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PENN STATE AXIAL FLOW TURBINE FACILITY: PERFORMANCE AND NOZZLE FLOW FIELD

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The objective of the research presented in this paper is to gain a thorough understanding of the flow field in a turbine stage including three-dimensional inviscid and viscid effects, unsteady flow field, rotor-stator interaction effects; including unsteady blade pressures, shear stress and velocity field in rotor passages. A brief progress report on the research carried out towards this goal is presented in this paper. The performance of the turbine facility at the design condition is measured and compared with the design distribution. The data on the nozzle vane static pressure and wake characteristics are presented and interpreted. The wakes are found to be highly three-dimensional, with substantial radial inward velocity at most spanwise locations.

Notations

C	Chord length
C_p	Static pressure coefficient $(P_{atm}-p)/0.5\rho U_t^2$
C_{ps}	Blade static pressure $(p-P_{atm})/0.5\rho V_{x_1}^2$
C_{pt}	Stagnation pressure coefficient $(P_{atm}-p)/0.5\rho U_t^2$
C_{pw}	Wake static pressure $(p-P_{atm})/P_{atm}$
p	Static pressure
P	Stagnation pressure
P.S.	Pressure side of wake
R	Radius normalized by blade tip radius
S	Streamwise distance
S.S.	Suction side of wake
U_t	Blade tip speed
V_θ, V_r, V_x	Absolute tangential, radial and axial velocity components
V	Absolute velocity
X	Axial distance normalized by axial blade chord (=0 at LE, =1 at TE)
Y	Tangential distance normalized by blade spacing (=0 at wake center, + ve on pressure side, - ve on suction side)
α	Flow outlet angle measured from axial direction

Subscripts

r,θ,x	Radial, tangential and axial components
h	Hub
t	Tip
1,2,3	Inlet, exit of nozzle, exit of rotor

INTRODUCTION

The present knowledge of turbine flow field, especially the rotor flow field is not adequate. The flow field is three-dimensional and unsteady, with the presence of laminar, transitional and turbulent regions near the blade surface. Some of the three dimensional effects present are compressibility, radial density (or temperature) gradient, radially varying thickness, annulus wall area changes and flaring, radially varying enthalpy, radial component of blade force, radially varying blade heat transfer, non-uniform entry flow and temperature field, and leakage and secondary flows. The three dimensional viscid flows and turbulence effects are mainly caused by the three dimensional boundary layers on blades and wakes, annulus wall and hub wall boundary layers, shock boundary layer interaction, and secondary flows in annulus wall and hub wall boundary layers. The presence of horseshoe vortex near the blade leading edge, combined with thick blades and rapidly varying passages and flow turning, makes the flow field truly complex.

There are many other basic problems related to turbines that remains unresolved. These are the vane-blade interaction and its effect on the unsteady pressure, reliability, unsteady heat transfer and vibration. These interactions are both inviscid and viscid in nature and can considerably affect the aerothermodynamic performance of a stage. A major objective of this research is to develop and validate quantitative understanding of the unsteady interactions in a turbine. Large scale, low speed rig testing will permit extensive use of sophisticated instrumentation that will facilitate a better understanding of the vane-blade interaction process. The experimental results directly feed and support the analytical and computational tool development. The large scale, low speed rig available at Penn State will facilitate these experiments because it permits extensive use of high frequency response instrumentation on the stationary vanes and, more importantly, on the rotating blades. Furthermore, it facilitates detailed nozzle wake, rotor wake and boundary layer surveys. The large size of the rig also has the advantage of operating at Reynolds numbers representative of the engine environment. This allows duplication of Reynolds-number-sensitive fluid flow characteristics, such as wakes and boundary layers. The time dependent static pressure distributions will directly validate the computational results from the unsteady, time marching flow solution under development at Penn State and elsewhere.

FACILITY DESCRIPTION

The Axial Flow Turbine Research Facility of The Pennsylvania State University is an open circuit facility 91.4 cm in diameter and a hub to tip radius ratio of 0.73, with advanced axial turbine blading configurations. The facility consists of a large bellmouth inlet, a turbulence generating grid section, followed by a test section with a nozzle vane row and a rotor. There are 23 nozzle guide vanes and 29 rotor blades followed by outlet guide vanes. Provisions exist for changing the vane-blade axial spacing from 20 to 50 percent of chord. The bellmouth inlet is housed in an enclosure covered with wire mesh and a thin layer of rubber foam to filter the air prior to entry to the inlet. A complete description of the facility is given in Reference 1 and a brief description is given in Reference 2.

A variable through flow is provided by two auxiliary, adjustable pitch, axial flow fans and an aerodynamically designed throttle. This system allows accurate control of the mass flow through the experimental stage up to a maximum of 22,000 cfm. The two fans in the series produce a pressure rise of 74.7 mm Hg (40" of water) with a mass flow of 10.4 m^3 per second under nominal operating conditions. The power generated by the experimental turbine rotor assembly is absorbed by an eddy-current brake which is capable of absorbing up to 90 Hp. The speed of the rotor can be varied between 175 and 1695 RPM with the "dynamatic-adjustor speed" control system and can be held constant to ± 1 RPM, with normal fluctuations in line voltage. The eddy current brake is cooled by a closed loop chilled water cooling system.

The rotor and nozzle vane passages are instrumented with high frequency instrumentation to measure steady (time averaged) and unsteady pressures, shear stresses. The details of the instrumentation used on the nozzle vane, rotor blade, nozzle casing, rotor hub, and nozzle hub is described in References 1 and 2. Provision has been made for a laser window for LDV measurement of the flow field upstream of the nozzle, nozzle passage, spacing between the rotor and the nozzle, rotor passage, and downstream of the rotor passage. The facility is equipped with two traversing mechanisms. One of the probe traverse units is mounted directly behind the rotor disk and has provisions for the radial and circumferential traverses in the rotating frame. It is controlled by a stepping motor driven by a computer indexer at tangential increments of 0.019 degrees/step to allow accurate measurement of the rotor wakes.

The rotating to stationary interface data transmission system, attached to the rotor shaft ahead of the nose cone, is an integral part of the facility. It consists of a 150 ring mechanical (brush/coin type) slip ring unit, and a specialized ten-channel low noise/signal ratio mercury slip ring unit. A 32 channel electronic pressure scanner unit is located in the rotating drum downstream of the turbine rotor. The electrical signals carrying the pressure information is carried to the stationary frame through the slip ring assembly. The rotor frequency will be accurately determined by using an infrared emitter/receiver sensor located on the casing of the turbine rotor. This device senses the reflected infrared emissions from the tip of a selected rotor blade and directly provides the rotor frequency (once per revolution pulse-OPR).

A completely automated data processing system is built around a micro-computer with a clock rate of 27 MHz. The system consists of a 32 bit computer with 8 Mb random access memory, a disk operating system, 150 Mb hard disk storage space, printer and plotter. All of the data from both stationary and rotating instrumentation can be processed on-line. One of the long range goals of the turbine research is to acquire unsteady heat transfer and aerodynamics data simultaneously.

The aerodynamic design, while not representing any specific current future GE product, does embody modern turbine design philosophy. Stage loading flow coefficient, reaction, aspect ratios, and blade turning angles are all within the ranges of current design practice. State-of-the-art quasi-3D design methods were used to design the airfoil shapes. It is felt that the design is fully capable of meeting the intended research applications. At the inception of the design the objective was that, where possible, the blading should be representative, both geometrically and aerodynamically, of a state-of-the-art HP turbine. Detailed design characteristics, philosophy, and design performance parameters were presented in Reference 1 and 2.

PERFORMANCE MEASUREMENTS AT DESIGN CONDITION

The probes and instrumentation used for the performance measurements includes a 5-hole probe, a pitot probe, a single sensor hot-wire probe and the wall static pressure taps.

In order to determine the axisymmetry and turbulence upstream of the nozzle, a single sensor hot wire probe is used to measure the radial distribution of axial turbulence intensity and mean velocities at three tangential locations (120 degrees apart) at the inlet. The flow was axisymmetric and the axial turbulence intensity was nearly constant at around 1 to 1.5 percent, except near the hub and casing. The freestream velocity was 89.2 ft/s with a Reynolds number of 3.30×10^5 based on nozzle vane chord at midspan. The wall boundary layers were turbulent, with a thickness of 10% blade span at the hub (0.48 inches) and 20% blade span at the tip (0.96 inches). These radial and tangential velocities were almost negligible upstream of the nozzle.

The radial distribution of total and static pressures, total, axial, radial and tangential velocities, and rotor exit flow angle at design conditions were measured two chords downstream of the rotor blade row using a five hole probe. Figures 1 through 3 show the experimental data compared with the design values. The stagnation and static pressure drop coefficients, shown in Figure 1, are about 8 percent less than the design values and this is consistent with the design and estimated efficiencies. The total absolute velocity at the exit (Figure 2) is close to the design values, with higher than design values near the mid-span and lower than the design values near hub and annulus walls. Likewise, the axial velocity distribution shown in Figure 3 indicates the axial velocities are higher in the mid-third of the blade height (due to blockage effect) with low values in the secondary and horseshoe vortex regions. Similar trend can be observed in the tangential velocity distribution shown in Figure 3. The radial velocities are negligibly small (Figure 2). Since the measuring station is located about two chords downstream, this is as expected. Evidence of substantial secondary flow region near the hub is clear from the tangential velocity distribution shown in Figure 3. No attempt is made to draw any conclusions regarding the magnitude of secondary flows, as this data represents average values of rotor flow sensed by a stationary five-hole probe.

NOZZLE FLOW FIELD DATA

Nozzle Vane Pressure Distribution

The nozzle vane has one fully instrumented passage with 154 static pressure taps at several chordwise and radial locations on the suction and the pressure surfaces. The static pressure holes are more closely spaced near the hub and the tip, since the vane surface static pressure distribution changes more rapidly in this region due to the complexity of the endwall flow. Figure 4 shows the static pressure distribution at R=0.87 and 0.74 at 1300 rpm at design conditions. The experimental blade pressure distribution is compared to that obtained by the panel code and the design distribution. On the pressure surface an initial rapid acceleration is followed by a very slow acceleration which occurs up to midchord. From midchord to the trailing edge, the flow accelerates rapidly. On the suction surface there is a steady acceleration of flow until close to the trailing edge, after which the flow decelerates until the outlet pressure is reached at the trailing edge. The agreement between the computational and the measured pressure distribution is good on the pressure surface, but on the suction surface the measured flow accelerates less rapidly than the design values. This could be attributed to the boundary layer growth on the suction side.

Nozzle Wake Data

Measurements of the pitch and yaw angle and pressures were taken in the wake region of the nozzle vane at one axial and three radial locations (X=1.08, R=0.74, 0.79 and 0.87). A five-hole probe connected to a scanivalve and a pressure transducer is used to measure the velocity, static and stagnation pressures.

A plot of the total and axial velocity profile across the wake at three radii at 8% of the axial chord downstream of the trailing edge (X=1.08) is shown in Figure 5. The streamwise distance is approximately 15% of the total chord at this location. The wake decay is much faster than those measured in cascades and compressor rotors (Ref. 3). One of the causes of this faster decay is the radial velocity that exists in this wake. The wake is appreciably thick (about 20 to 30 percent of blade spacing) at all three radial locations and the wake width is maximum near the tip of the blade. The axial velocity profile is similar to the total velocity and in all cases, the wake is asymmetric, and the wake defect is nearly constant for various radii. Similar wake measurements have been reported by Dring, et al. (Ref. 4) and Goldman and Seasholtz (Ref. 5). The tangential velocity profile across the wake at R=0.92, 0.87, 0.79 are shown plotted in Figure 6. The tangential velocity profiles are similar to axial and total velocity profiles presented earlier. The data presented later indicate that the outer angle variation is ±2 degrees across the entire wake. One of the most interesting features is the radial velocity distribution shown in Figure 6. Radial velocities are inward at all locations and the maximum values occur near the tip of the blade. The static pressure gradient is nearly constant in the wake, but the centrifugal force in the radial direction caused by the tangential velocity, decreases as the wake center line is approached. This induces radial inward velocity which is consistent with the data shown in Figure 6. The hub has the least radial inward velocity and the tip has the maximum inward velocity. These inward velocities represent approximately 10 degrees in the pitch angle. Thus, the wakes emanating from the nozzle vanes are three-dimensional and with a substantial variation in tangential, axial and the radial component across the wake. The wakes are fairly thick and this should have a substantial influence on the unsteady pressure and velocity distribution, in the subsequent rotor passage. Attempts will be made to measure the wake at other axial locations including one near the rotor blade leading edge using laser doppler velocimeter.

The outlet angles variation across the wake is shown in Figure 7. This indicates that the outlet angle variation is not substantial. The maximum deviation being ±2 degrees with overturning on one side of the blade, underturning on the other side as expected. The static pressure distribution across the wake is also shown in Figure 7 and this indicates that the static pressure is nearly constant across the wake at this axial location.

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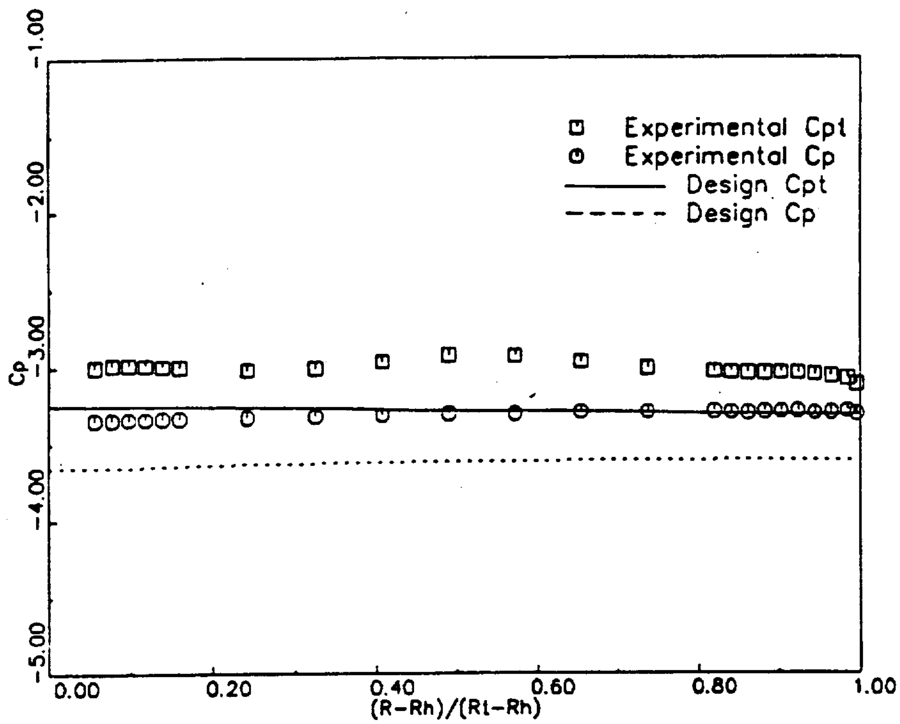


Figure 1 Total & Static Press. Coeffs. 2 Chords Downstream of Rotor

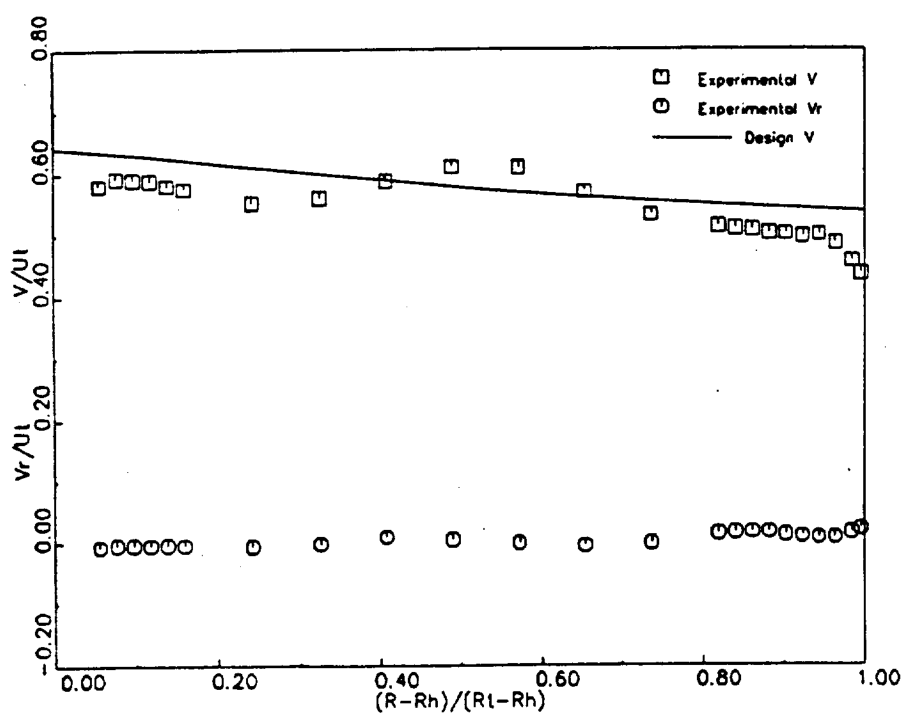


Figure 2 Velocity Profiles 2 Chords Downstream of Rotor

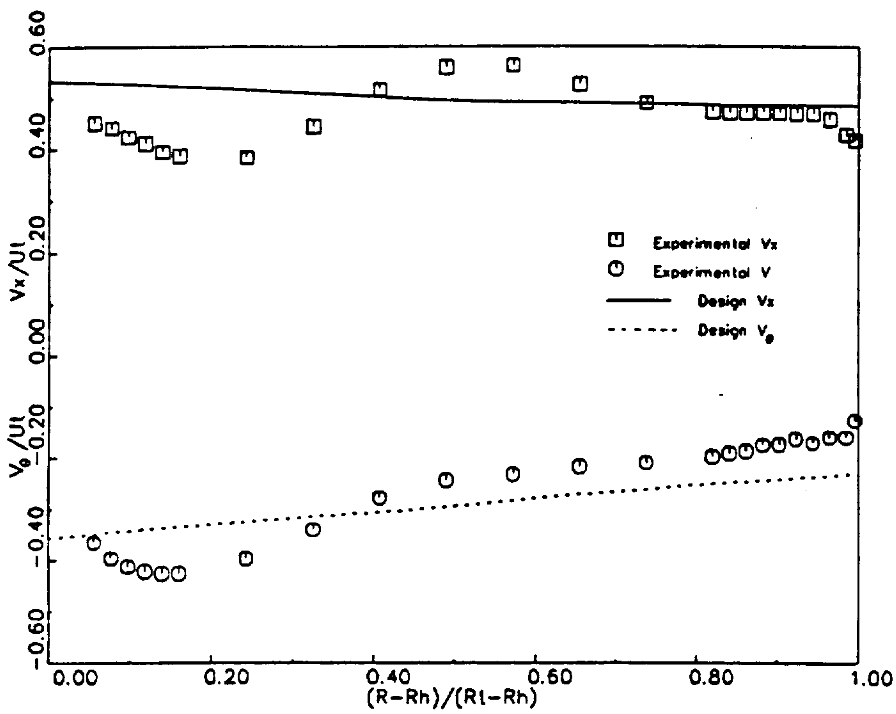


Figure 3 Velocity Profiles 2 Chords Downstream of Rotor

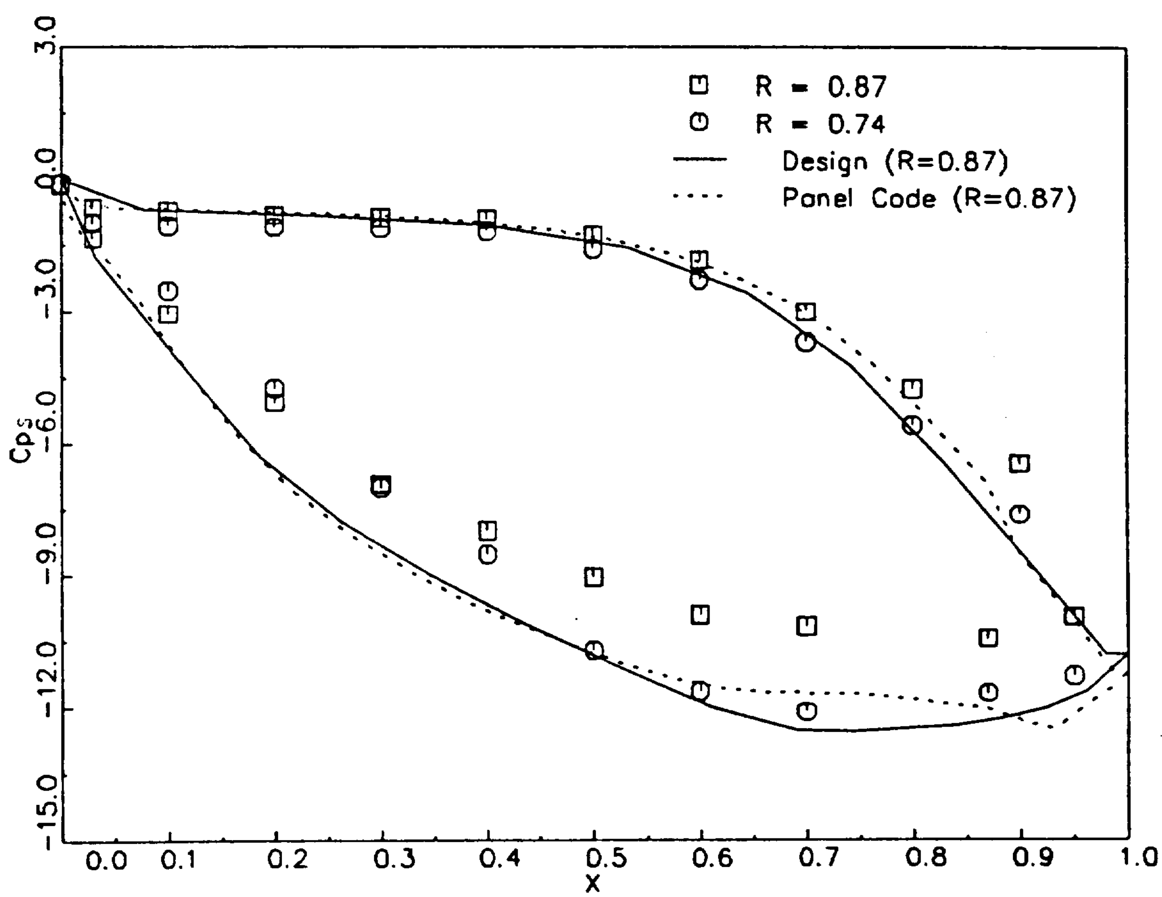


Figure 4 AFTRF NOZZLE SURFACE STATIC PRESSURE DISTRIBUTION

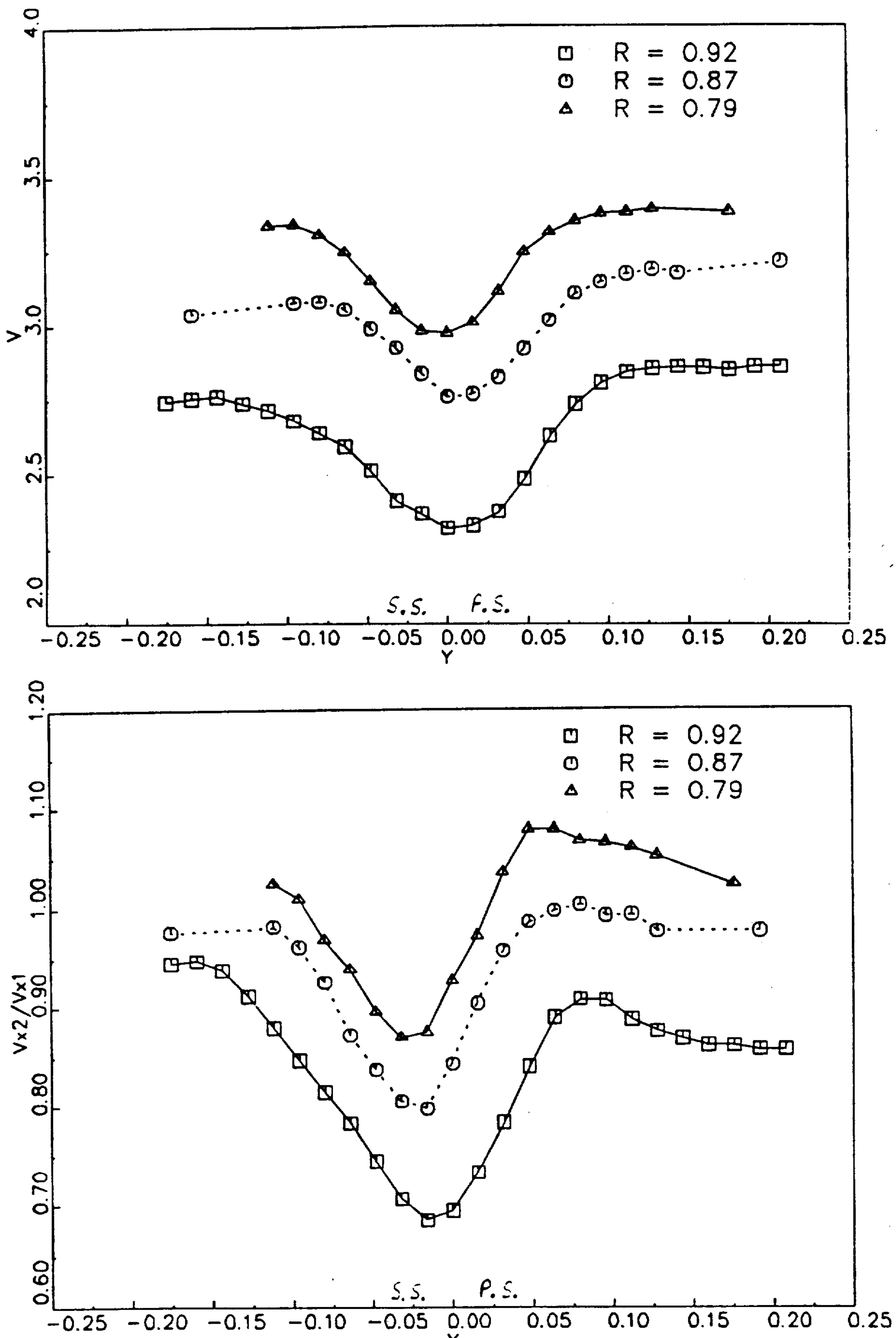
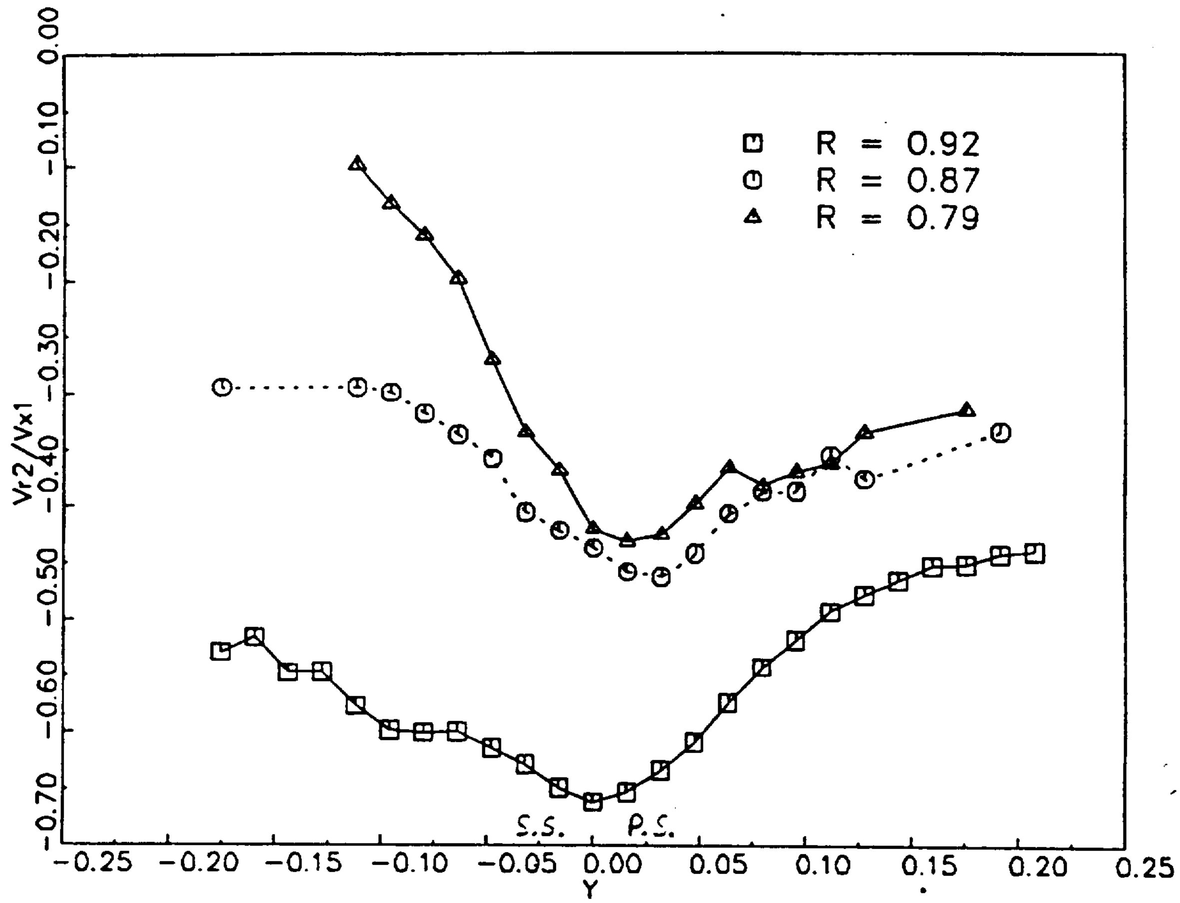


Figure 5. Total and axial velocity variation across the nozzle wake (X=1.05)



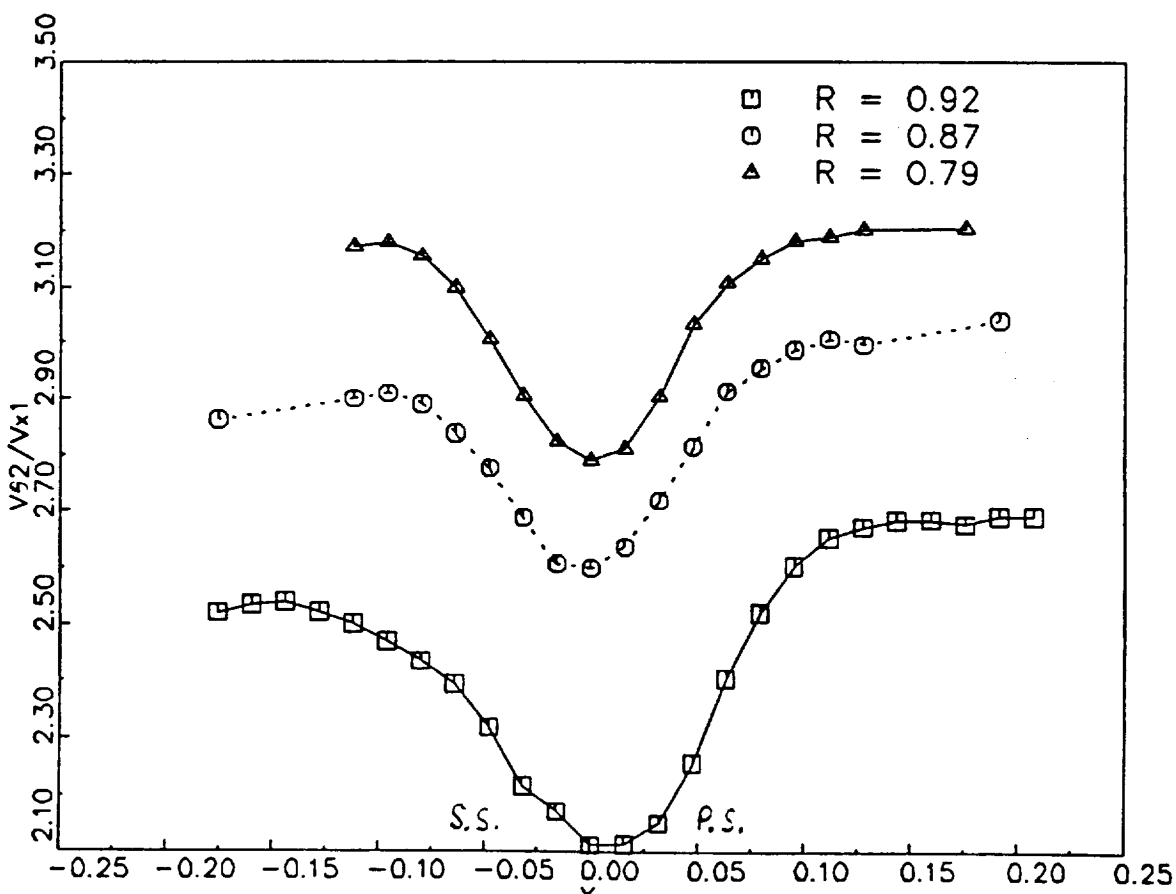


Figure 6. Tangential and radial velocity profiles across the nozzle wake (X=1.08)

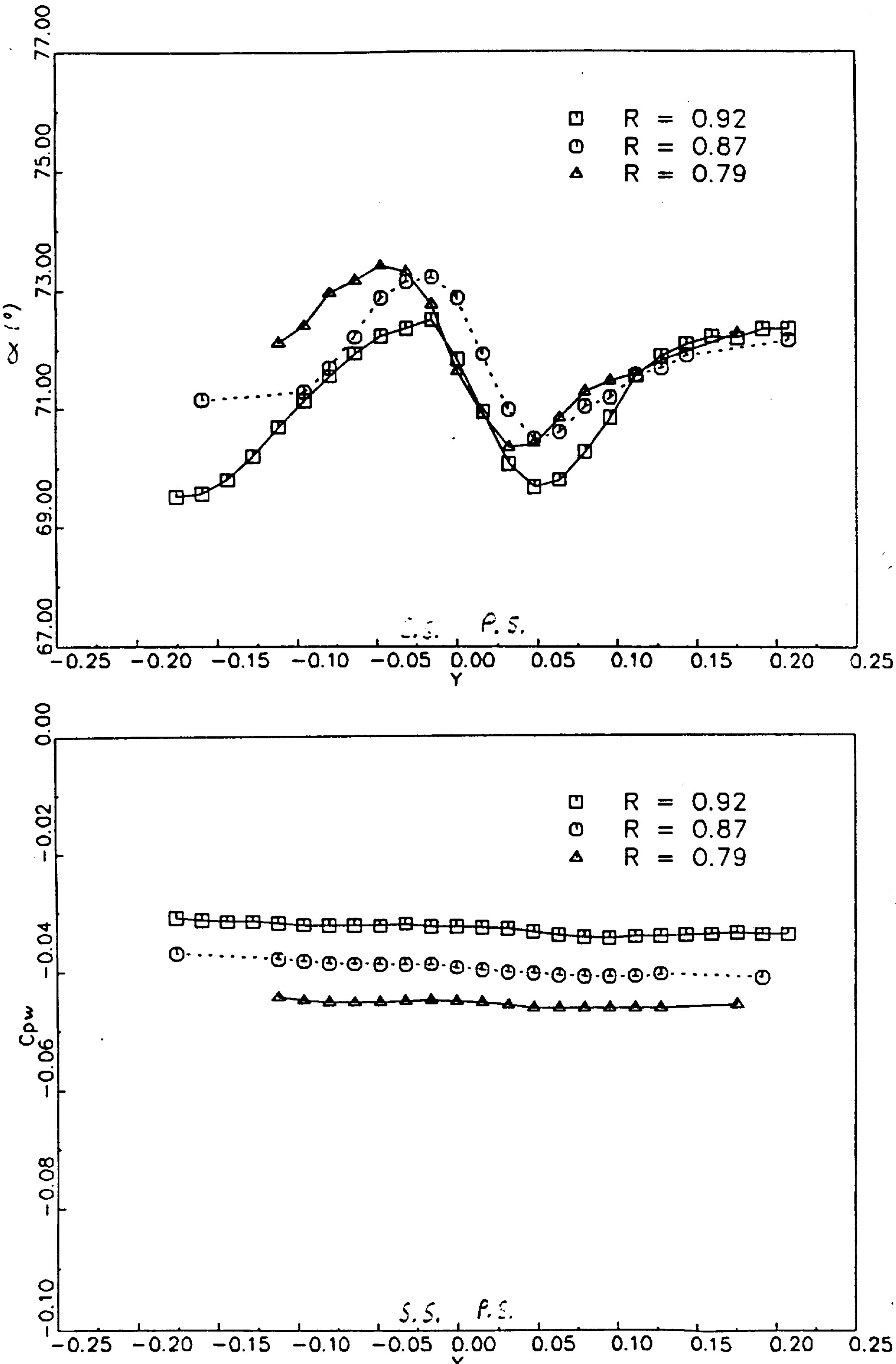


Figure 7. Flow outlet angle and static pressure distribution across the nozzle wake (X=1.08)

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16. Abstract
A two-day conference on the structural integrity and durability of reusable space propulsion systems was held on May 14 and 15, 1991, at the NASA Lewis Research Center. Presentations were made by industry, university, and government researchers organized into four sessions: aerothermodynamic loads; instrumentation; fatigue, fracture, and constitutive modeling; and structural dynamics. The principal objectives of the conference were to disseminate research results and future plans in each of four areas. This publication contains extended abstracts and the visual material presented during the conference.

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