

DOE/PC/93221--T8

# Combustion of Pulverized Coal in Vortex Structures

Grant No. DE-FG22-93PC93221

Quarterly Progress Report No. 8

Period Covered: July 1, 1995 -September 30, 1995

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Document Control Center  
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October 1995

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## Abstract

This eighth quarterly report describes the activities and accomplishments of the research team at the University of Oklahoma, Norman, Oklahoma, related to the project entitled "Combustion of Pulverized Coal in Vortex Structures" during the period July 1, 1995 to September 30, 1995. The work performed in this quarter consisted of the following four tasks: (i) Completion of the schlieren flow visualization experiments, (ii) Conducting experiments with particulate laden shear layers in cold flow to measure mean velocity and turbulence intensity field, (iii) Conducting experiments with particulate laden shear layers in heated flow where the initial temperature was above the pyrolysis temperature of the coal, (iii) Conducting experiments with particulate laden shear layers in heated flow where the initial temperature was above the ignition temperature of the coal, and (iv) Revising and preparing the final version of a paper for the Energy Conference to be held in Houston in 1996. A 90-day no-cost extension of the project was obtained. In the final quarter, we plan to complete this work by conducting the final task of measuring concentration fields.

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## **I. INTRODUCTION**

This eighth quarterly progress report covers the overall objectives, the specific objectives for the reporting period, the organizational details, the work that has been accomplished during the reporting period, the work planned for the next quarter, and an assessment of the anticipated problems.

## **II. OVERALL OBJECTIVES**

The overall objectives of the project are: (i) to investigate the changes in the characteristics of large scale vortex structures in the shear layer caused by the introduction of inert solid particles in one of the feed streams; (ii) to understand the effects of pyrolyzing solids on the shear layer behavior; (iii) to study the effect of combustion of the pyrolysis products on the shear layer structure, heat release rate, and pollutant emission characteristics; and (iv) to study the effect of modifying the shear layer characteristics on the ensuing flame behavior.

## **III. SPECIFIC OBJECTIVES FOR THE REPORTING PERIOD**

The specific objective for the reporting period was to conduct experiments with particulate laden shear layers to measure mean velocity and turbulence intensity field in cold flow, and in the shear layer where one of the streams was heated above the coal (a) pyrolysis temperature and (b) ignition temperature.

## **IV. ORGANIZATIONAL DETAILS**

Mr. Nelson Butuk, a graduate student in the School of Aerospace and Mechanical Engineering, pursuing his Ph. D. degree program continued to work as a research assistant assisting the principal investigator, Professor S. R. Gollahalli. Another graduate student Mr. Michael Babb helped Mr. Butuk. The mechanical engineering technician of the School, Mr. Bill Hill helped the research team during the reporting period.

## V. WORK ACCOMPLISHED DURING THE REPORTING PERIOD

### VA Mean Velocity and Turbulence Intensity Measurements in the heated Particulate -Laden Shear layers

Because the three-dimensional traverse that was designed and constructed in the previous quarter to traverse the laser velocity meter required refocusing the beams at every location after each movement the experiments consumed an inordinate amount of time. Therefore, in this quarter, the experimental facility was modified such that the entire shear layer test section could be traversed leaving the LDV and the optics stationary. This was achieved by a series of stepper motor driven gear-shaft mechanism. The vertical traverse of the test section in the vertical z direction was also computer-driven and controlled as in the experiments of the previous quarter. The soft ware-using Strawberry systems WORKBENCH program was adopted for traversing, and recording pressure and temperature readings in the test section and Pitot-tube data on-line. A GATEWAY microcomputer was used for this purpose.

The LDV is based on a helium-neon laser and grating-controlled detector system. The system was operated in forward scatter-mode. The laser Doppler analyzer operated with a transmitter lens of focal length 500 mm, a receiver lens of focal length 500 mm, and a 10 mW helium-neon laser. The transmitting and receiving optics were mounted on two identical precision x-y traversing mechanisms located on opposite sides of the combustion chamber. These devices had a traverse resolution of 80  $\mu\text{m}$ . The instrument was operated in the forward scatter mode with a beam separation of 23.8 mm and a beam intersection waist width of 176  $\mu\text{m}$ . Both nozzle and air-flow streams were seeded with magnesium oxide particles whose average size was about 5  $\mu\text{m}$ . A microcomputer-based data acquisition system with a 16-MHz clock was used to acquire and process the output data of the LDV. The mean velocity in the axial direction,  $U$ , and the root mean square value of the fluctuating component,  $u'$ , were determined from the LDV measurements. During experiments with cold jets only nitrogen was used as the jet fluid and its flow rate was adjusted to yield the same exit Reynolds number as that of the fuel jet of the corresponding flame. In all runs 200-2000 validated samples with a sampling time less than 15 seconds were acquired. The preliminary experiments showed that above 200 samples per run the measured values of the mean and r.m.s. components of the velocity were not sensitive to the sampling rate. For temperature measurement, a type K thermocouple (0.25 mm diameter) was used. Some experiments were repeated 3 to 5 times to

establish repeatability. The estimated values of the uncertainties in the measurements with thermocouple and LDV, and are  $\pm 3\%$  and  $\pm 10\%$  respectively.

For measuring continuous phase velocity, magnesium oxide particles of mean diameter  $2\ \mu\text{m}$  were injected with a fluidized bed feeder into the top stream. When coal particles were injected they were fed into the top stream with the same feeder. Both MgO and Coal particles prepared following the procedure explained in the sixth quarterly progress report were treated heated in furnace at  $75\ ^\circ\text{C}$  for over four hours, again to minimize agglomeration. The fluidization was achieved by supplying air from a compressor or bottled nitrogen through a rotameter. The flow rate of gas that carries the fluid into the stream was maintained less than  $0.01\%$  of the flow rate of the top stream. The fluidizing gas was passed through a moisture absorber to avoid coagulation of particles in the feeder. An electric solenoid valve was installed in the gas line entering the feeder with on-off switches located in the control room and in the test cell. With these switches, particle flow into the stream could be established for the desired measurement period only. The dispersed phase velocities were measured using injected particles. A COMPAQ microcomputer and data processors were used for data acquisition and on-line/off-line data analysis. The data obtained include, streamwise component of mean velocity, r.m.s value of the fluctuating components of the streamwise velocity, and size-velocity correlations.

For simultaneous measurement of particle and continuous phase velocity, MgO and pulverized coal were mixed and placed in the particle feeder. Histograms of velocity versus size show binary distribution. From the velocity-particle size correlation data the velocity associated with particle size could be isolated and thus particle and continuous phase velocities were obtained.

### **VB Experiments with Pyrolyzing Coal Particles**

The pyrolysis temperature of the coal employed in this study is  $570\ \text{K}$  (Prasad, 1987). Hence, to study the effects of pyrolyzing particles on the shear layer characteristics, the stream into which the particles are injected has to be heated above that temperature. Since, the temperature drops in the shear layer due to mixing with the other stream, to ensure the temperature remains above the coal pyrolysis temperature the particle stream was to be heated to about  $1000\ \text{K}$ . Also, to achieve ignition and sustain combustion of coal particles

in the shear layer, the shear layer has to be maintained above the ignition temperature of coal which in the present case is about 673-1073 K (Bartok and Sarofim, 1991). To allow for the radiation cooling and convective heat transfer to the test section walls, we decided to maintain a over ventilated diffusion flame of natural gas in the test section. For accomplishing both these goals, we designed a burner system fueled with compressed natural gas. This burner was designed such that it could be mounted at different distances upstream of the splitter plate and could be easily exchanged from the top stream to the bottom stream.

The natural gas burner constructed for this purpose and described in the previous quarterly report was employed in this series of experiments. Natural gas flow rate was adjusted such that one of the streams was always maintained at  $1100 \pm 20$  K. Experiments were conducted at two velocity ratios of the streams (top stream velocity / bottom stream velocity equal to 12.5/7.1 and 7/4.5 (m/s)/(m/s)). In each case, for baseline comparison, all measurements were taken without injection of coal particles also.

Figures 1 to 8 show the u-component velocity profile development in the test section with and without coal particles injected into the top stream and the bottom stream was heated to 800 K. The concentration of coal particles in the top stream was held at  $1 \text{ g/m}^3$ . Coal particles come in contact with the heated stream just at the splitter plate edge and undergo pyrolysis while the shear layer is being formed and is developing. Hence, the modulation of the velocity profile may be attributed to the processes of devolatilization which include endothermic reactions and mass addition to the shear layer.

One set of experiments was also conducted with a higher concentration coal ( $2 \text{ g/m}^3$ ). The results are being analyzed at the time of writing this report and will be included in the final report.

#### **VC Experiments With Burning Coal Particles in the Shear Layer.**

This series of experiments was similar to the pyrolysis experiments except that the temperature of the bottom stream was raised to a temperature so that coal particles in the top stream were ignited and burned in the shear layer. Higher temperatures of the top stream were accomplished by increasing the natural gas input to the burner and also moving the burner location closer to the splitter plate edge. In many experiments a gas flame supporting the continued combustion of coal in the test section was also maintained. The gas stream temperature at the splitter plate edge was  $1500 \pm 20$  K.

These experiments were also conducted at two velocity ratios and at two concentrations of coal particles in the stream. The values were maintained same as those in pyrolysis

experiments. The data are being processed and will be included in the final report of the project.

## **VI. WORK PLANNED FOR THE NEXT QUARTER**

In the next quarter, we plan to pursue the following: (i) conduct gas analysis for composition of samples drawn from the shear layers with pyrolyzing and burning coal particles, (ii) complete the data analysis, and (iii) begin the preparation of the final report.

## **VII. ENCOUNTERED and ANTICIPATED PROBLEMS**

Many problems encountered in the previous quarter were solved and the experiments proceeded smoothly in this quarter. We do not anticipate any major problems and hope to complete the project as planned.

## **VIII. CONCLUDING REMARKS**

During the eighth quarter we have achieved substantial progress in the project. The accomplishments include (i) completion of all LDV measurements in cold homogeneous flows, (ii) completion of all LDV measurements in both cold and heated flows with pyrolyzing and burning coal particles, (iii) completion of schlieren flow visualization experiments, (iv) revising a paper on heated shear layers for the 1996 Energy conference in Houston, Texas (the final version of the paper is accepted for presentation and publication)

## **IX. REFERENCES**

- Bartok, W. and Sarofim, A. F., 1991, "Fossil Fuel Combustion, A Source Book," John Wiley and Sons, Inc., New York, NY, USA.
- Brown, G. L. and Roshko, A., 1974, "Density Effects and Large Scale Structures in Turbulent Mixing Layers," J. Fluid Mechanics, Vol. 26, pp. 225-236.



## Figures 1 to 8.

Development of velocity profiles in the shear layer with and without pyrolyzing coal particles in the top stream; bituminous coal, mean particle size =  $45\ \mu\text{m}$ , bottom stream velocity =  $7.1\ \text{m/s}$ , top stream velocity =  $12.5\ \text{m/s}$ , bottom stream temperature =  $800\ \text{K}$ , top stream temperature =  $300\ \text{K}$ ,  $x$  = distance from the splitter plate edge, subscript o = pure gas flame in the bottom stream and air in the top stream, subscript p = gas flame in the bottom stream, and air/coal particles in the top stream.

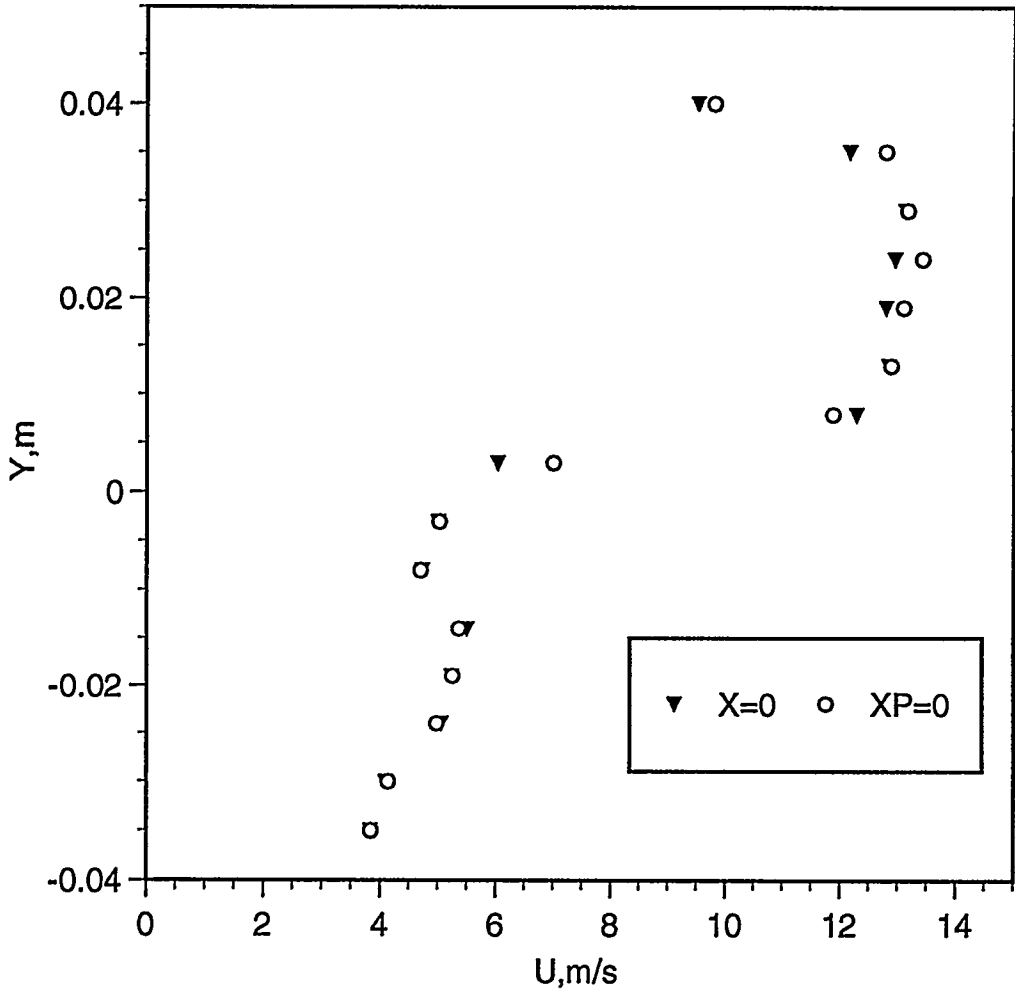


FIG 1

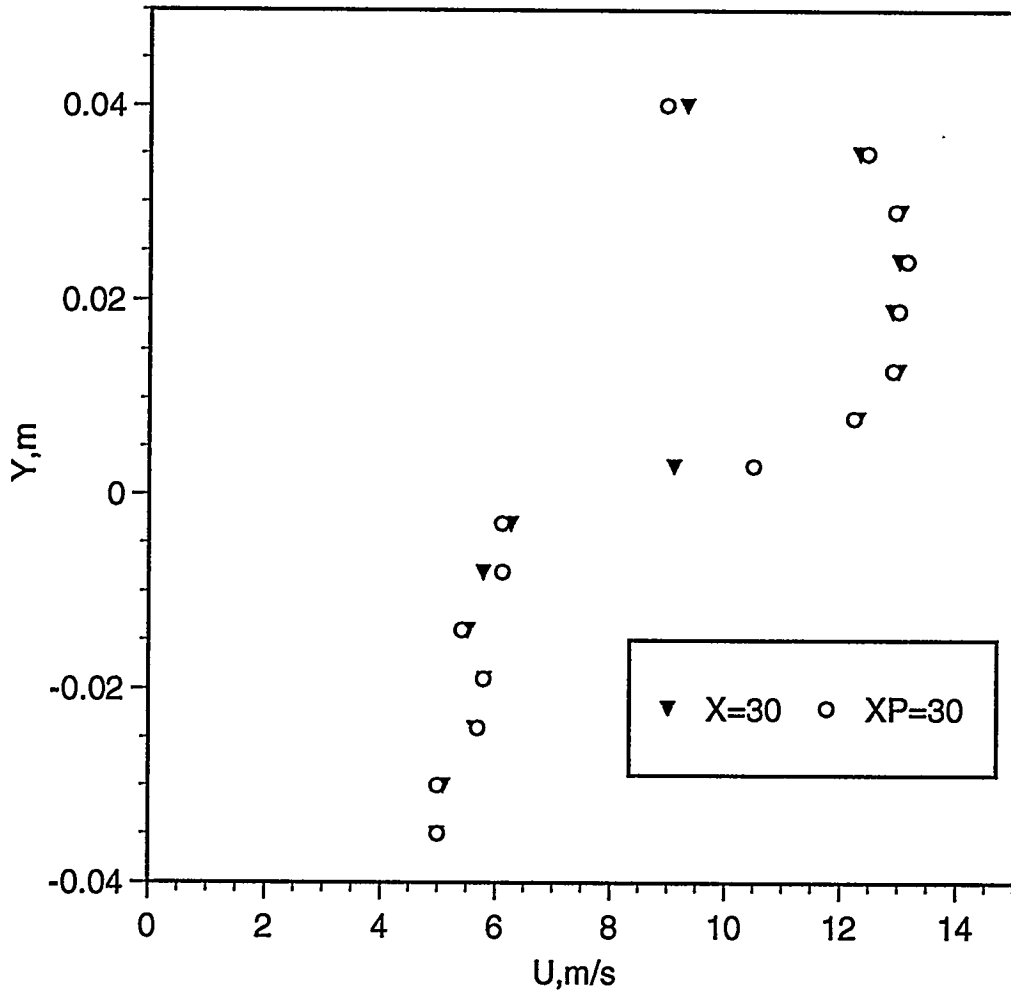


FIG. 2

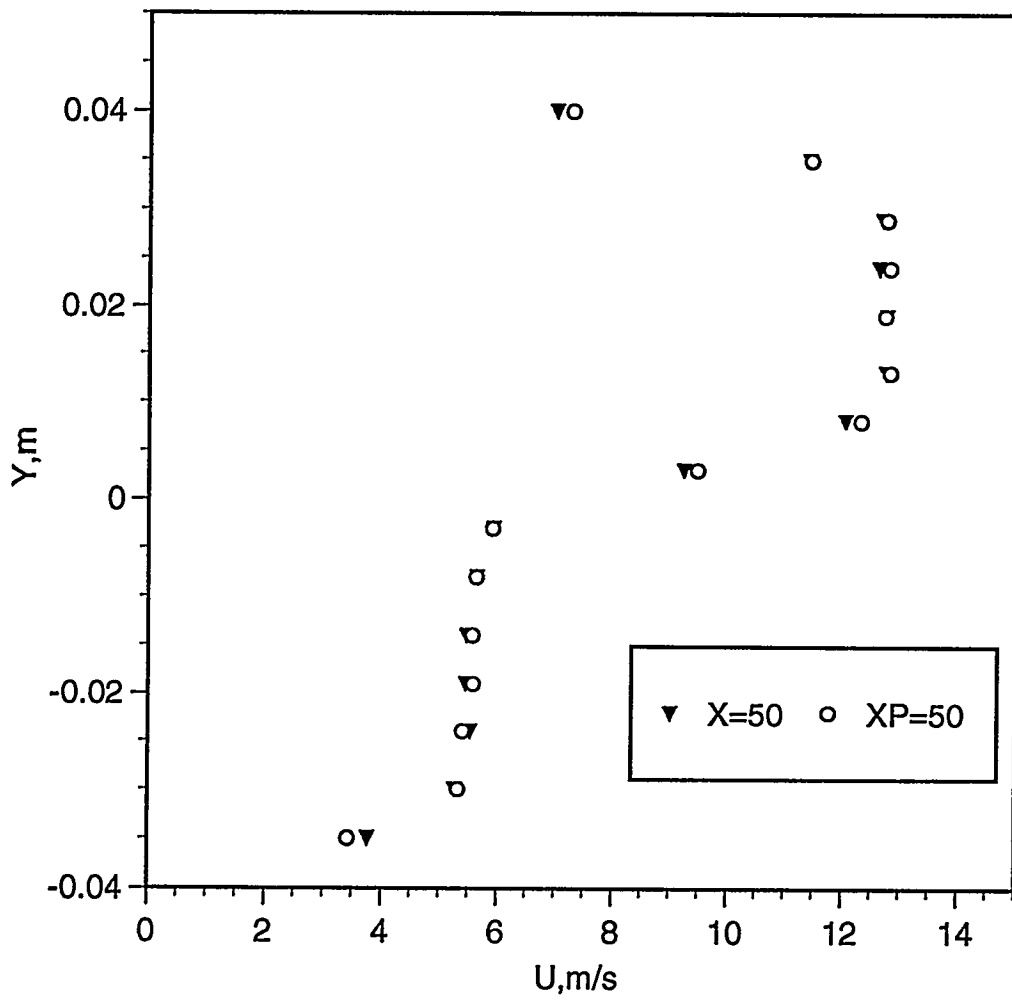


FIG-3

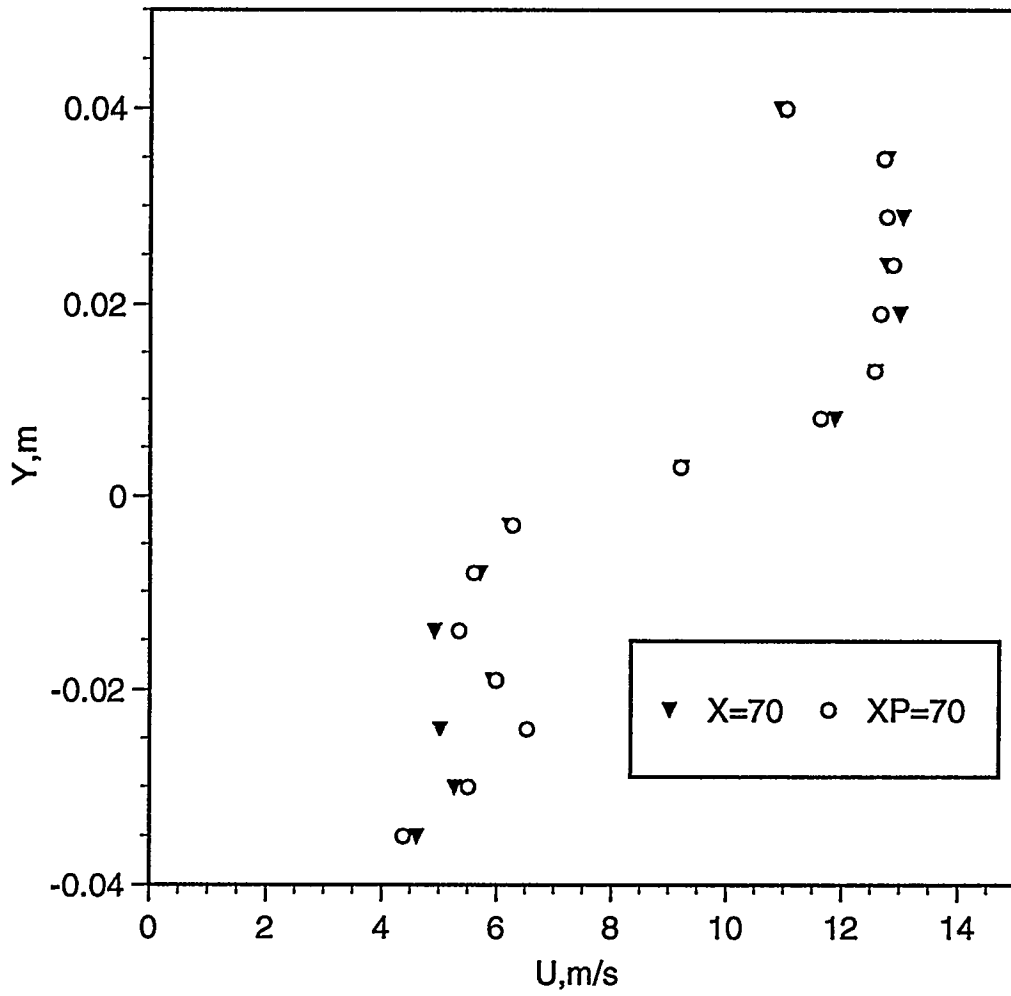


FIG. 4

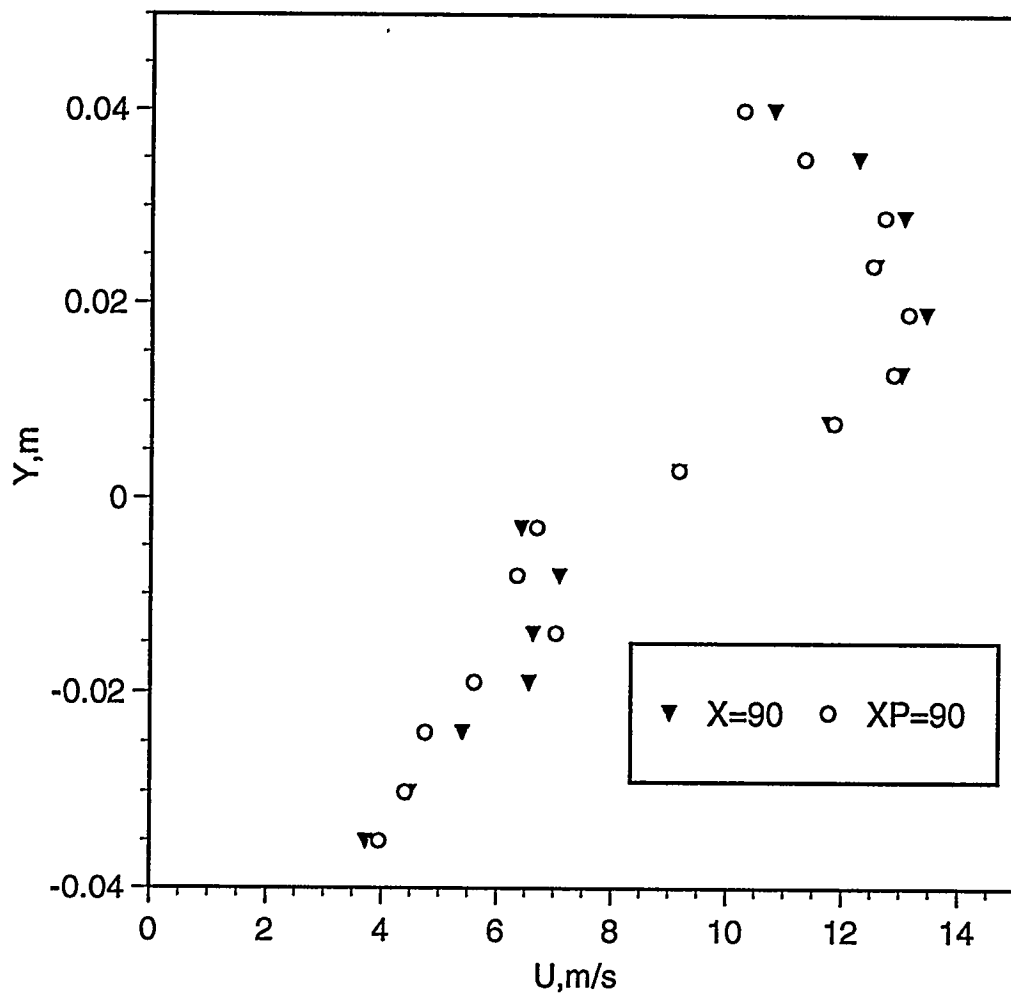


FIG-5

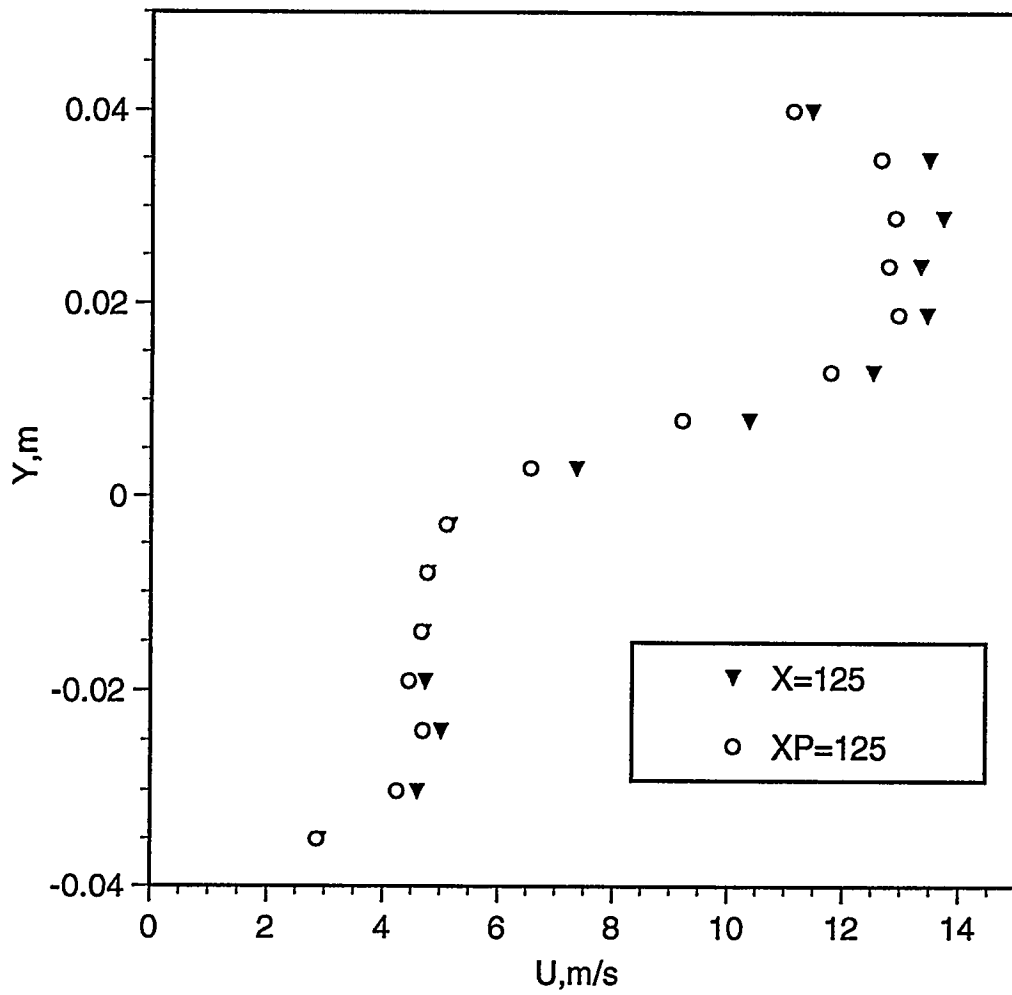


FIG. 6

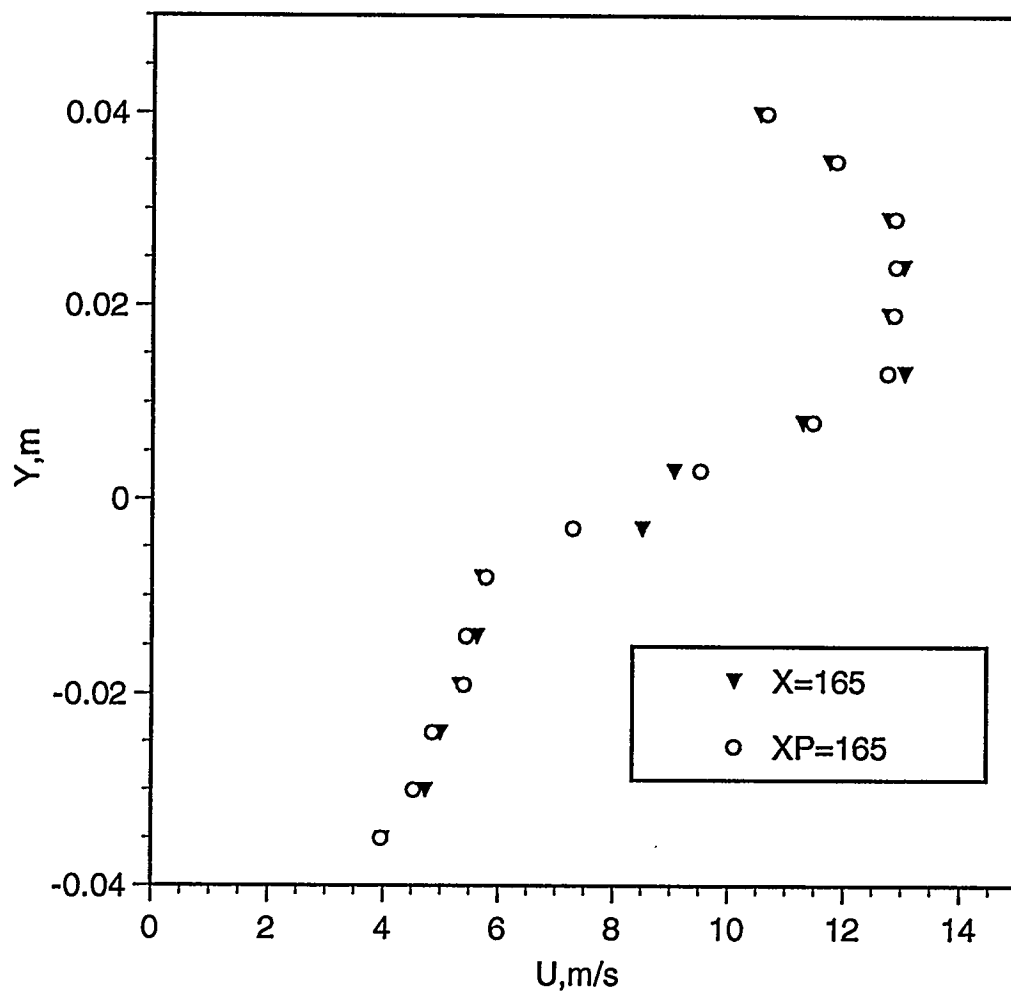


FIG. 7



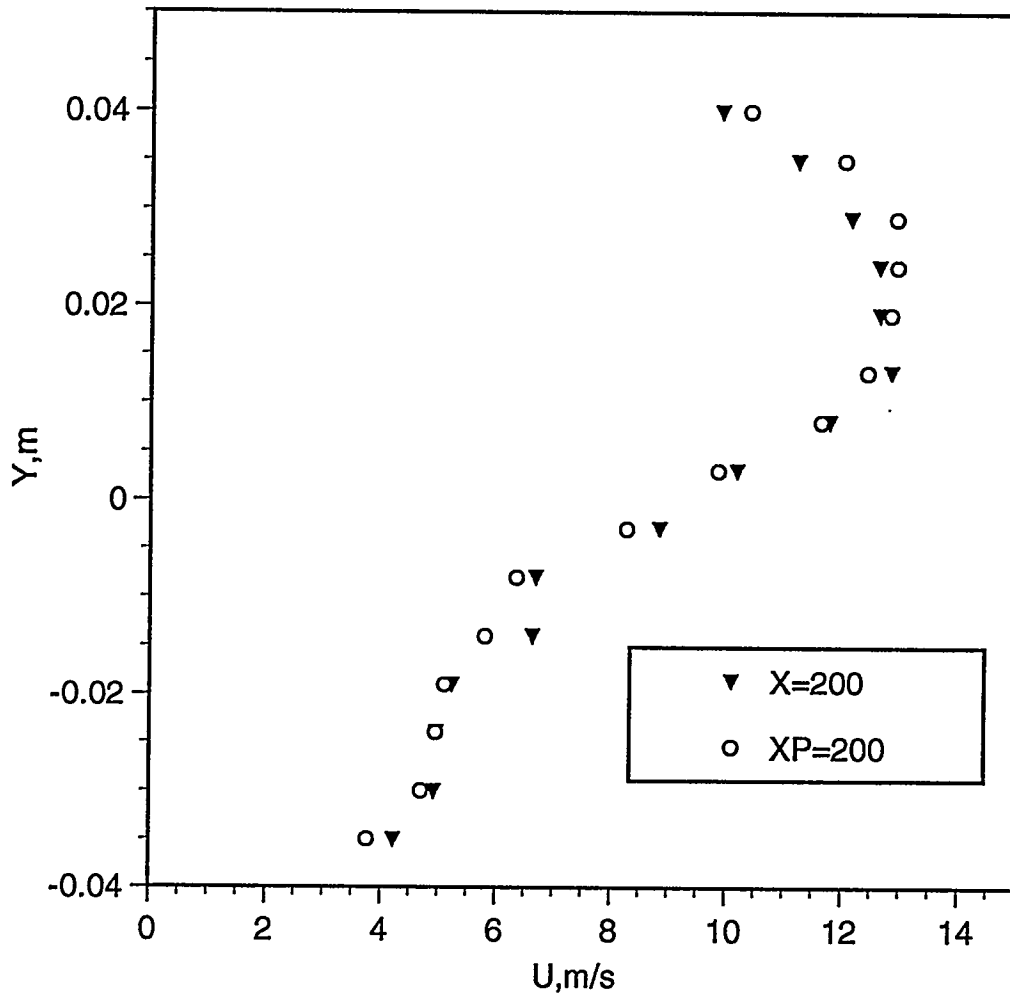


FIG. 8