# Intercooler Flow Path Optimization for Gas Turbines

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## Abstract

The primary objective of this project is to maximize the benefits of gas turbine intercooling through isolating, minimizing or eliminating flow nonuniformities in the compressor sections, and through reduction in pressure losses in the intercooler flow path. The components of the intercooler system are: a diffuser or the expansion passage, a heat exchanger or the intercooler, and a contraction or the intake. All of these components are annular in an on-axis configuration. The major tasks in this projects were: design of the intercooler flow path, development of a wind-tunnel system, fabrication of a test model, instrumentation and cold flow experiments, and developing design procedures and guidelines. The intercooler design was based on the computational fluid dynamics (CFD) analysis, the wind-tunnel provided the desired flow conditions, the test model was a 1/4th geometric scale model of industrial-size gas turbines, instruments included pressure probes and hot-wire anemometer, and flow experiments were intended to develop design guidelines by validating and/or refining the CFD analysis.

An aerodynamic optimization procedure employing CFD was developed to design annular flow passages with contoured walls. The geometry of the passage was described by its geometric centerline and the area distribution function. A procedure to generate nearly orthogonal grid in body-fitted coordinates was also developed. The flow computations were done using fully-elliptic Navier-Stokes equations with standard $\kappa$-$\epsilon$ turbulence model and wall functions. The optimization aimed to align the mean flow with the geometric centerline of the flow passage. Together with a weighing function which enabled the geometric constraints to be maintained, the deviations among the geometric centerline and three physical centerlines (of mass flux, mass-averaged energy and momentum fluxes) served as guide or objective function for the optimization. An outwardly canted annular diffuser was designed to demonstrate the procedure. The results showed that the optimization strategy produced a design with improved flow characteristics, while imposing geometric constraints (the passage length and exit location) and ensuring smooth surfaces.

The test model consisted of an annular diffuser with an outwardly canted prediffuser followed by a faired expansion. The diffuser had an annulus height of 0.052m at its inlet, an area ratio of 5.4 and a length of 0.533m. The inner and outer diameters of the annulus at the diffuser exit were 0.51m and 0.84m, respectively. The annular heat exchanger simulator was 0.45m long. It was followed by a 0.46m long annular inlet of the same inlet and exit dimensions as the diffuser. The test model was instrumented with 250 wall pressure taps and 20 probe access ports at 4 circumferential locations.

Detailed experiments were conducted at different flow rates with fully developed inlet velocity profile;

with and without flow resistance in the heat exchanger. Data obtained include static wall pressure distributions, and profiles of axial and radial velocities, static and total pressures, turbulence intensities, and shear stress. These measurements were then used to characterize the diffuser and inlet flows and to identify pressure loss mechanisms. The results show good pressure recovery in the prediffuser although the flow separated in the faired expansion. A uniform flow at the heat exchanger inlet was obtained when a longer diffuser was used. Results indicated need for modifications to the diffuser to achieve higher intercooler performance. Experimental data in the annular inlet showed uniform flow at the exit. The exit flow was uniform in spite of large variations in turbulence intensities at the inlet. For all test cases, the total pressure loss in the inlet was relatively small.

Several modifications to the pre/dump diffuser were considered analyzing the experimental data. CFD analysis showed that uniform flow at the diffuser exit could be obtained by placing splitter plates to divide the diffuser flow into multi-annular regions. It was found that only one splitter plate dividing the flow into two annular passages was adequate to obtain uniform flow at the diffuser exit.

One of our graduates students completed summer internship at the Allison Engine Company. Recommendations for future work include detailed experiments in the modified diffuser configuration. The optimization procedure developed in this project can be applied to design curved wall annular diffusers used in various gas turbine applications.

## Acknowledgements

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# INTERCOOLER FLOW PATH OPTIMIZATION FOR GAS TURBINES

**CONTRACT NUMBER 94-01-SR-029**

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# OBJECTIVES

- **Develop design of an intercooler system**
- **Obtain experimental data in a scale model**
- **Develop CFD based Inverse Design/Optimization Techniques**

# INTERCOOLING

**Involves cooling of air between LP and HP compressor sections**

**Benefits:**

- **Decreases compression work**
- **Allows effective turbine blade cooling because of lower air discharge temperature**
- **Heat rejected in the intercooler may be used for feedwater or cogeneration**

**Concerns/Issues:**

- **Minimize pressure losses in the flow path**
- **Isolate LP and HP compressors from intercooler flow non-uniformities**
- **Provide uniform flow at the intercooler inlet**
- **Minimize the overall length for structural concerns**

# EXPERIMENTAL

## Test Section

- **Scale Model of an on-axis annular intercooler system with**

  **- A contoured wall annular diffuser (prediffuser + dump section)**
  **- A shell-and-tube heat exchanger flow simulator (air as the tube fluid)**
  **- A compact contoured wall annular contraction**

- **Geometric Details**

**- Length**

| | |
|---|---|
| **Overall :** | **1.47 m** |
| **Diffuser:** | **0.53 m** |
| **Intercooler:** | **0.48 m** |
| **Contraction:** | **0.46 m** |

**- Inner Diameter:**

| | |
|---|---|
| **Diffuser inlet/contraction exit:** | **0.352 m** |
| **Diffuser exit/contraction inlet:** | **0.477 m** |
| **Intercooler inlet/exit:** | **0.477 m** |

**- Outer Diameter:**

| | |
|---|---|
| **Diffuser inlet/contraction exit:** | **0.457 m** |
| **Diffuser exit/contraction inlet:** | **0.838 m** |
| **Intercooler inlet/exit:** | **0.838 m** |

# Primary Technical Data at the LP Compressor Discharge

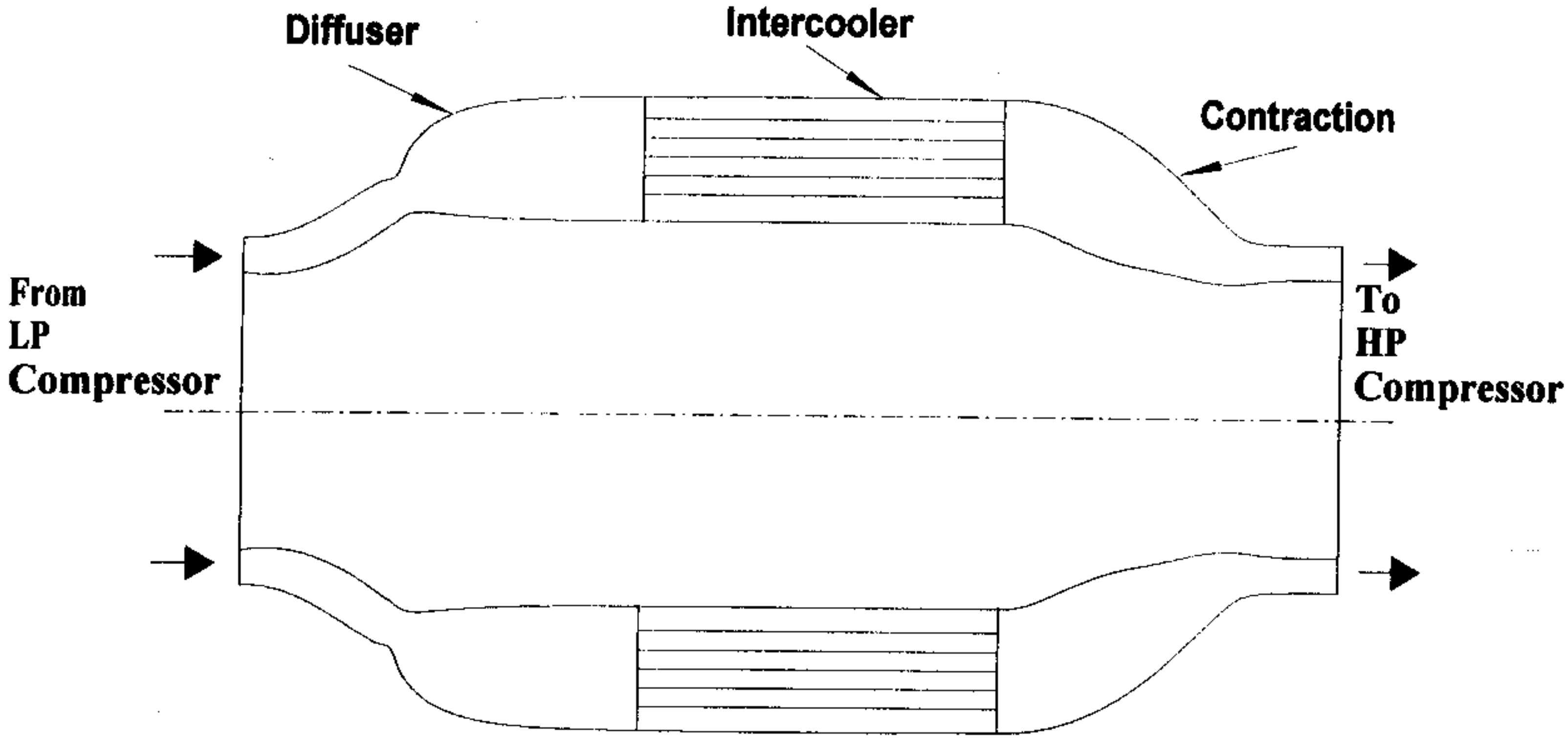
| Parameter | Utility Turbine | Industrial Turbine | Test Model |
|---|---|---|---|
| Annulus Height, m | 0.4 | 0.2 | 0.052 |
| Geometric Scale | 1 | 0.5 | 0.125 |
| Pressure, Atm. | 3 | 3 | 1 |
| Temperature, K | 410 | 410 | 300 |
| Density, $kg/m^3$ | 1.8 | 1.8 | 1.2 |
| Axial Velocity, m/s | 80 | 80 | 40 |
| Reynolds Number | 5,000,000 | 2,500,000 | 250,000 |
| Mass Flow, kg/s | 400 | 100 | 3 |
| Mach Number | 0.2 | 0.2 | 0.12 |

## Measurement Details

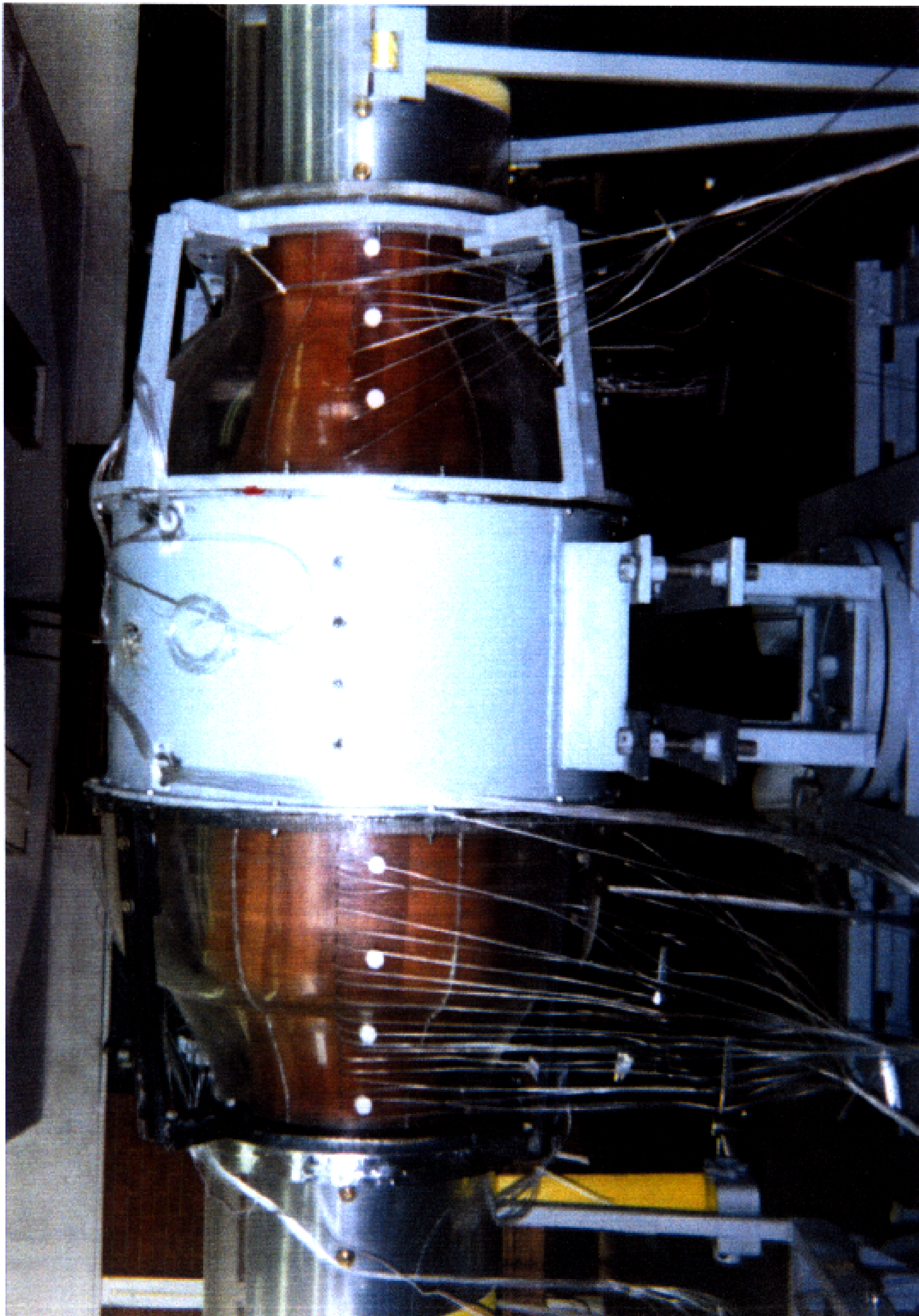
- **Wall-static pressure distributions: at 250 locations using pressure taps**
- **Total and static pressure distributions: 24 axial planes using 5-hole probe**
- **Axial/radial velocity profiles: 24 axial planes using 5-hole probe and cross-film anemometer**
- **Axial/radial turbulence intensity profiles: 24 axial planes using cross-film anemometer**
- **Shear stress profiles: 24 axial planes using hot-film anemometer**

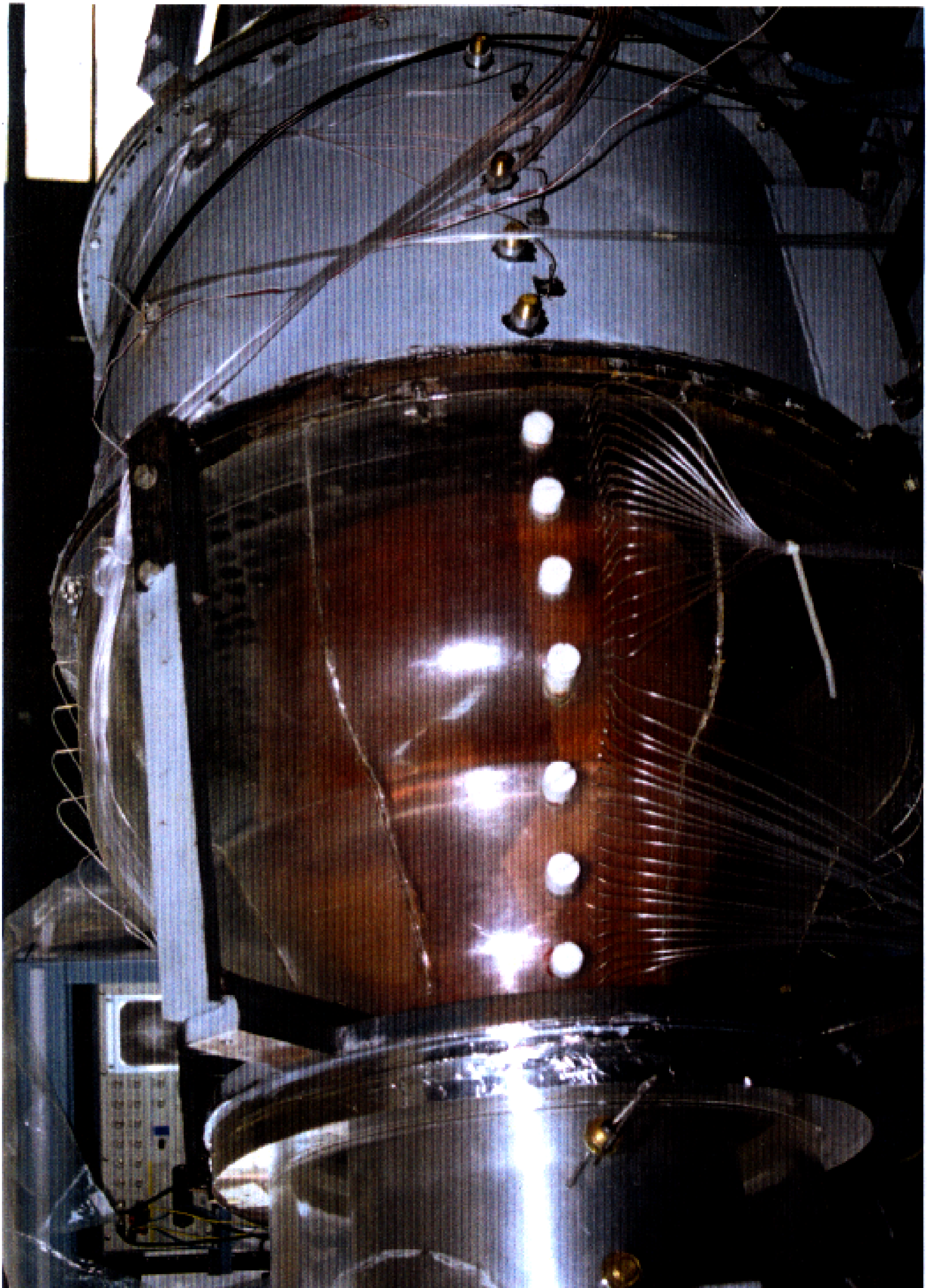
## Test Conditions

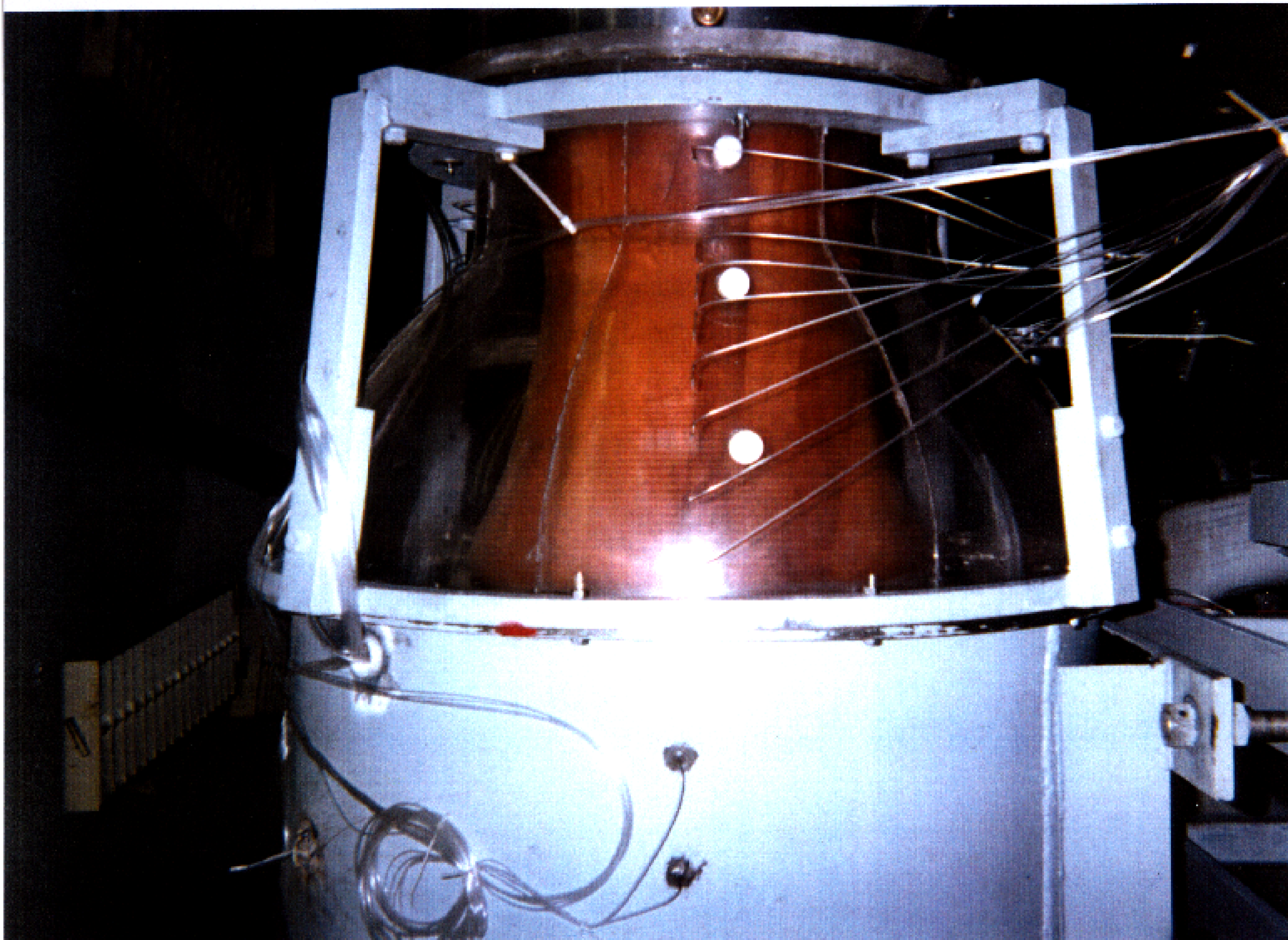
- **Case 1: Maximum flow rate, entire test section, without intercooler tube header**
- **Case 2: Maximum flow rate, no diffuser section, without intercooler tube header**
- **Case 3: Maximum flow rate, entire test section, with intercooler tube header**
- **Case 4: Reduced flow rate, entire test section, with intercooler tube header**

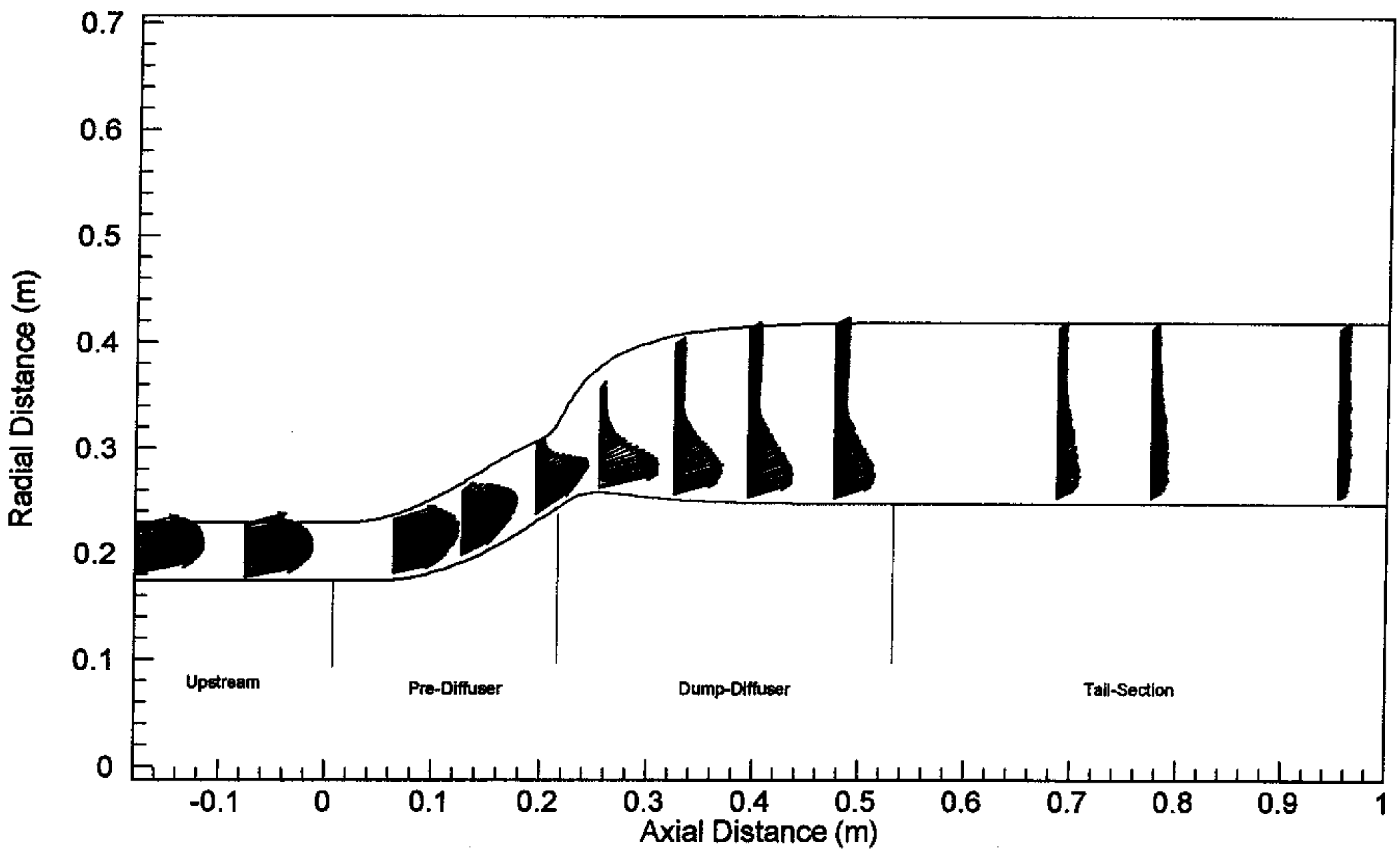



# Schematic of the On-axis Intercooler Flow Path

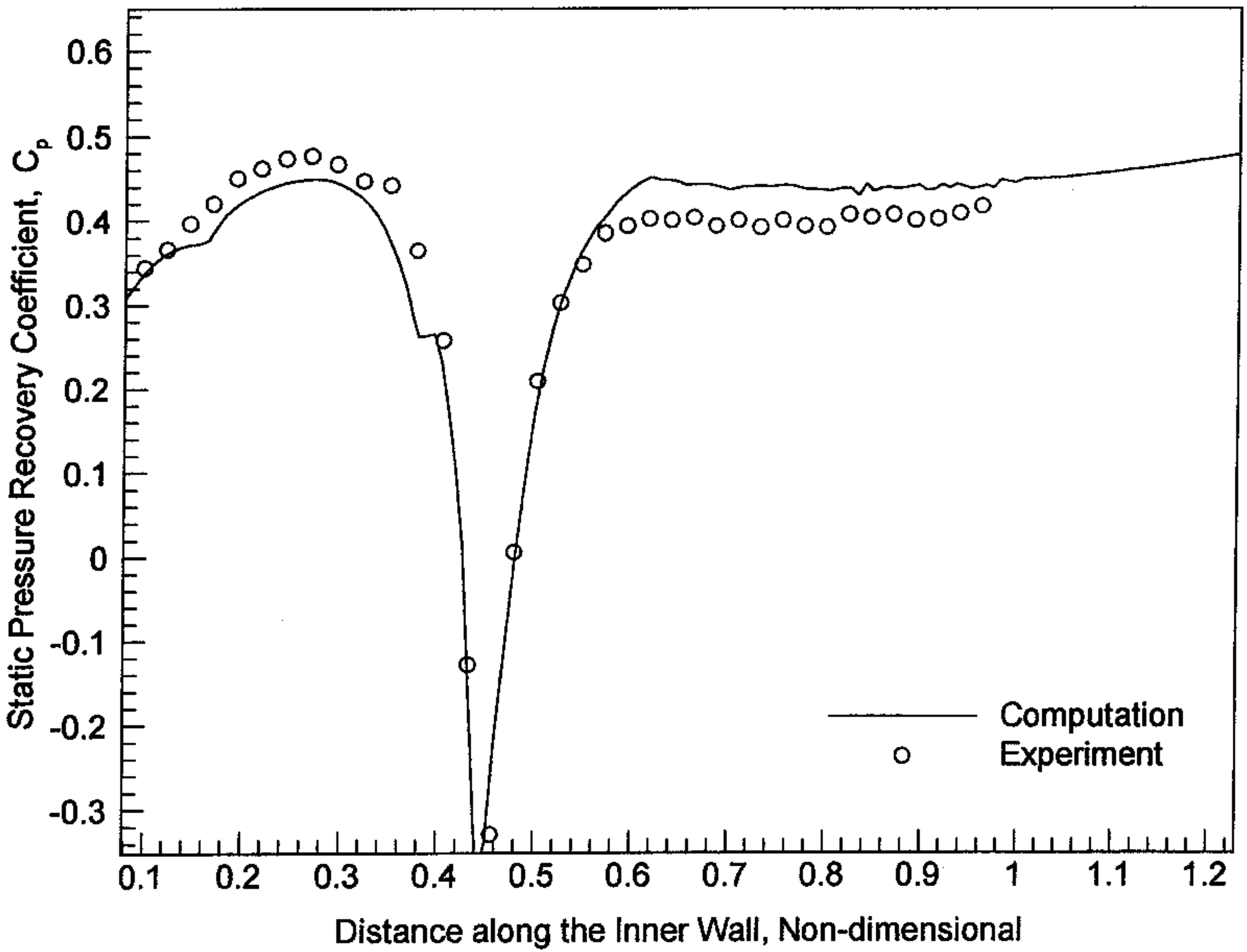




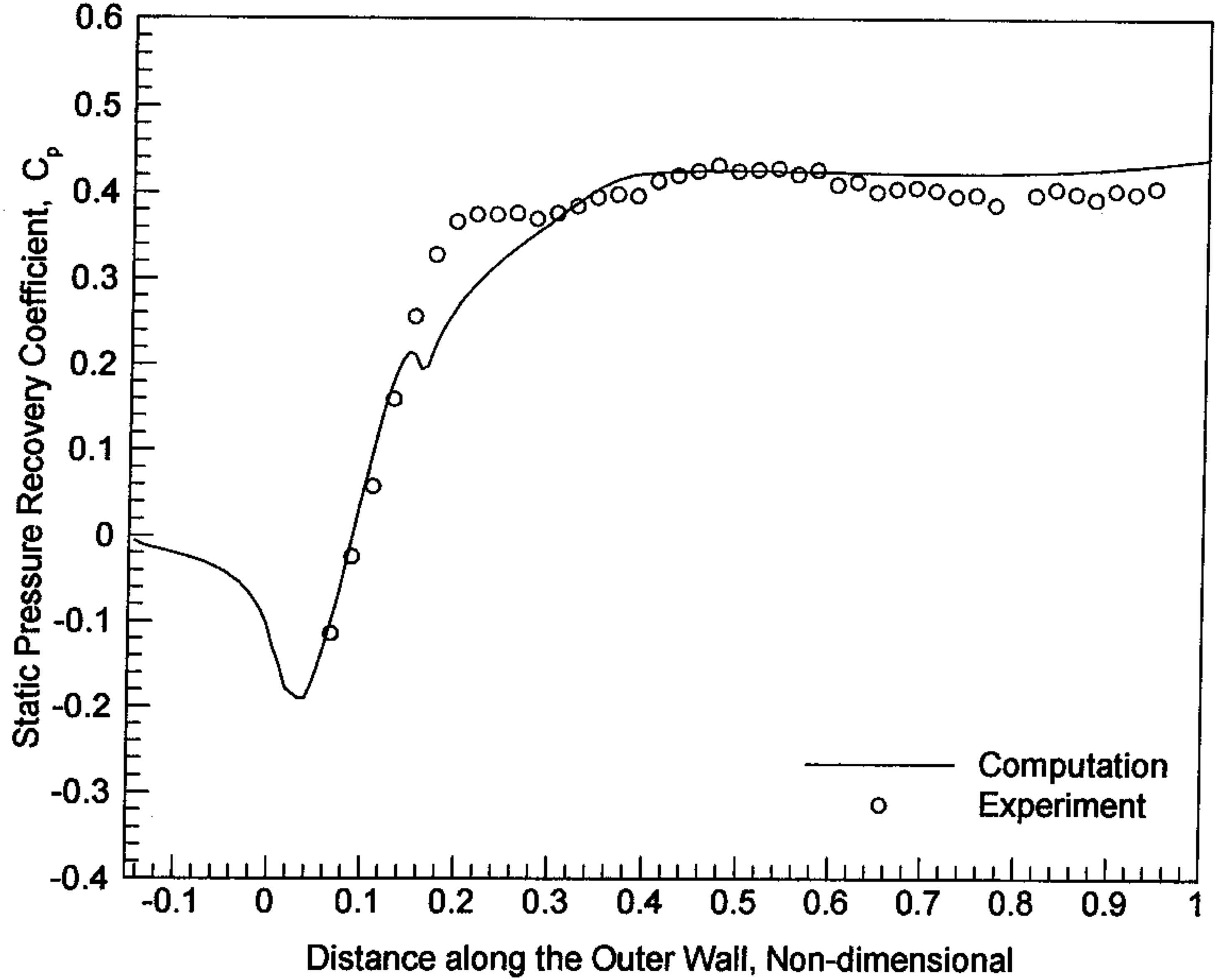




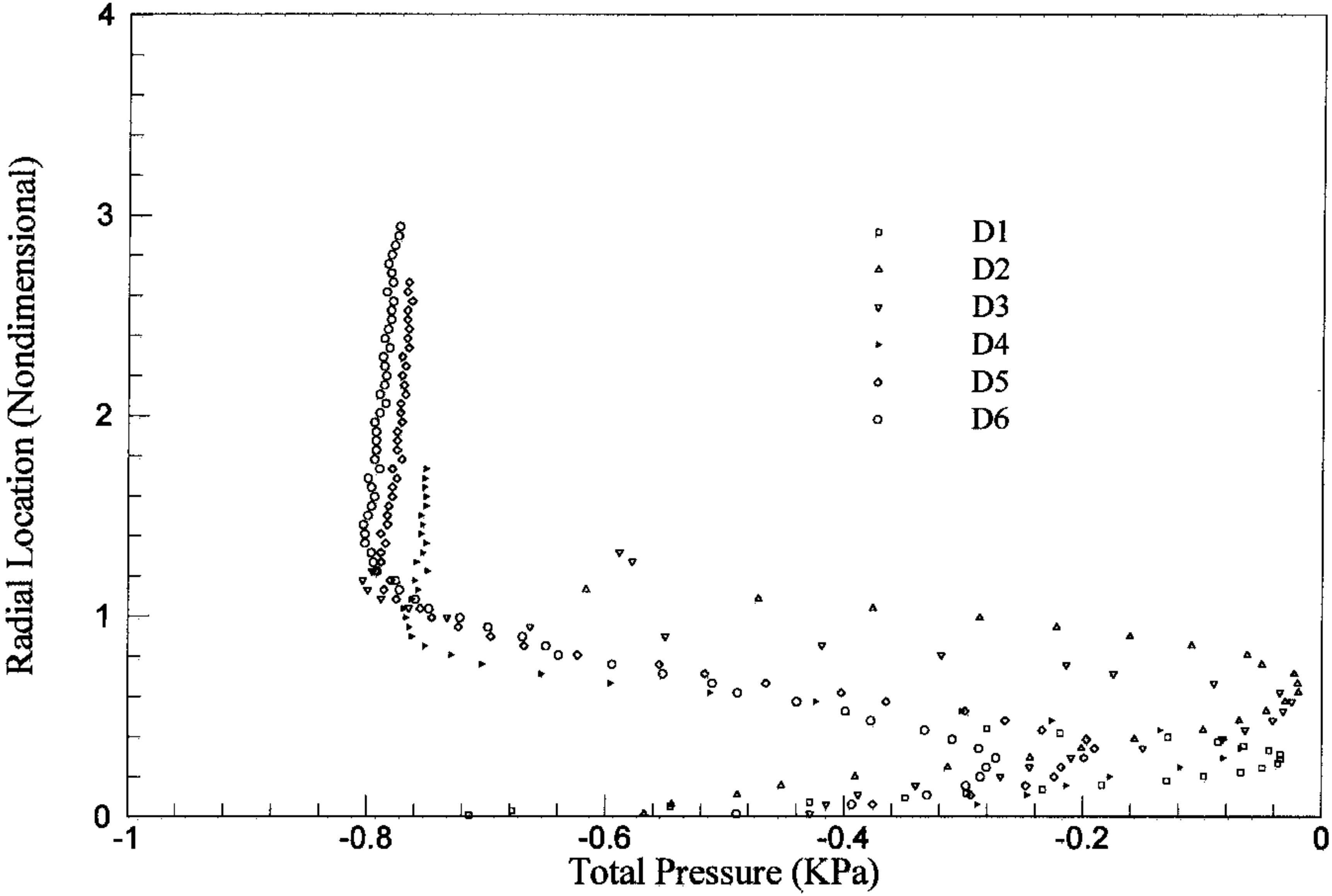

**Velocity Vectors in the Diffuser Obtained from Hot-Film Anemometer**



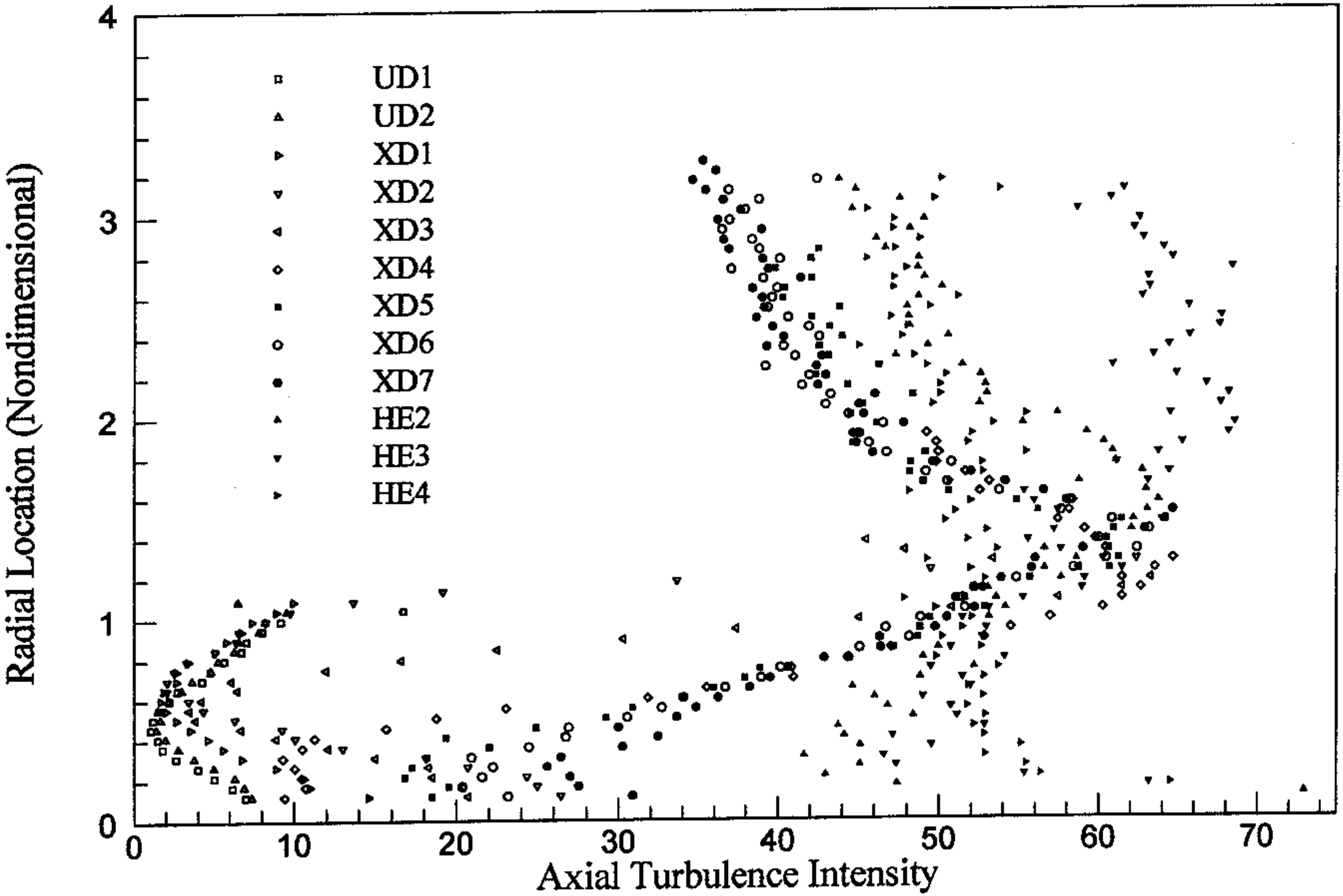

**Pressure Recovery Coefficient along the Diffuser Inner Wall**



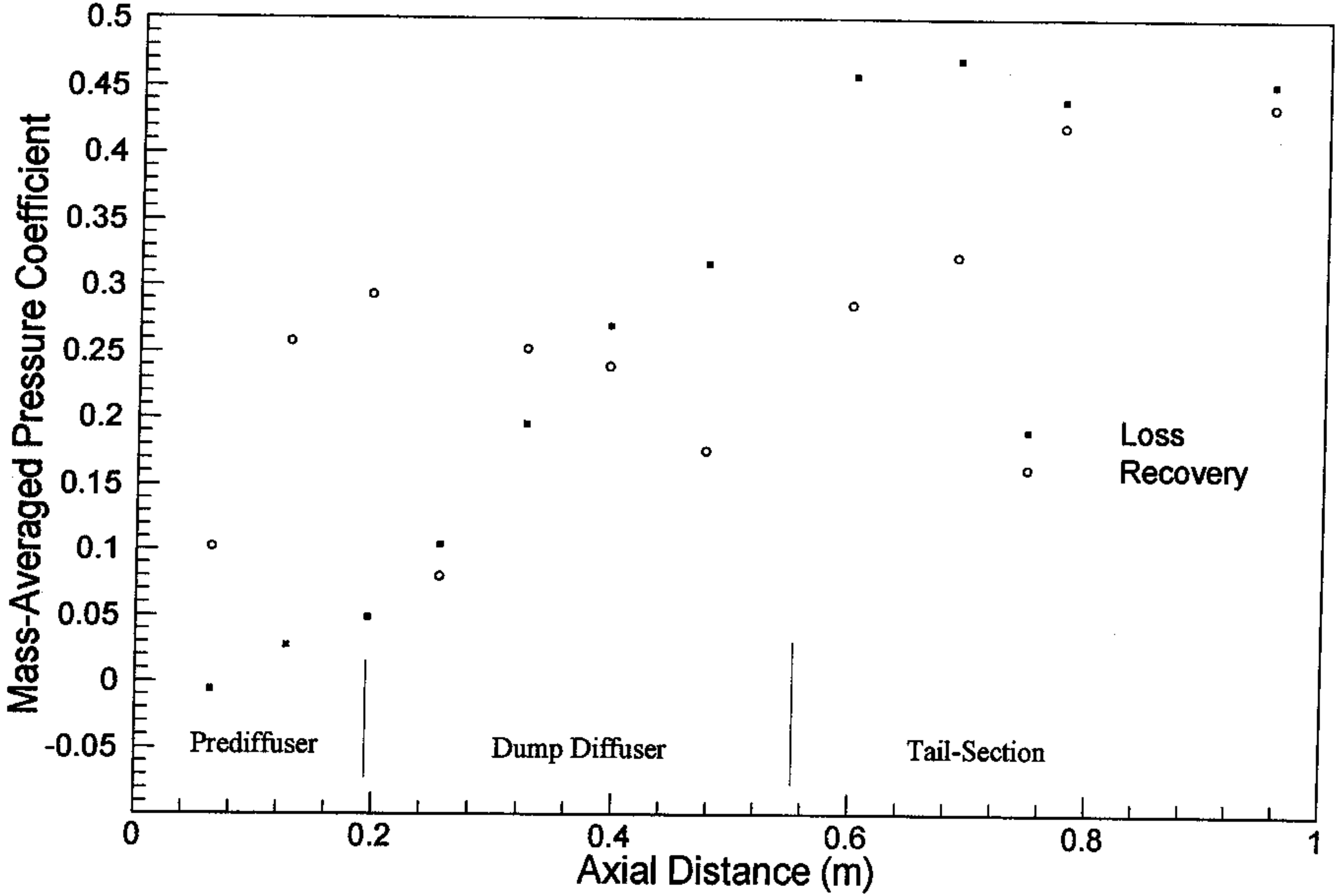

**Pressure Recovery Coefficient along the Diffuser Outer Wall**



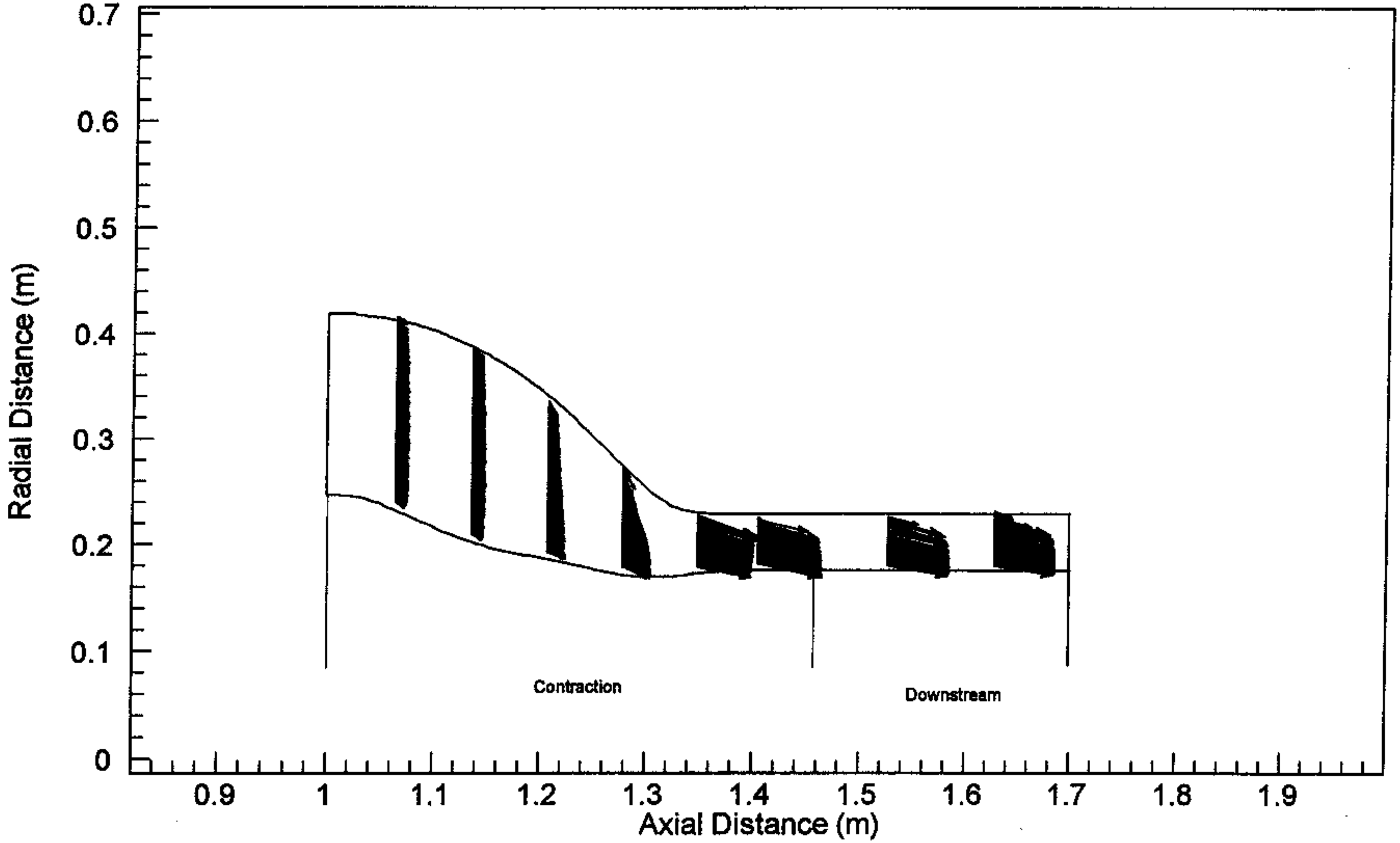

Total Pressure Profiles in the Diffuser



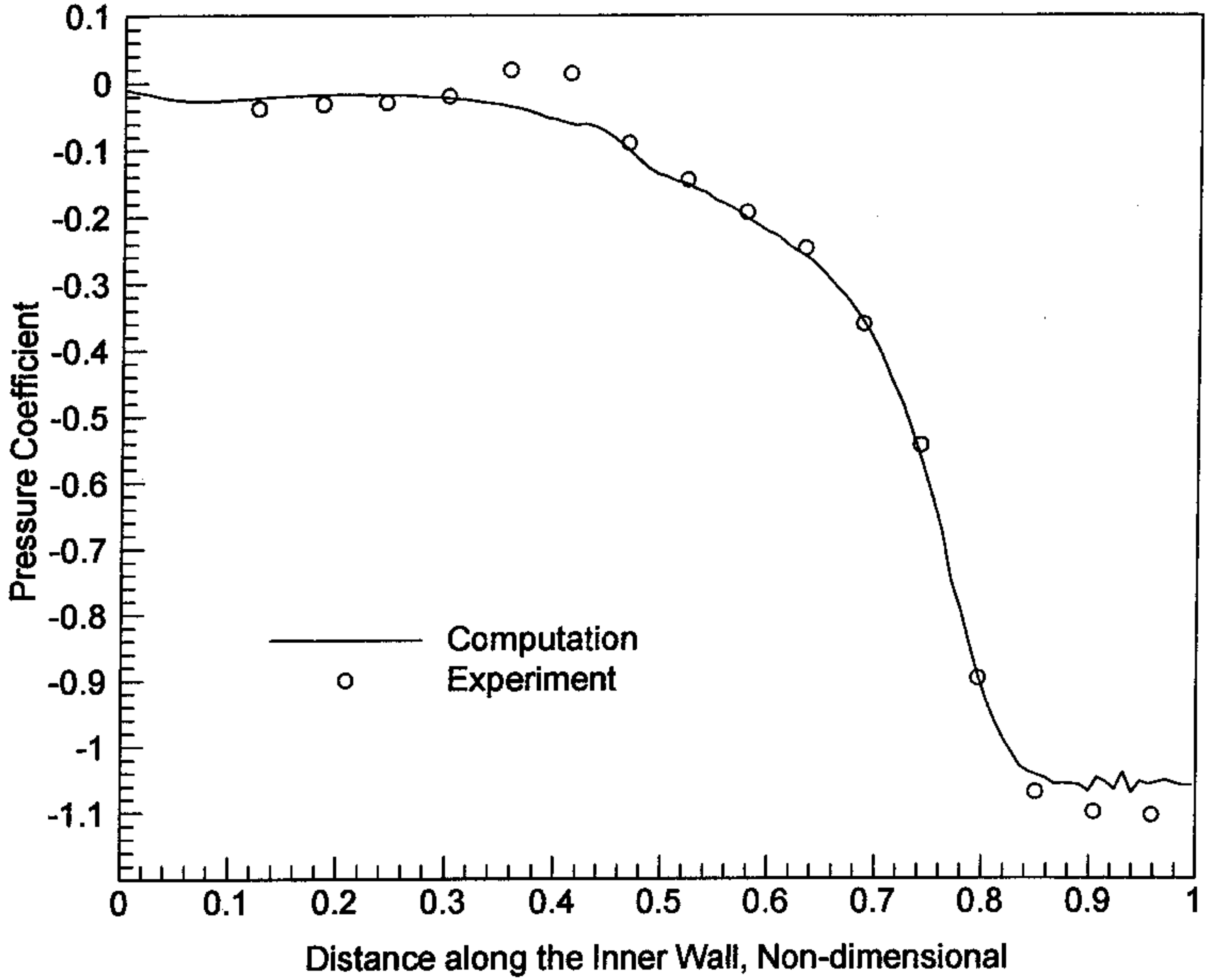

**Axial Turbulence Intensity Profiles in the Diffuser**



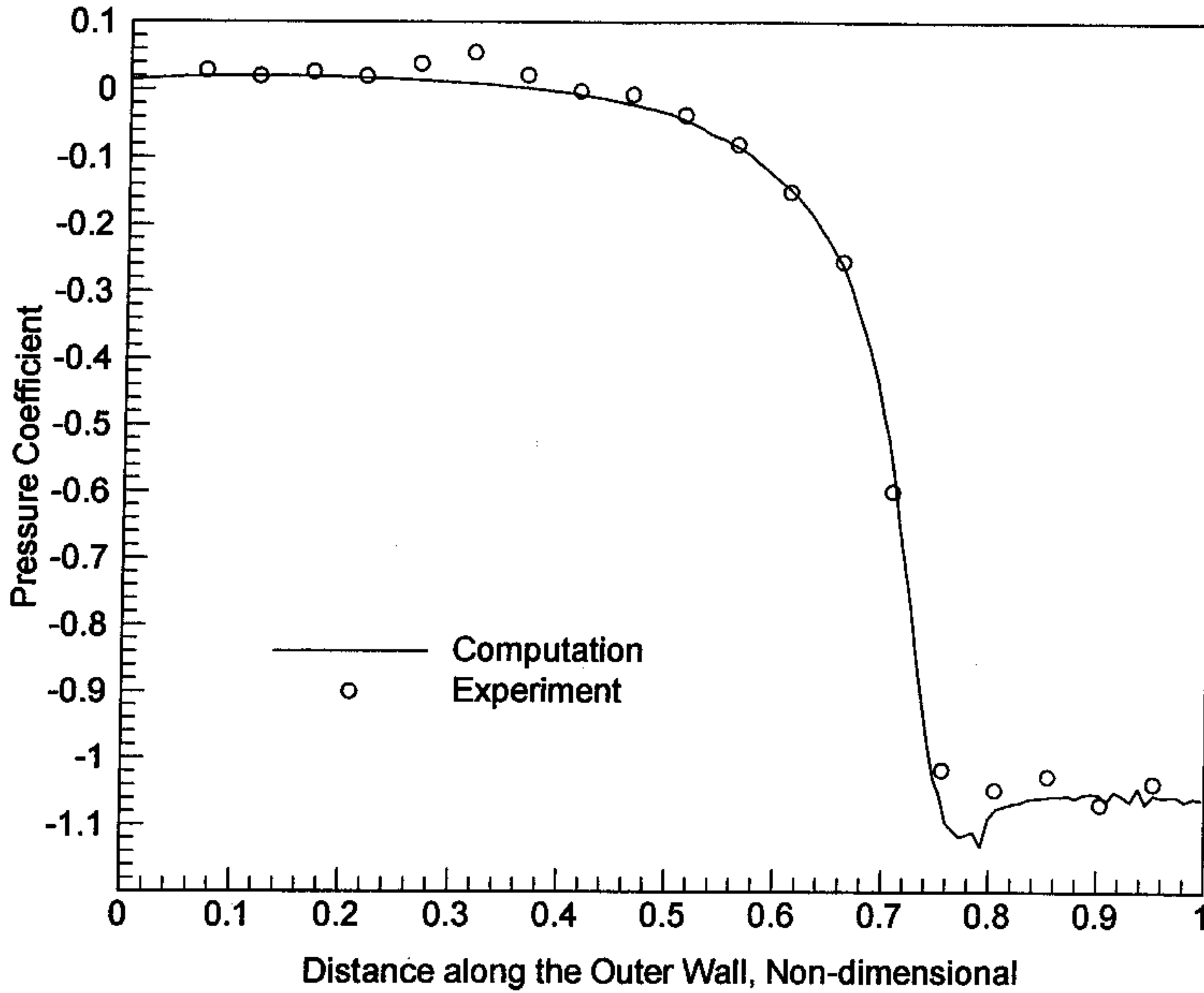

**Mass-Averaged Pressure Loss/Recovery Coefficients in the Diffuser**



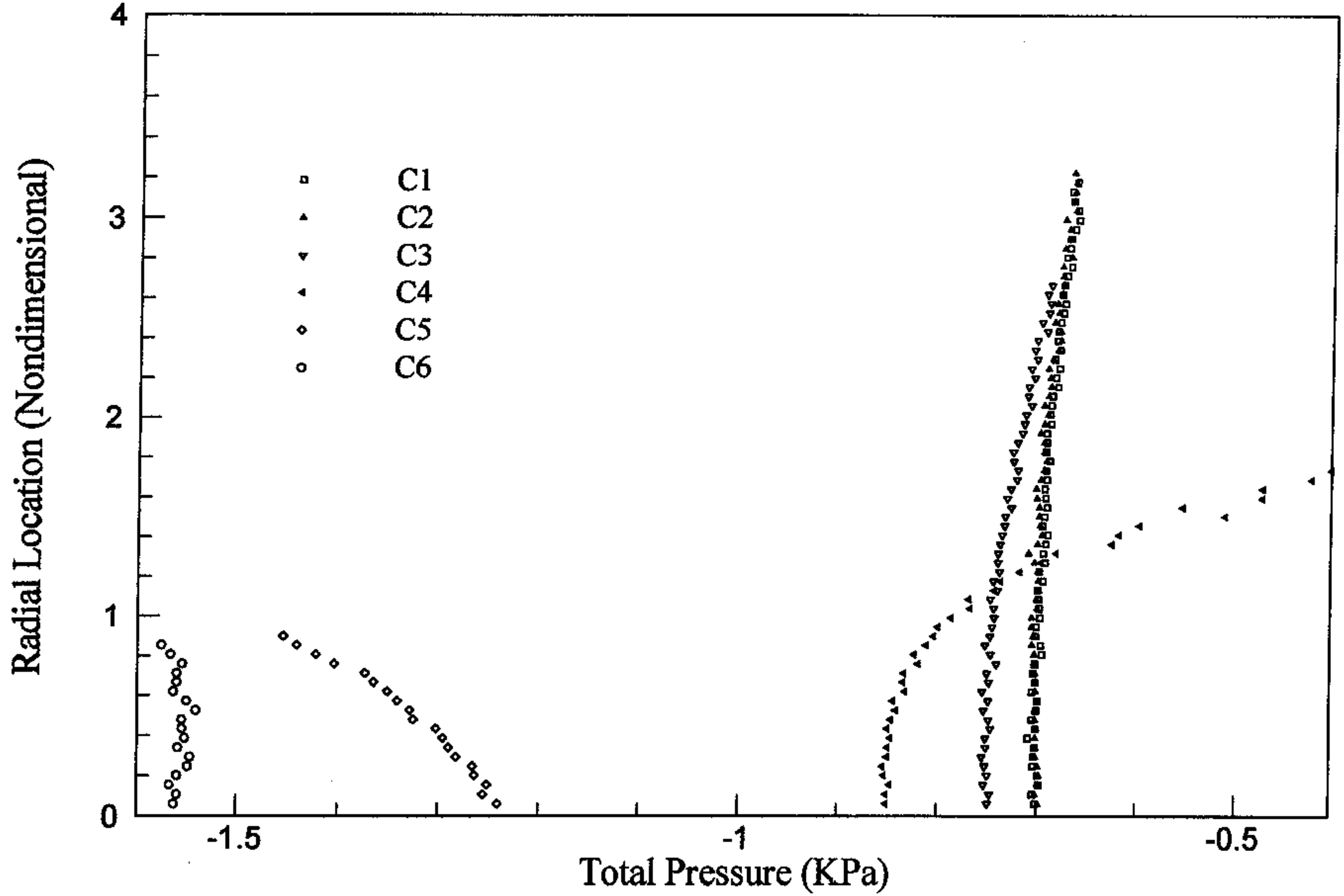

**Velocity Vectors in the Contraction Obtained from Cross-Film Anemometer**



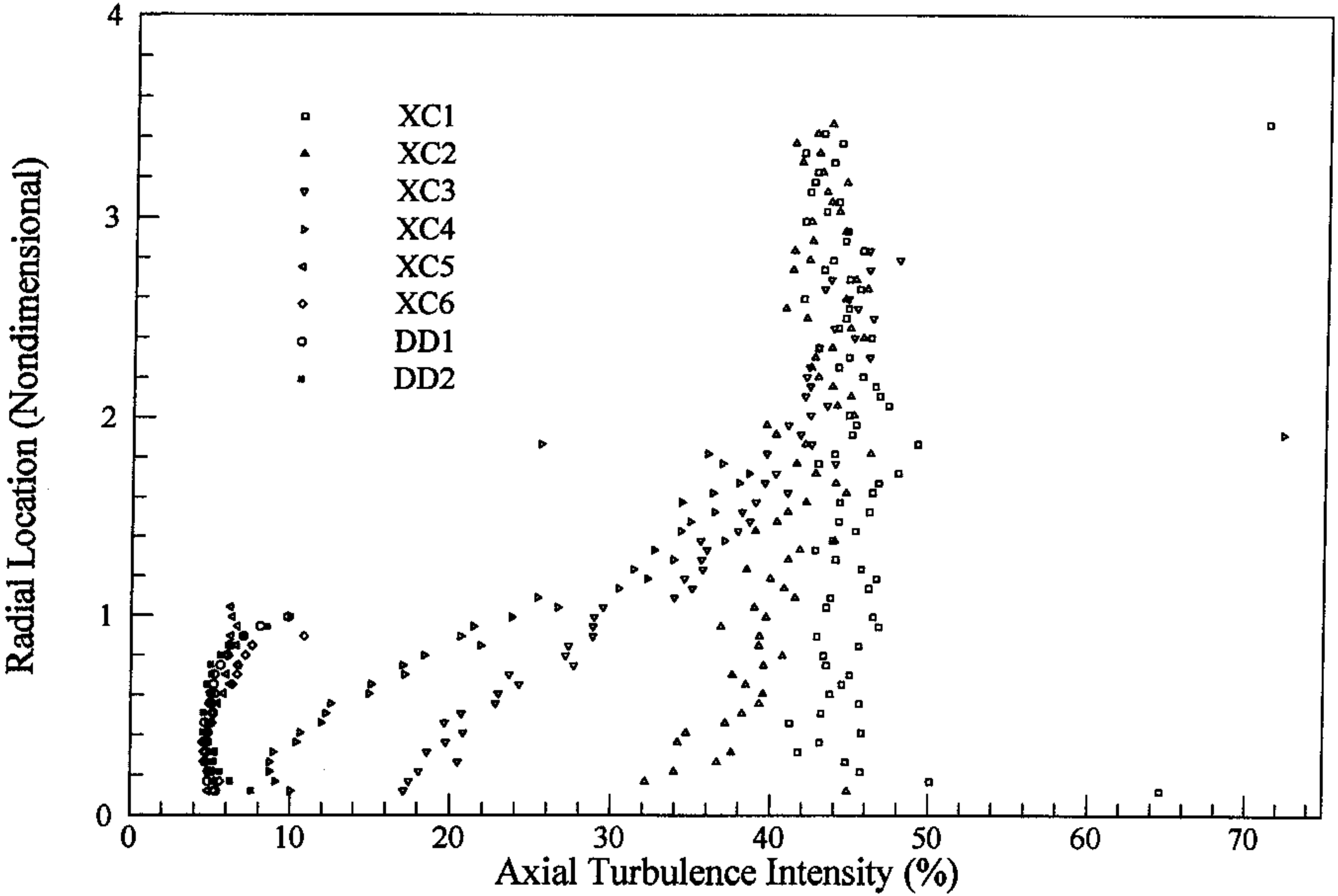

**Pressure Coefficient along the Contraction Inner Wall**




**Pressure Coefficient along the Contraction Outer Wall**




Total Pressure Profiles in the Contraction




**Axial Turbulence Intensity Profiles in the Contraction**

## INVERSE DESIGN/ OPTIMIZATION PROCEDURE

- **Guess the GCL for a given sectional area variation along the GCL.**
- **Construct the passage geometry and generate the computational grid.**
- **Compute the flow field using the flow solver.**
- **Compute centerlines of the mass, momentum and energy fluxes.**
- **Modify the GCL using the guess GCL and centerlines of the flow quantities.**
- **Repeat steps 2 to 5 until deviations among the centerlines reduce to an acceptable value.**

## Center of Mass Flux ($C_1$)

$$\int_{i}^{C_1} dm = C_m \int_{C_1}^{o} dm \qquad \textbf{(1)}$$

$C_m$ is the ratio of mass fluxes on the two sides of the geometric centerpoint at the inlet plane.

## Center of Mass-Averaged Energy Flux ($C_2$)

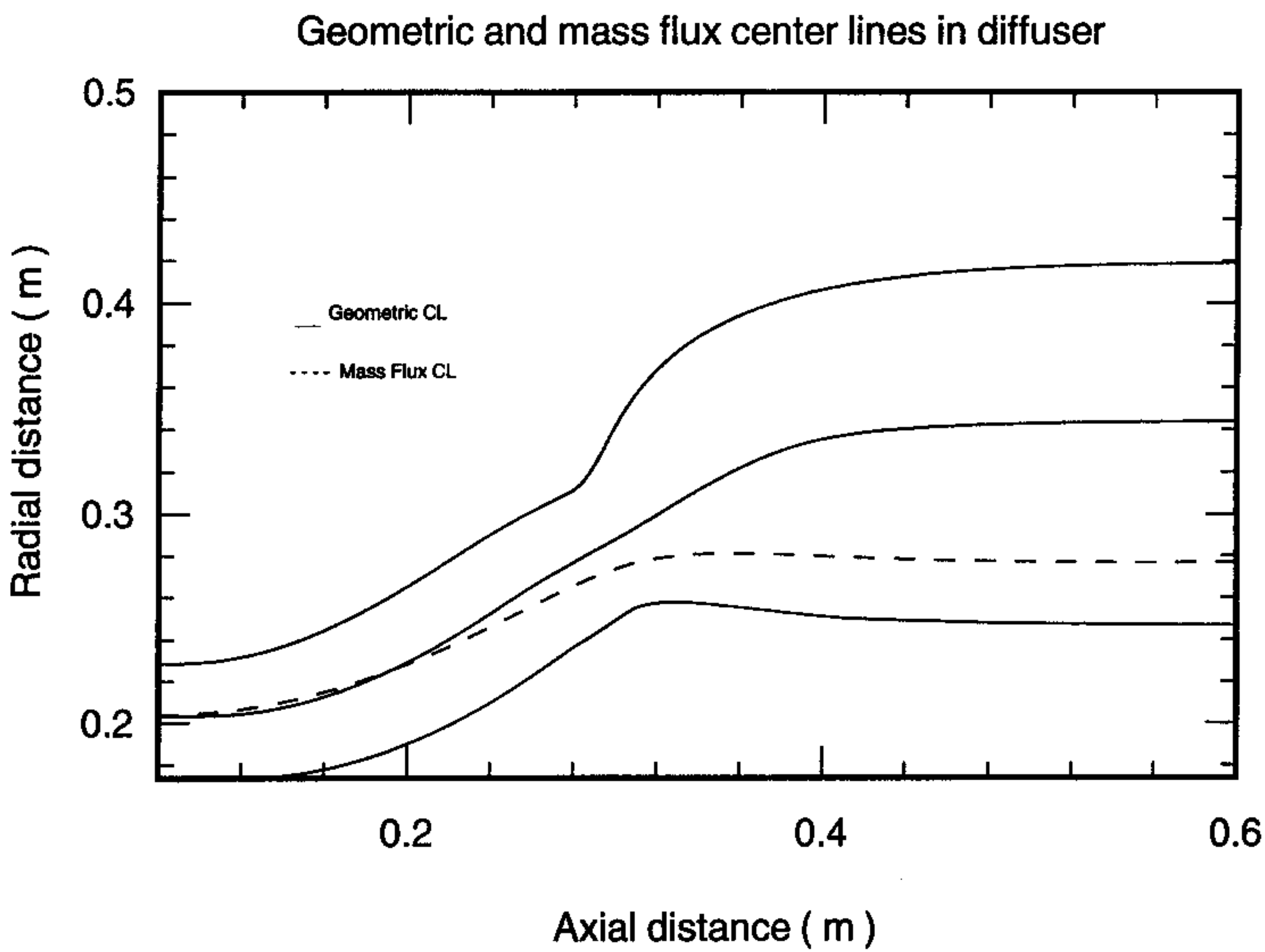
$$\int_{i}^{C_2} K \cdot dm = C_k \int_{C_2}^{o} K \cdot dm \qquad \textbf{(2)}$$

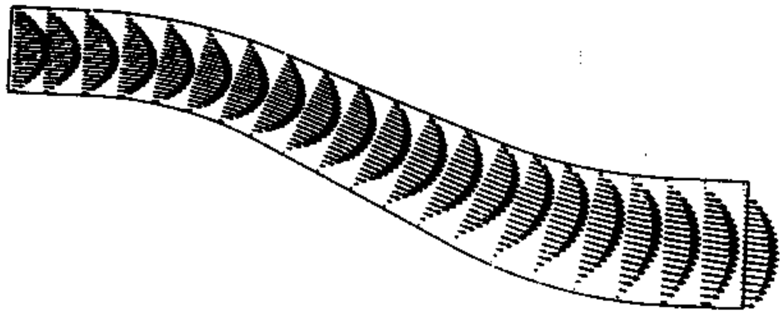
where K is the kinetic energy of the flow.

## Center of Mass-Averaged Momentum Flux ($C_3$)

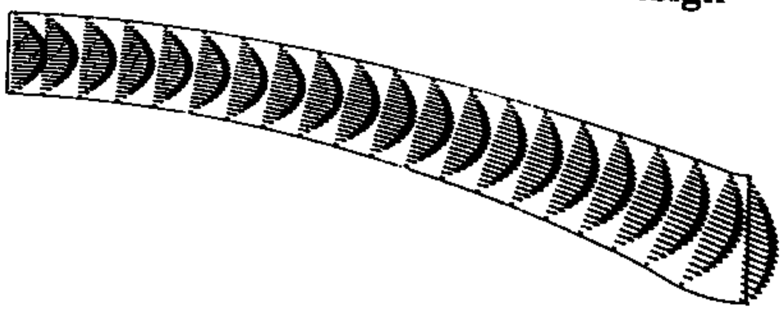
$$\int_{i}^{C_3} T \cdot dm = C_t \int_{C_3}^{o} T \cdot dm \qquad \textbf{(3)}$$

where T is the specific momentum.

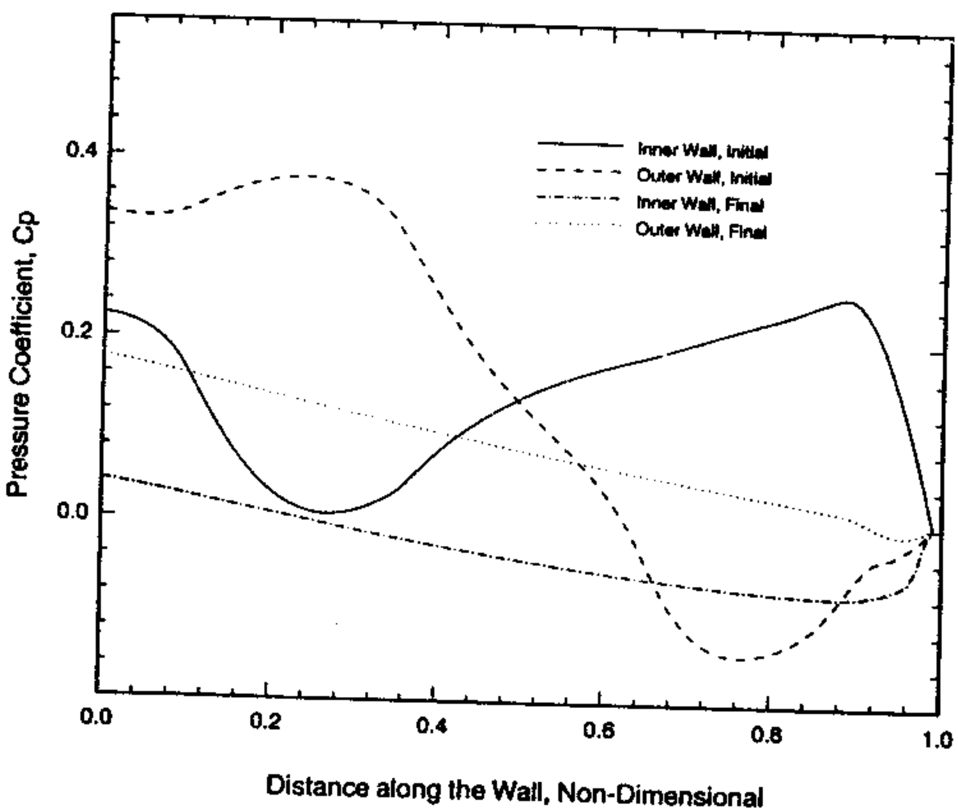

Geometric and mass flux center lines in diffuser
0.5
0.4
0.3
0.2
Radial distance ( m )
Geometric CL
Mass Flux CL
0.2
0.4
0.6
Axial distance ( m )



Velocity vectors in the initial design



Velocity vectors in the final design




Pressure coefficient along the annulus walls

## CONCLUSIONS

- **On-axis intercooler flow path incurs total pressure loss of about 1.0 percent (or 0.5 dynamic head). This loss should be added to the heat exchanger pressure loss. Off-axis arrangement would incur additional pressure loss.**

- **Majority of the pressure loss occurred in the dump region of the diffuser where the flow separated.**

- **Uniform flow at the diffuser exit was achieved with a longer length.**

- **Diffuser exit flow was highly turbulent; helpful in promoting heat transfer.**

- **Pressure loss in the contoured inlet was small. The flow accelerated uniformly regardless of the inlet turbulence intensity.**

- **The intercooler flow path may require a longer diffuser. The contraction length could be decreased without adverse effects.**

## BENEFITS TO INDUSTRY/ FUTURE WORK

- **Intercooling is under consideration by most major gas turbine manufacturers. This unique project has developed a conceptual design of an intercooler system, obtained experimental data to help in design of the prototype, identified pertinent issues, and provided suggestions for future work.**

- **The inverse design/ optimization technique developed in this work can be used to design annular flow passages for various gas turbine applications, e.g., inter-turbine diffusers, inter-compressor passages etc.**

- **Future work should consider how support struts affect the flow. Concepts such as multi-annular diffusers should be investigated to minimize the overall length.**