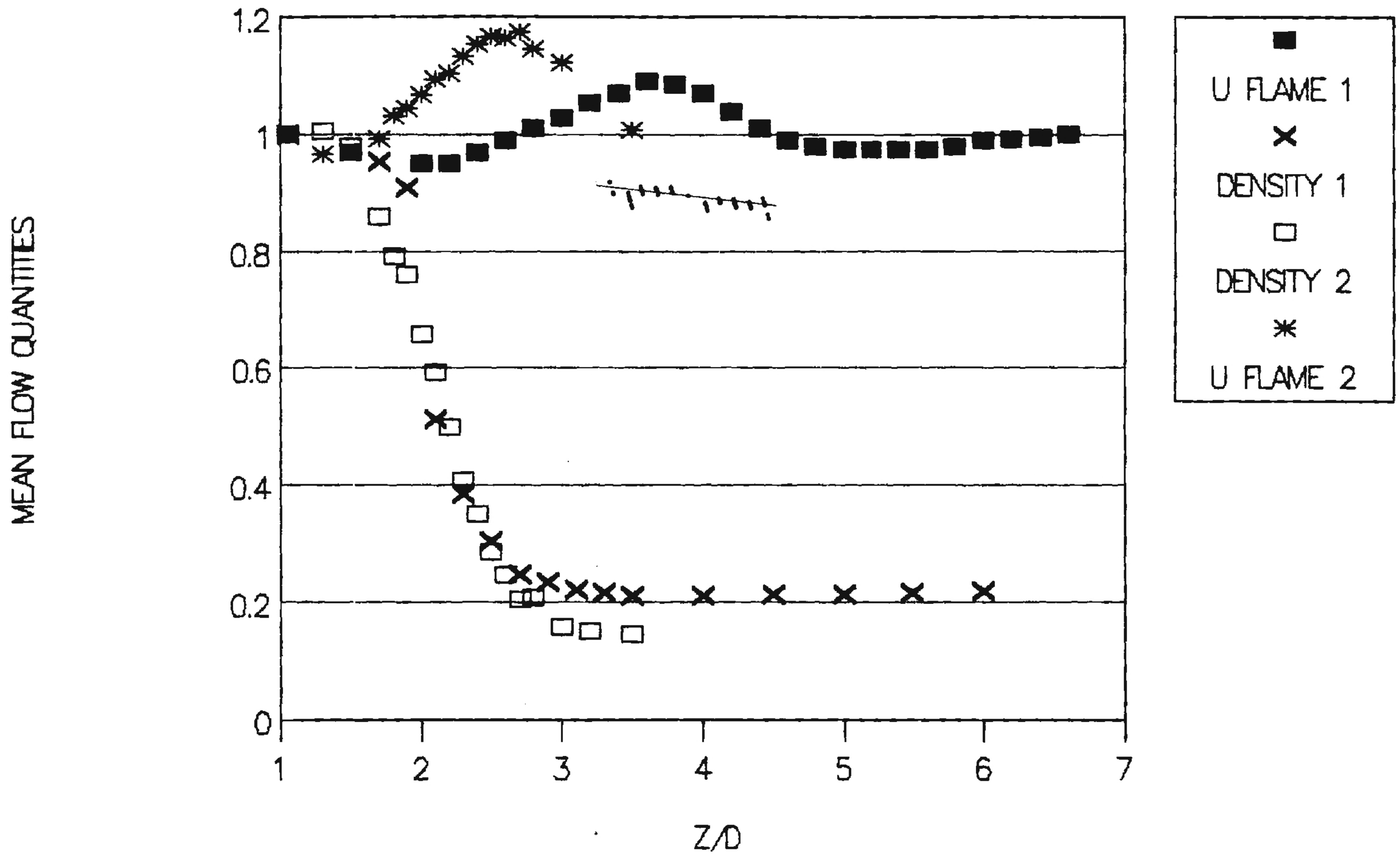
1. Jones, W.P.: Prediction Methods for Turbulent Flows (Kollmann,ed.) p. 379, Hemisphere, 1980.
2. Townsend, A.A.: Australian J. Sci. Research, 2A, 451, 1949
3. Wygnanski, I. and Fielder, H.: J. Fluid Mech., 38, pt. 3, 577, 1969.
4. Komerath, N.M. and Strahle, W.C.: AIAA Paper No. 83-0400, 1983.
5. Chandran S.B.S., Komerath N.M. and Strahle, W.C.: Twentieth Symposium (International) on Combustion, p. 429, The Combustion Institute, 1984
6. McMurtry, P.A., Riley J.J. and Metcalfe, R.W.: J. Fluid Mech., 199, p. 297, 1989.
7. Riley J.J. and McMurtry, P.A.: Comb. Flame (in review), 1989.
8. Strahle, W.C.: AIAA J., 26, 969, 1988.
9. Hegde U.G. and Strahle, W.C.: AIAA J.,23, 71, 1985.
10. Komerath, N.M., Hegde, U.G. and Strahle, W. C.: AIAA J., 23, 1320, 1985.
11. Chandran, S.B.S.:Ph.D. Dissertation, Georgia Institute of Technology, 1984.
12. Waldherr, G.A., deGroot, W.A. and Strahle, W.C.: Comb. Flame (in review), 1989.

LIST OF CAPTIONS


PRODUCTS
3
2
1
0
z/D
FLAME
SHEET
INNER
CORE
PILOT
FLAME
D
METHANE
+
AIR
METHANE

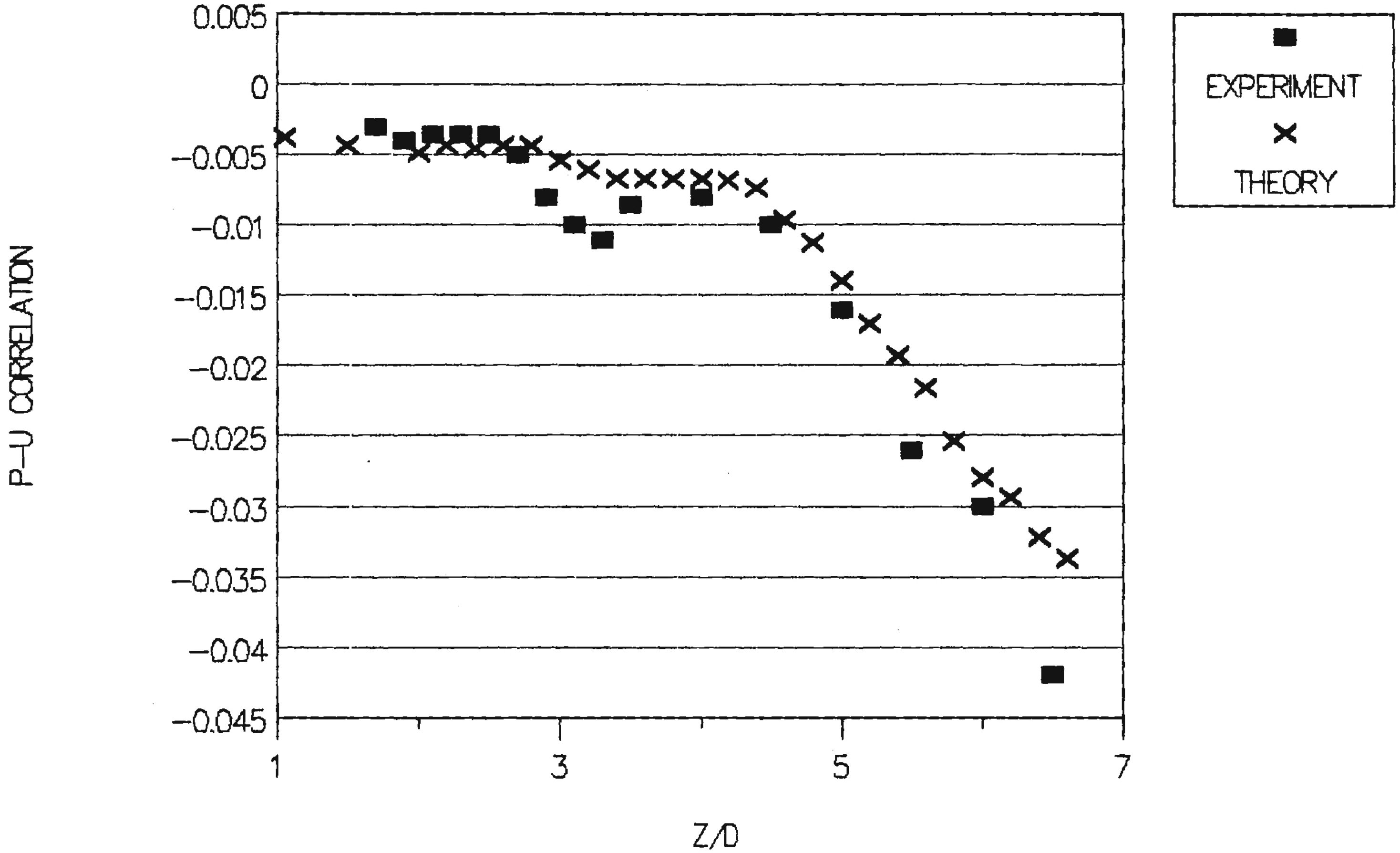
F1 WCd



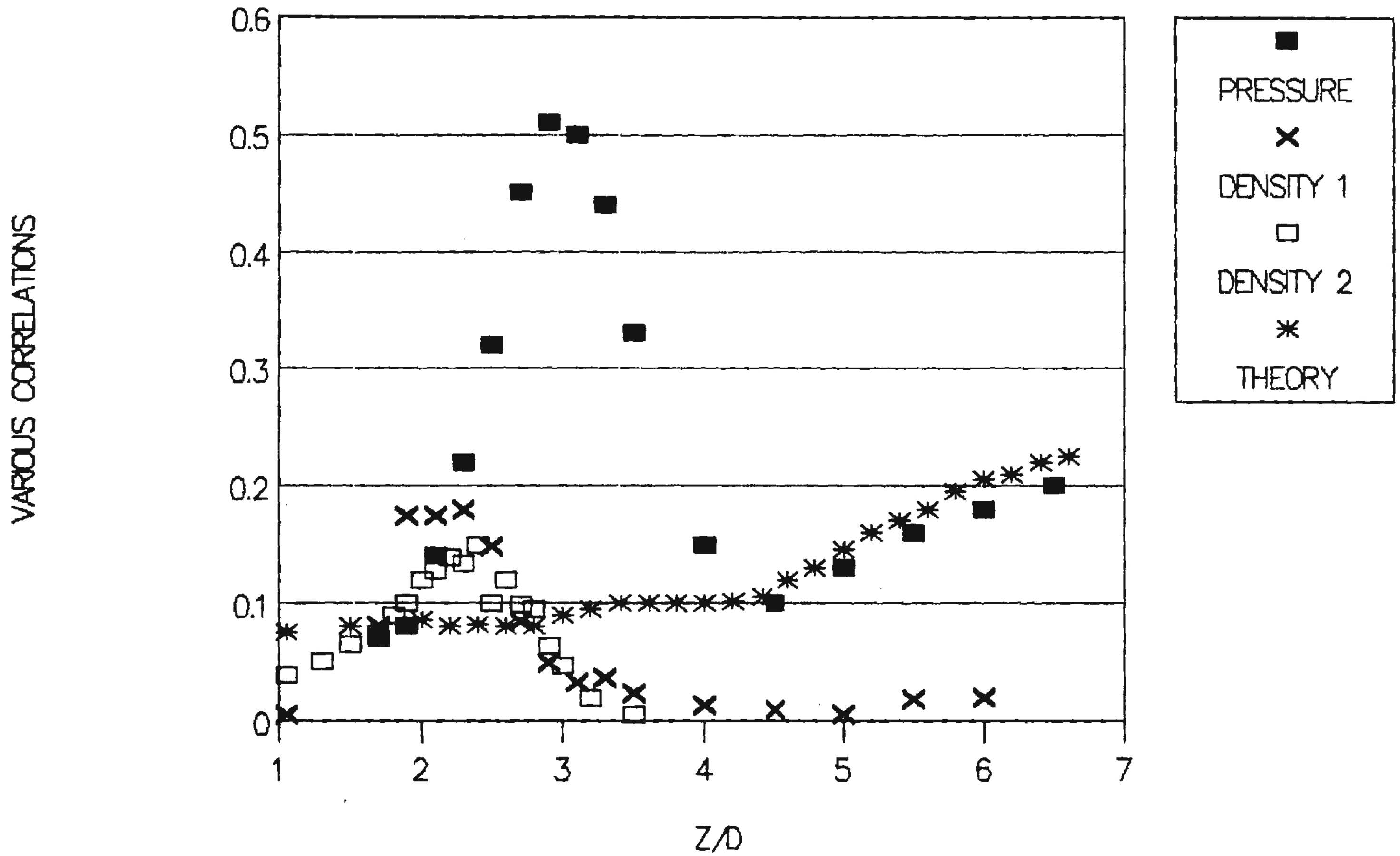


1.2
1
0.8
0.6
0.4
0.2
0
MEAN FLOW QUANTITIES
1
2
3
4
5
6
7
Z/D
U FLAME 1
DENSITY 1
DENSITY 2
U FLAME 2

F3 WCS

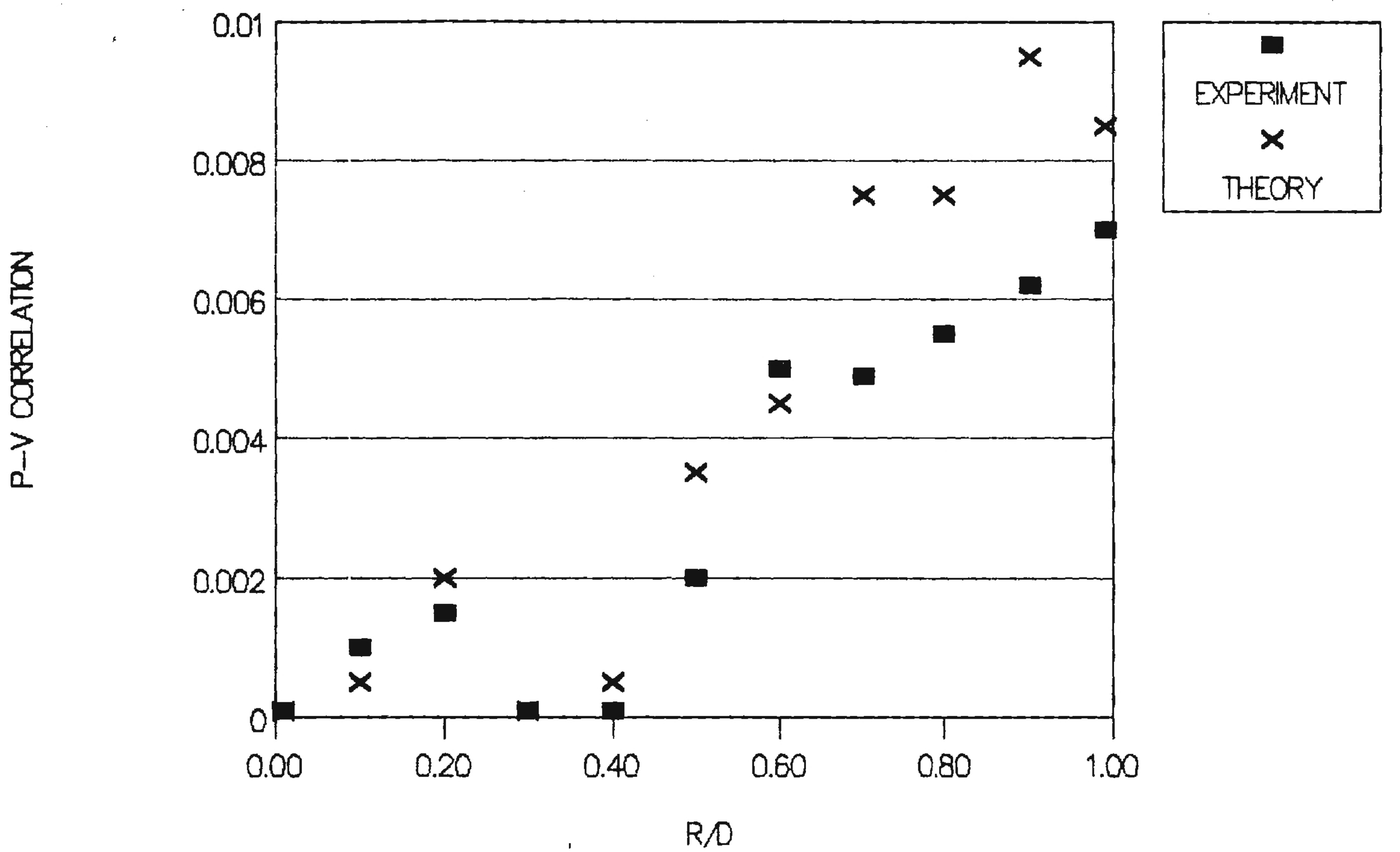

0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
-0.035
-0.04
-0.045
P-U CORRELATION
1
3
5
7
Z/D
EXPERIMENT
THEORY

F4 WG

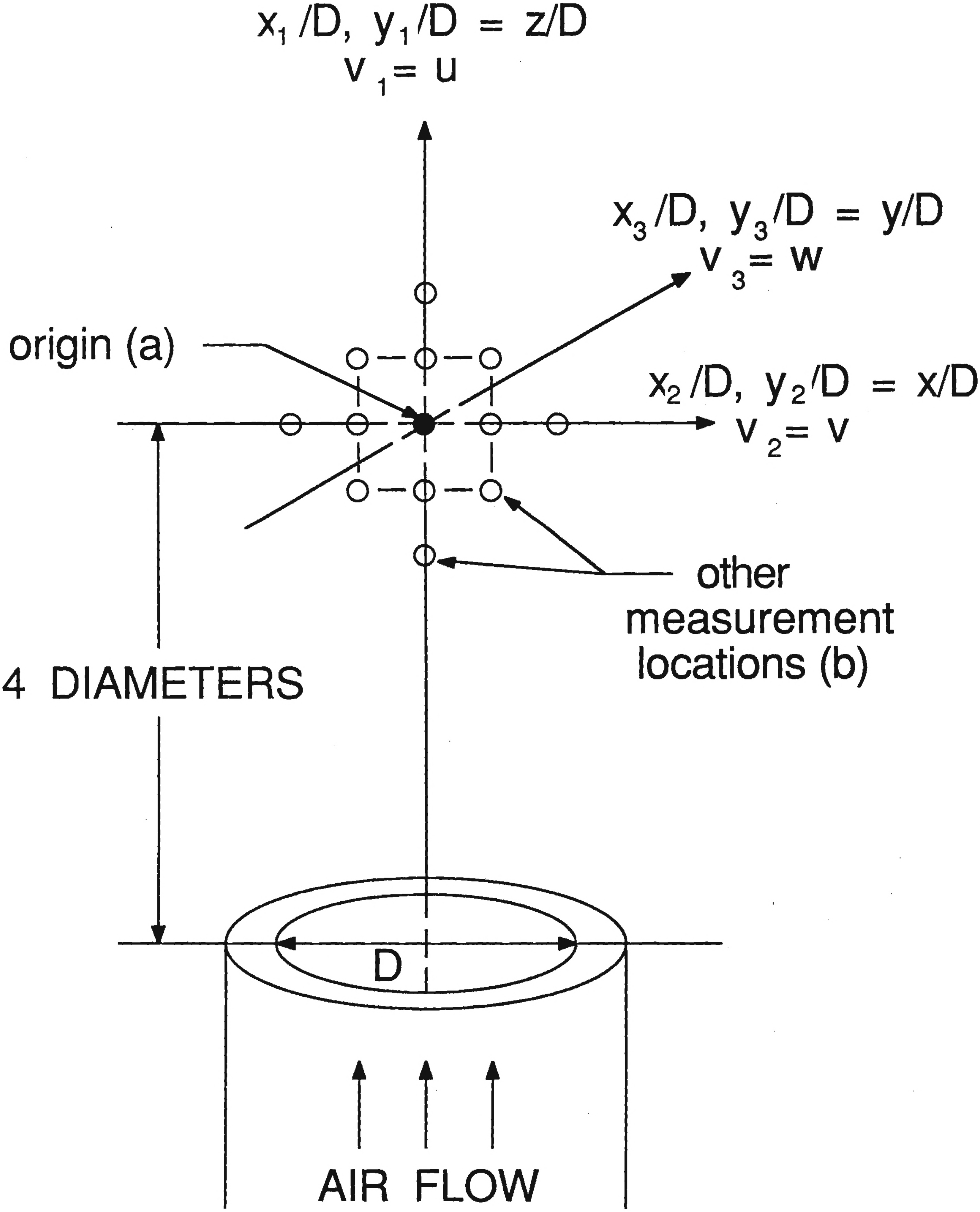


0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
VARIOUS CORRELATIONS
Z/D
PRESSURE
DENSITY 1
DENSITY 2
THEORY

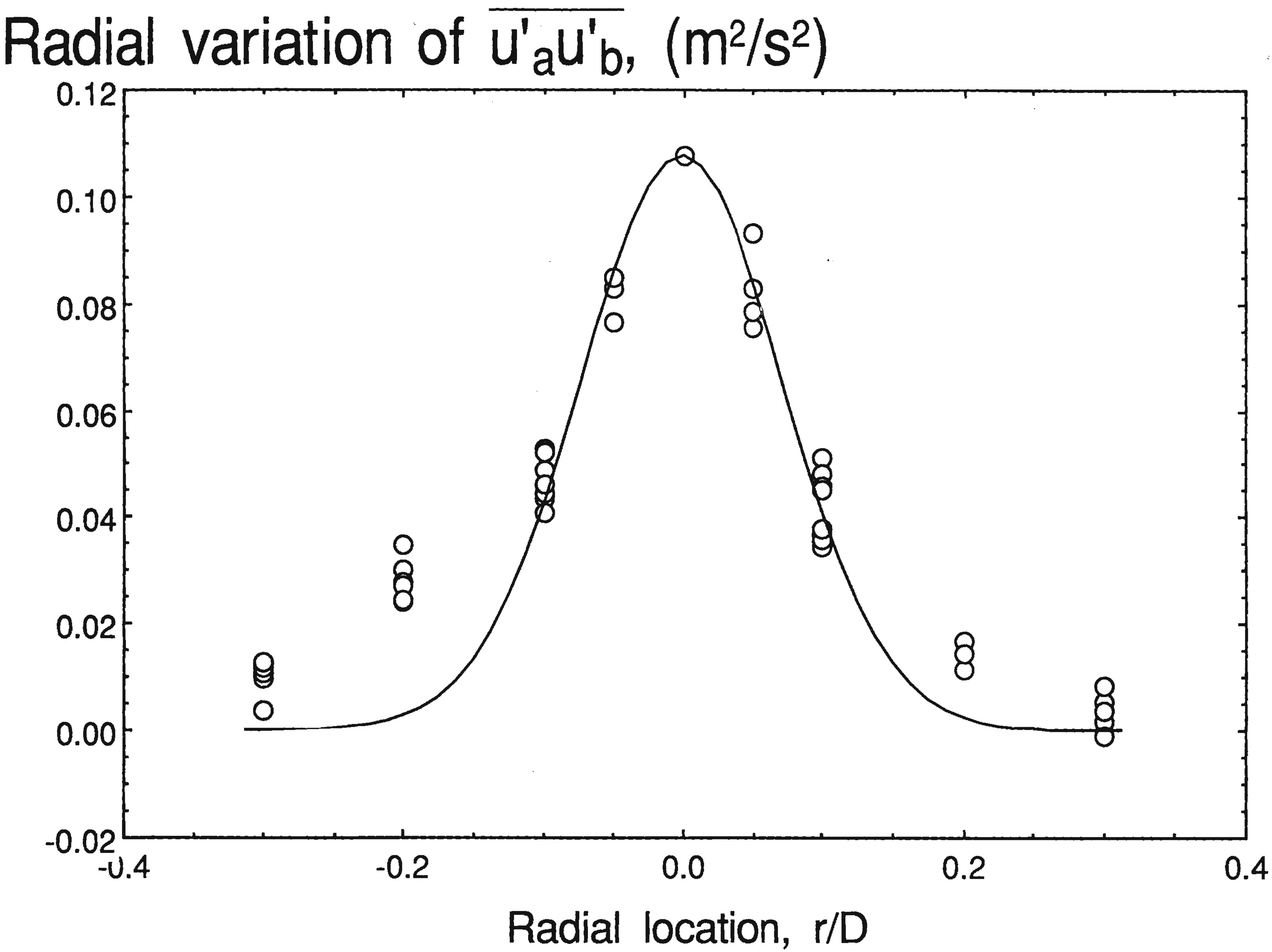
F5 WW


0.01
0.008
0.006
0.004
0.002
0
P—V CORRELATION
0.00
0.20
0.40
0.60
0.80
1.00
R/D
EXPERIMENT
THEORY

F6 W65

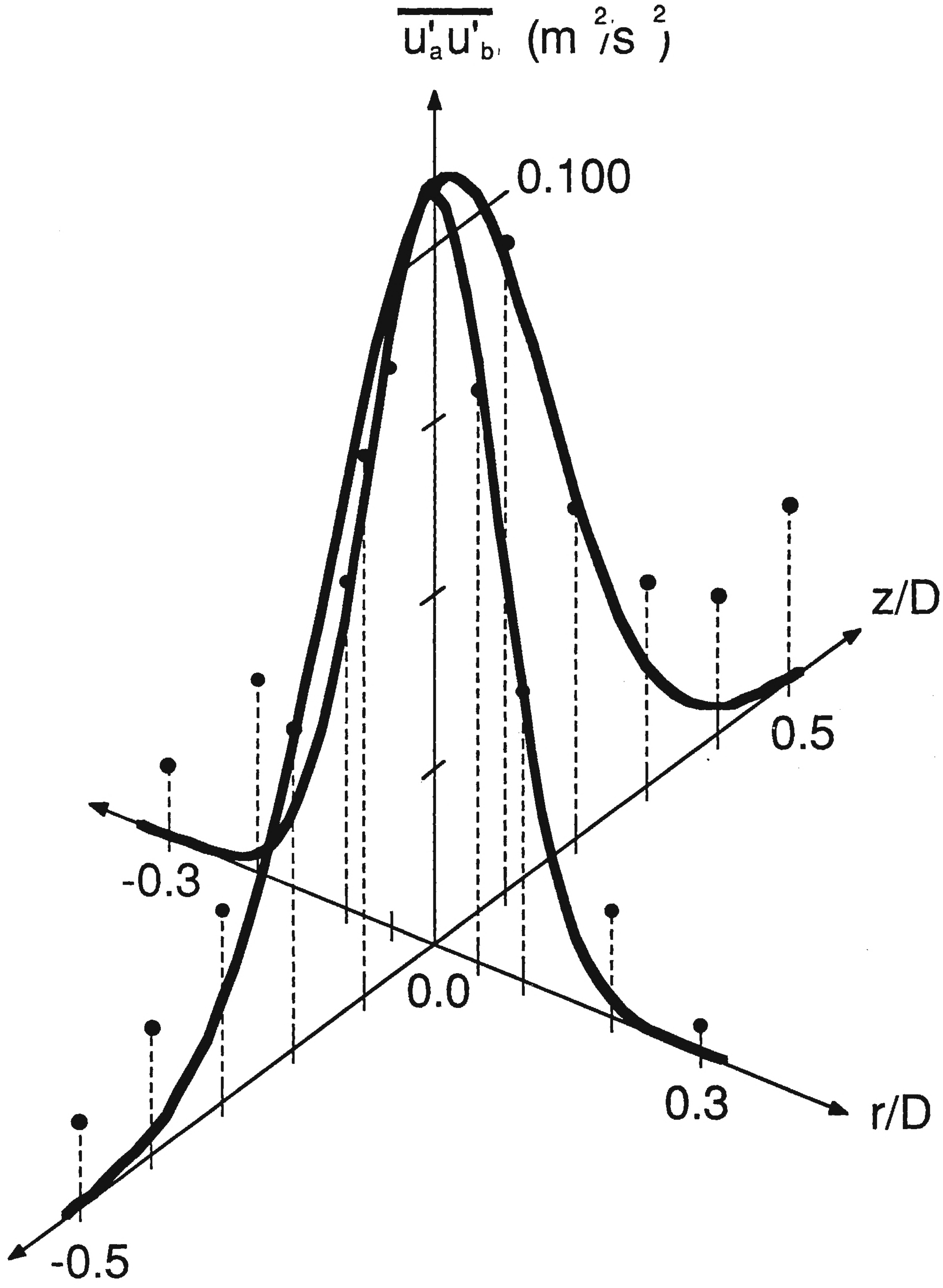

$x_1/D,\ y_1/D = z/D$
$v_1 = u$
$x_3/D,\ y_3/D = y/D$
$v_3 = w$
origin (a)
$x_2/D,\ y_2/D = x/D$
$v_2 = v$
other
measurement
locations (b)
4 DIAMETERS
D
AIR FLOW

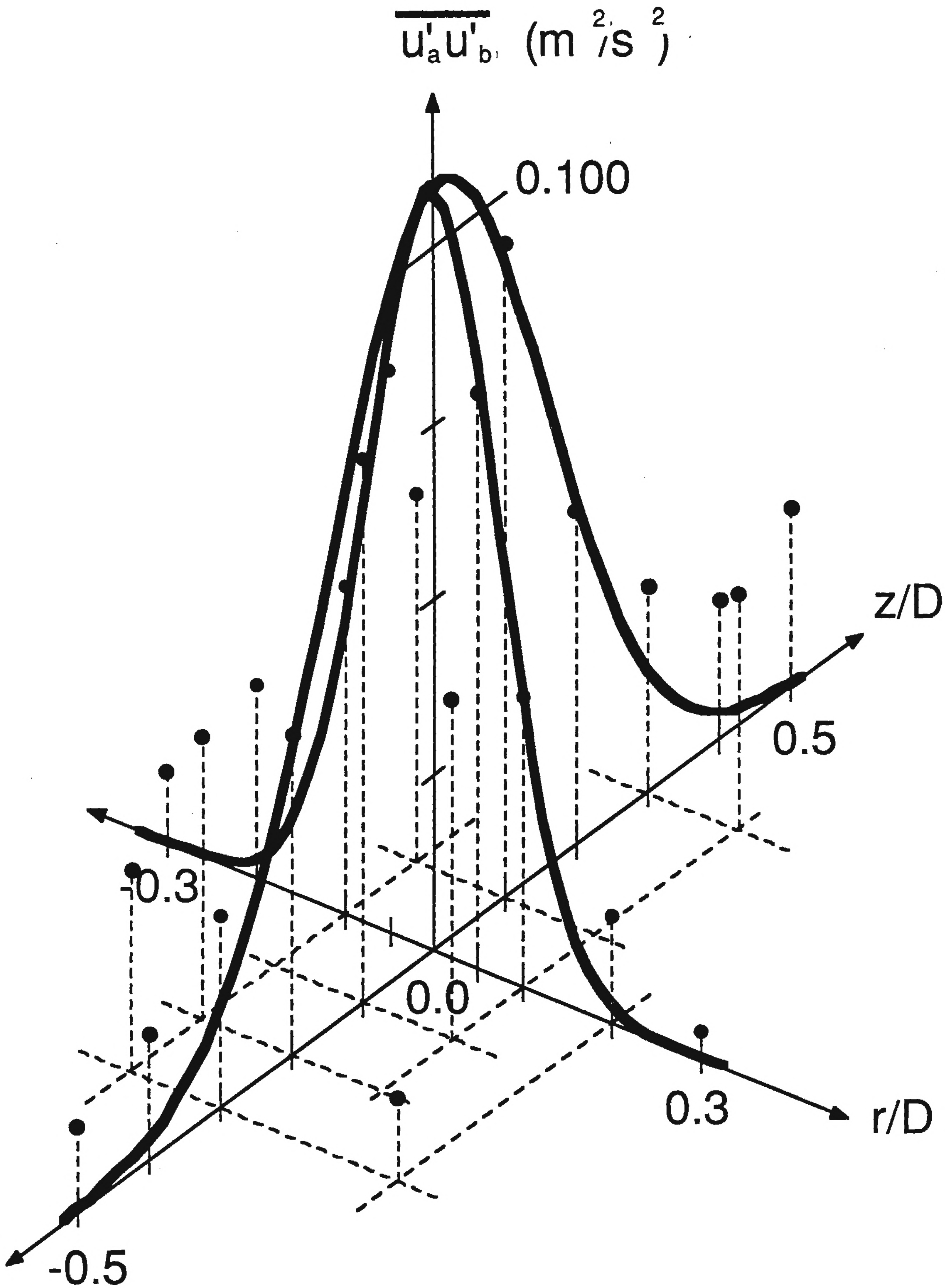
F7 WGS



Radial variation of $\overline{u'_a u'_b}$, (m^2/s^2)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.4
-0.2
0.0
0.2
0.4
Radial location, r/D

F8 wcl


$\overline{u'_a u'_b}$ (m^2/s^2)
0.100
z/D
0.5
-0.3
0.0
0.3
r/D
-0.5



F9 WCA