

Wang M.H., Calabrese R.V., Bakker A. (1995) Effect of Reynolds No. on the Flow Generated by Pitched Blade and High Efficiency Turbines. Presented at Mixing XV, 15th Biennial North American Mixing Conference, June 18-23, 1995, Banff, Canada.

# **Effect of Reynolds No. on the Flow Generated by Pitched Blade and High Efficiency Turbines**

by

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and

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- A Two- Color Laser Doppler Anemometer was used to measure the flow field generated by axial turbines in a fixed frame of reference over a broad Reynolds No. range. ( $7.5 < N_{Re} < 37500$ )

- Impellers Studied

Standard 45°,4-Bladed Pitched Blade Turbine

Chemineer HE-3 Impeller

- Tank Geometry

T = 30 cm

H/T = 1

D/T = 1/3

C/T=1/3

- Working Fluids:

Glycerine  $\longrightarrow$  Water

Glycerine-water Solutions

## **Purpose of Study**

- **Acquire quantitative information on how the impeller discharge flow is affected by fluid viscosity and Reynolds No.**
- **Characterize the transition from axial to radial flow with decreasing Reynolds No**
- **Determine how Reynolds No. affects the bulk circulation patterns in the tank.**
- **Acquire impeller boundary conditions for use in fixed frame CFD predictions.**
- **Acquire currently unavailable Reynolds stress data for fully turbulent conditions.**

## **Scope of Study**

- **Detailed data acquired for PBT-4 impeller.**
- **Limited data acquired for HE-3 impeller for comparison purposes**

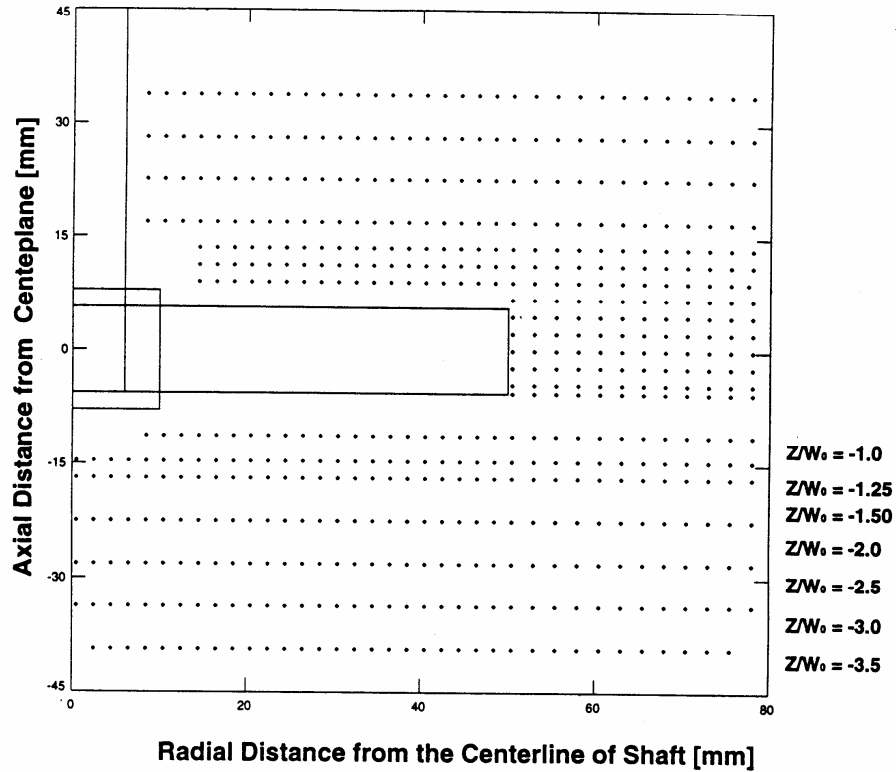
## **Results**

- **Circulation Patterns/Mean Velocity Data**
- **Impeller Discharge Flow**
  - Vector Plots**
  - Pumping Capacity**
  - Direction of Discharge**
  - Swirling No.**
  - Impeller Bounadry Conditions**
- **Turbulent Flow**
  - Mean and RMS Turbulent Velocity**
  - Reynolds Stress**
- **Details of Data Set Employed in Paper 10.3**  
**"Sliding Mesh Simulation of the Flow Patterns**  
**of Axial Pumping Impeller at Low & Intermediate**  
**Reynolds No." by A. Bakker (Chemineer),R.D. LaRoche**  
**(Cray),M.H. Wang & R.V. Calabrese (Maryland)**
- **Preliminary Analysis of Work to be Presented at the**  
**First International Symposium on Mixing in Industrial**  
**Processes, Quebec (15-18 October 1995)**

## Summary and Conclusions

- At low Reynolds No. the PBT-4 and HE-3 impellers behave like radial turbines with inflow from both above and below the impeller centerplane. There is a strong upper circulation loop and a weaker lower circulation loop.
- Vector plots around the impeller periphery show a smooth transition from radial to axial flow as the Reynolds No. increases. The radius of the upward or reversed flow region below the impeller also decreases. There is a smooth transition in the discharge angle. However, there is an abrupt transition ( $N_{Re} \cong 80$ ) in the magnitude of the velocity below the blade tip.
- At lower Reynolds No., the impeller discharge is a radial swirling flow, while at higher  $N_{Re}$  it is an axial swirling flow. A single definition of the Swirling No. may not be appropriate.
- The PBT-4 and HE-3 impellers show similar behavior with Reynolds No. For  $N_{Re} < 40$  both have equal pumping capacity. However, as  $N_{Re}$  increases the Flow No. for the PBT-4 becomes larger than that for the HE-3.
- For turbulent flow of a PBT-4, the three components of RMS turbulent velocity are of similar magnitude and extent. The radial-axial Reynolds stress shows a sinusoidal behavior with radial distance from the tank axis. The tangential- axial Reynolds stress shows a similar trend but is of lower magnitude.

### LDA Sampling Grid



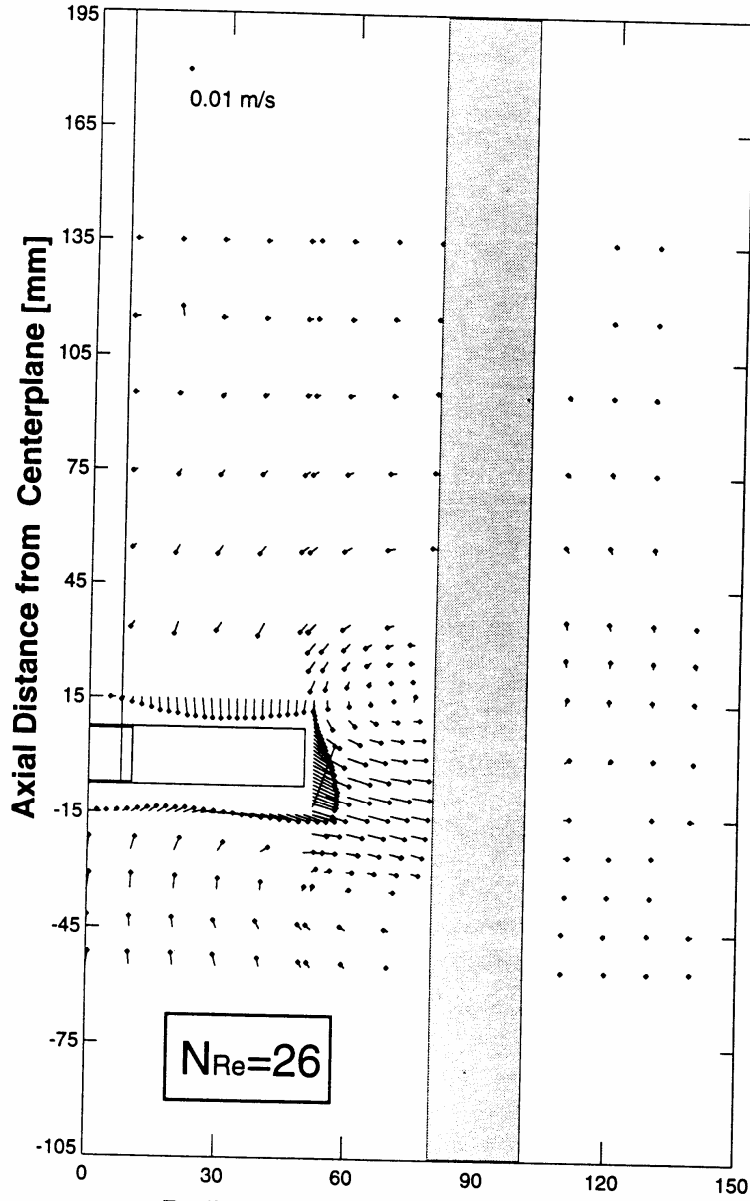
**PBT-4 and HE-3 : Data Acquired on Boundaries of Impeller Swept Volume**

**PBT-4 : Data also Acquired within Bulk of Tank for Selected Reynolds No.**

**Laminar and Intermediate Flow: only Mean Velocity Data Analysed**

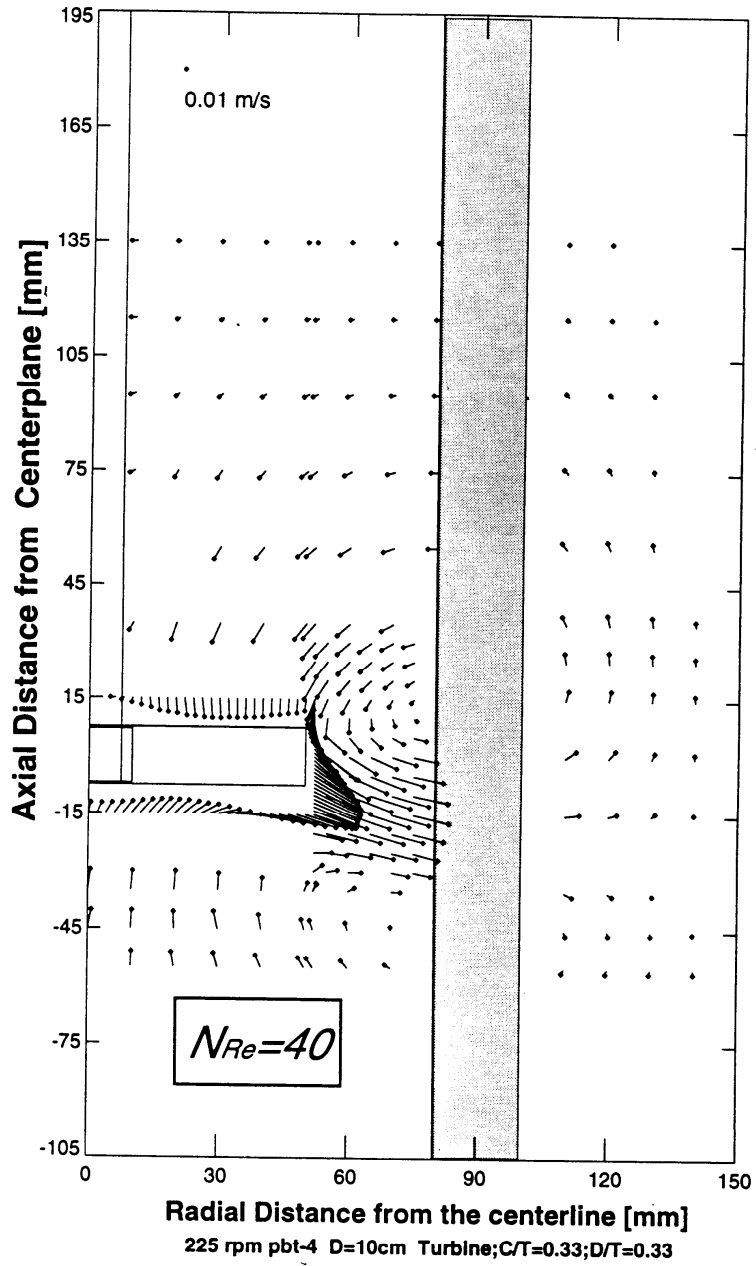
**Turbulent Flow : Turbulent RMS Velocity and Reynolds Stress Data also Analysed**

# Mean Velocity Vector Plot

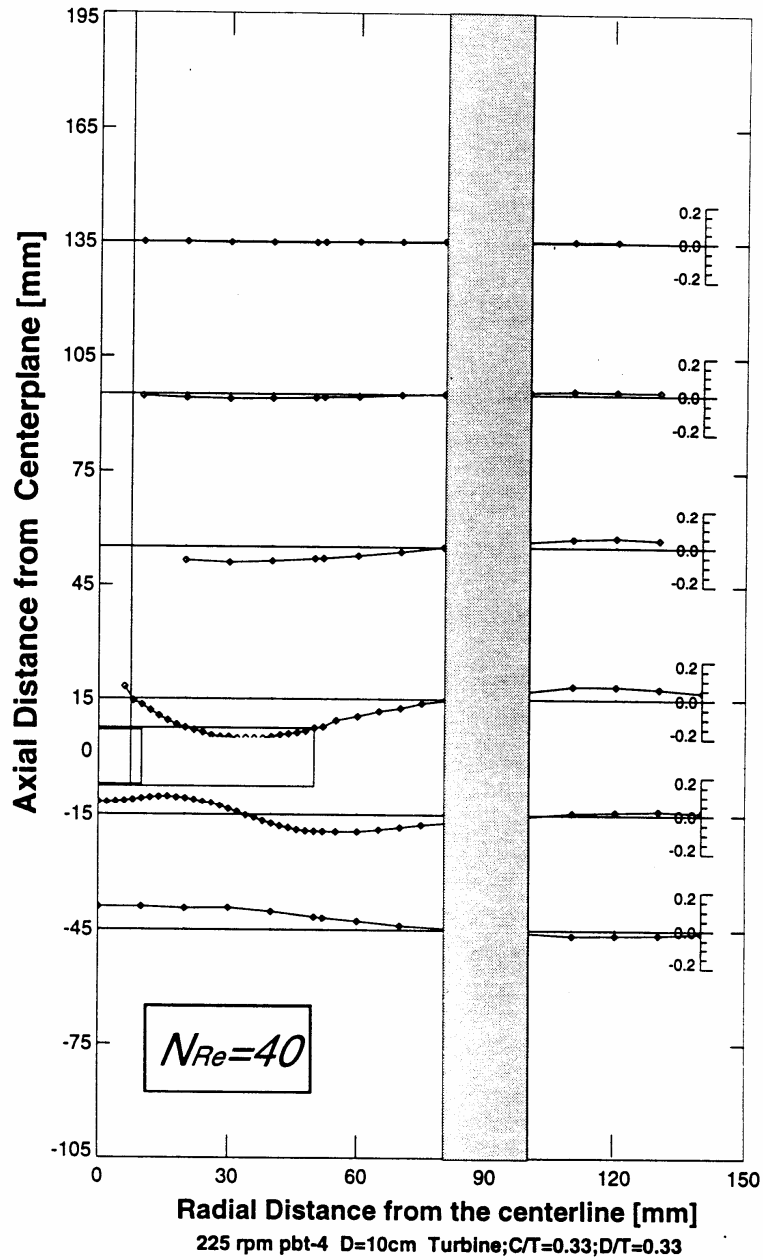


225 rpm pbt-4 D=10cm Turbine; C/T=0.33; D/T=0.33

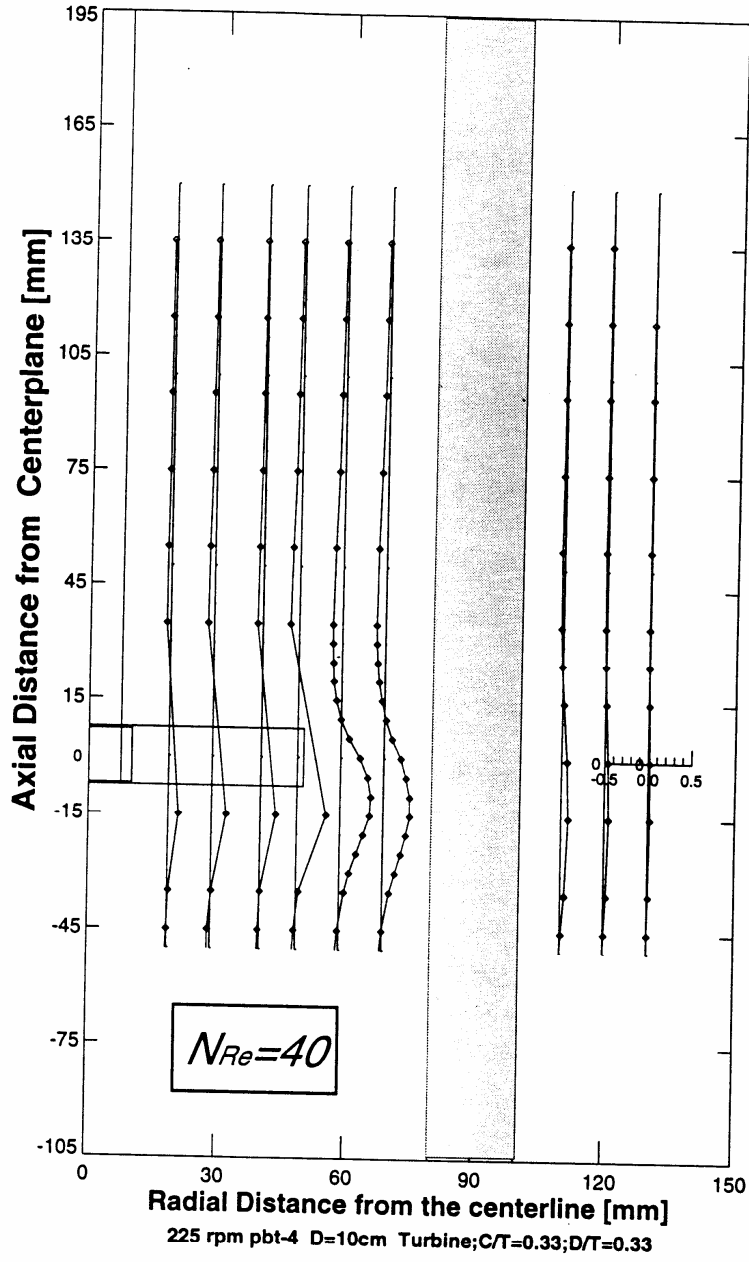
### Mean Velocity Vector Plot



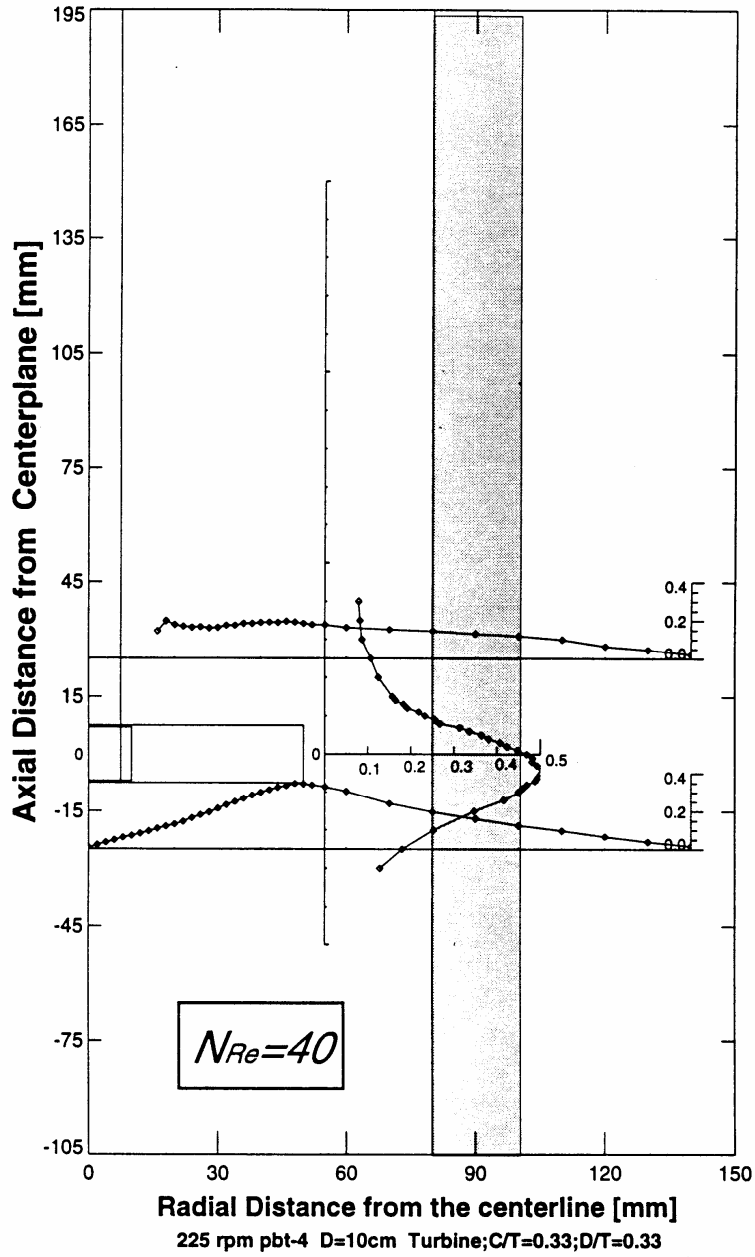
### Mean Axial Velocity (m/s)



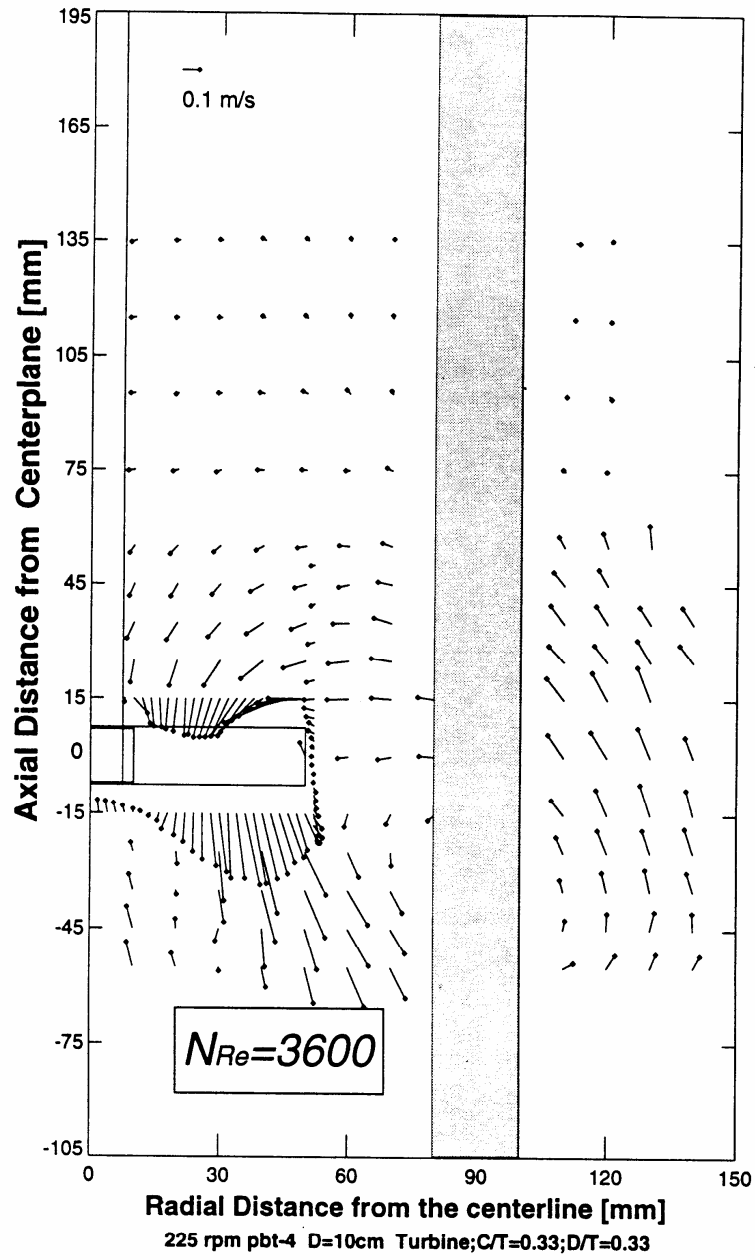
### Mean Radial Velocity (m/s)



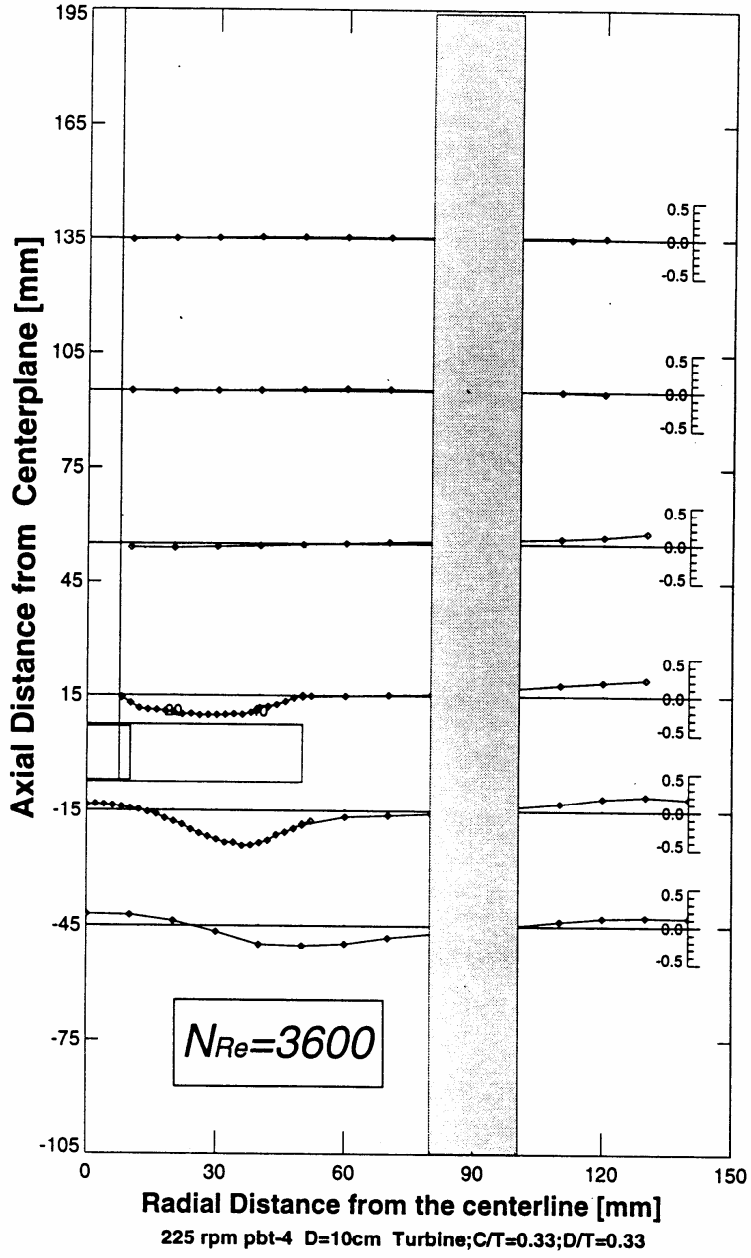
### Mean Tangential Velocity (m/s)



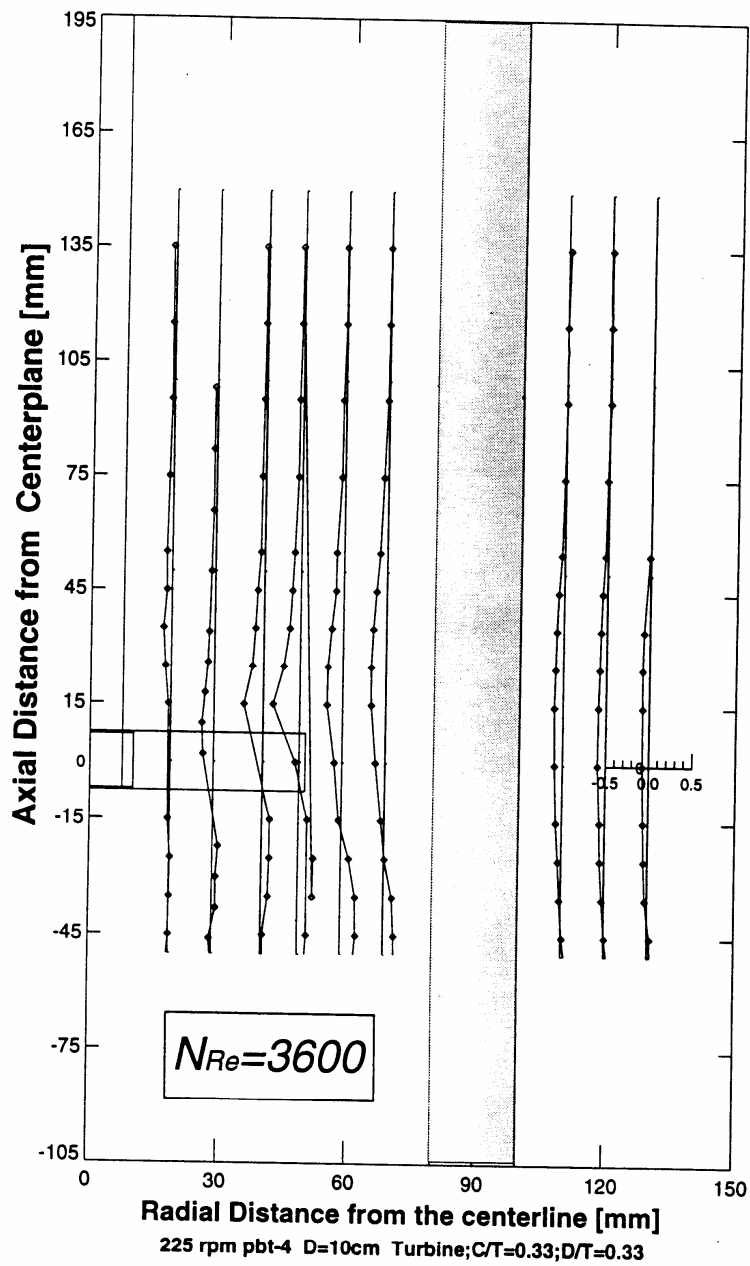
### Mean Velocity Vector Plot



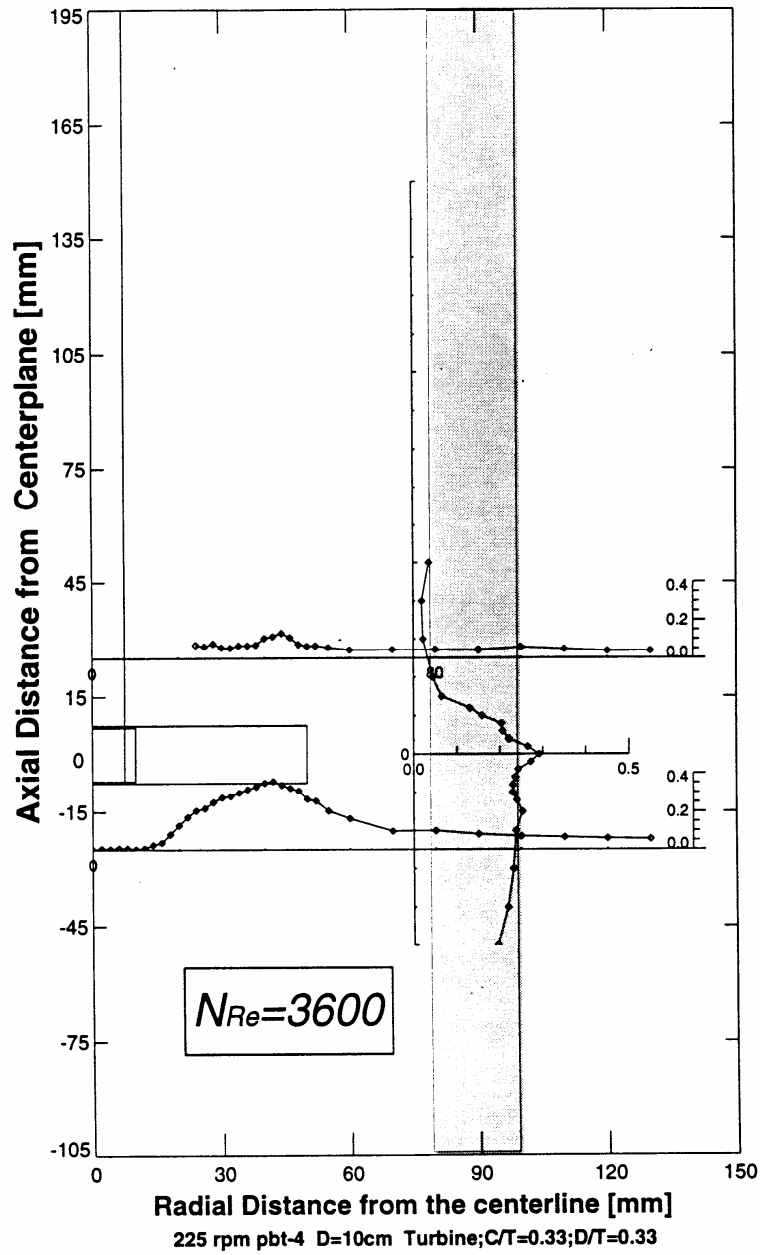
### Mean Axial Velocity (m/s)

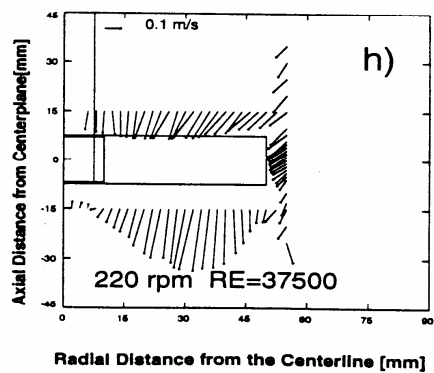
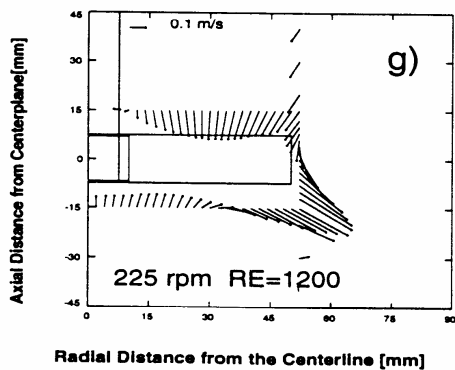
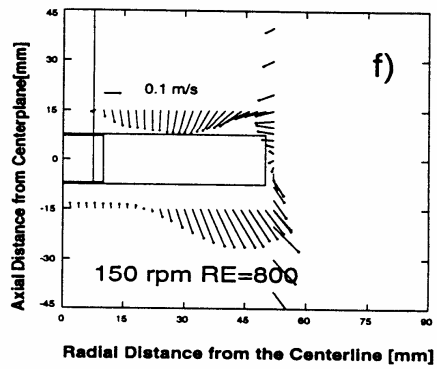
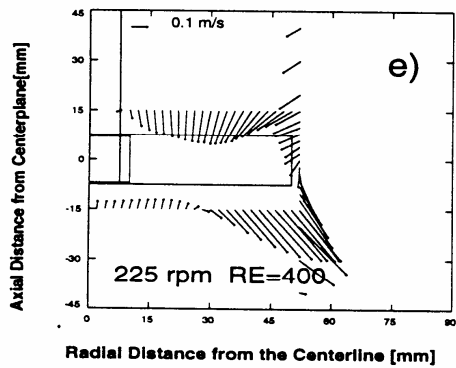
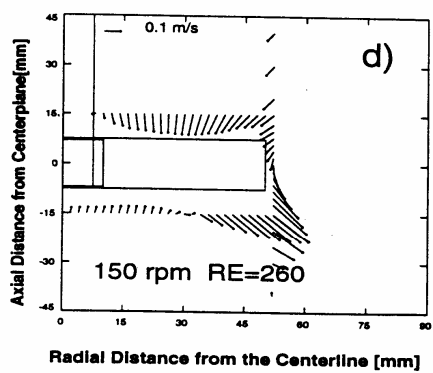
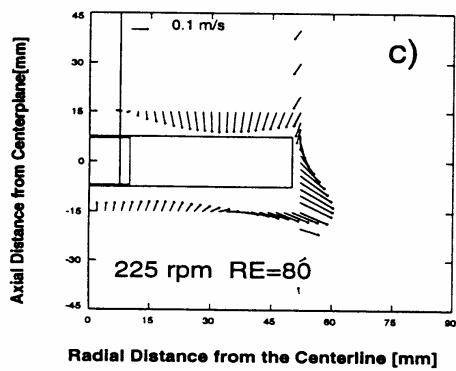
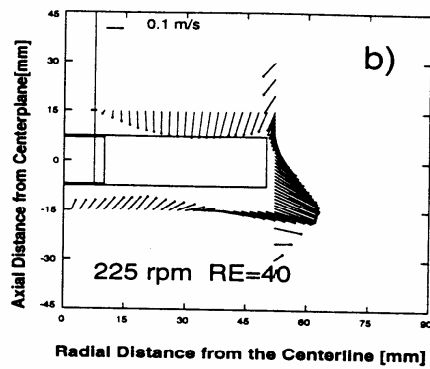
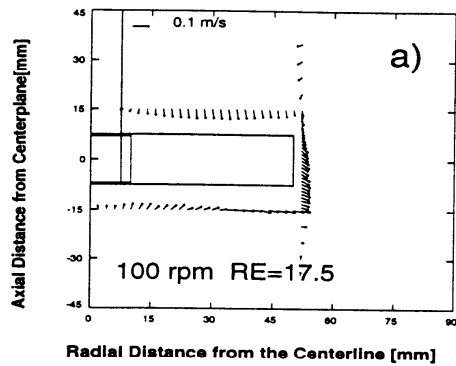


### Mean Radial Velocity (m/s)

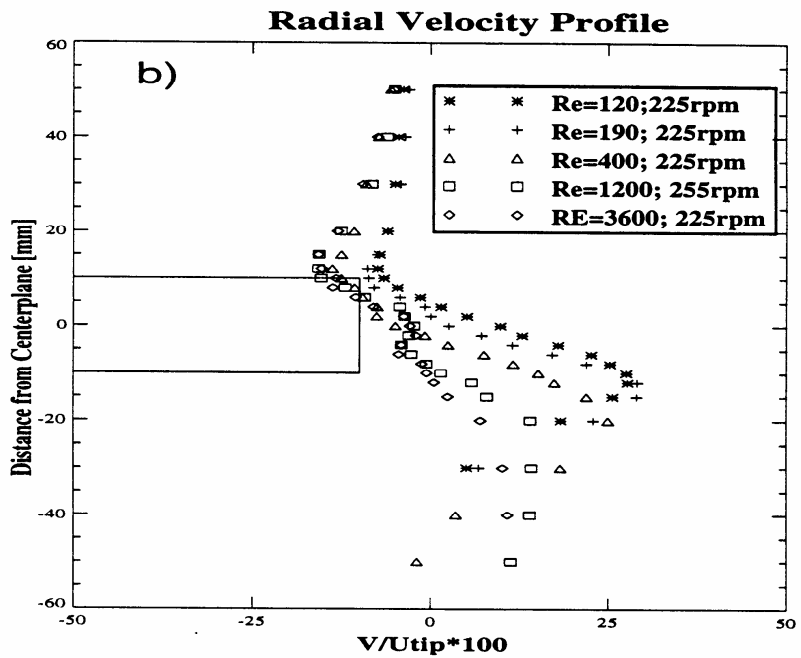
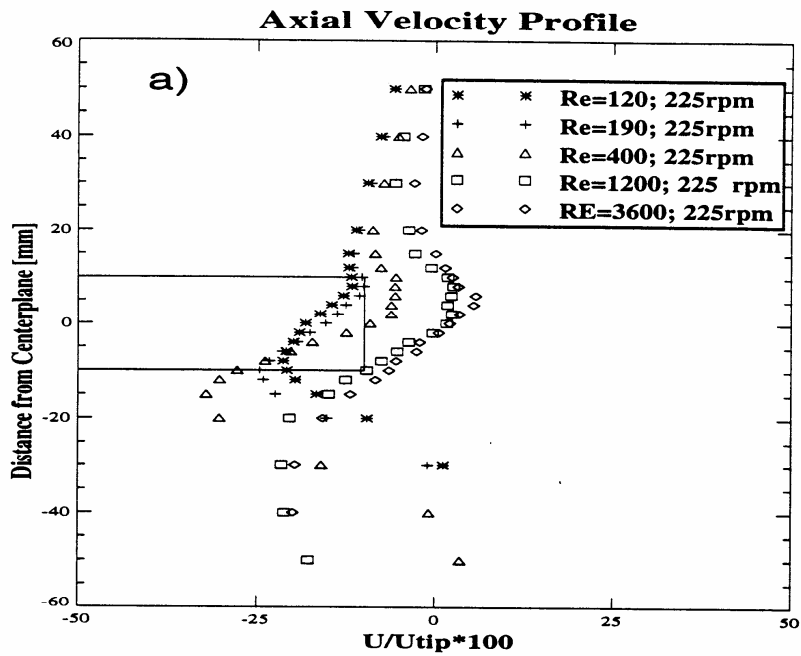


### Mean Tangential Velocity (m/s)





**Variation of Impeller Discharge Flow Pattern with Reynolds Number**

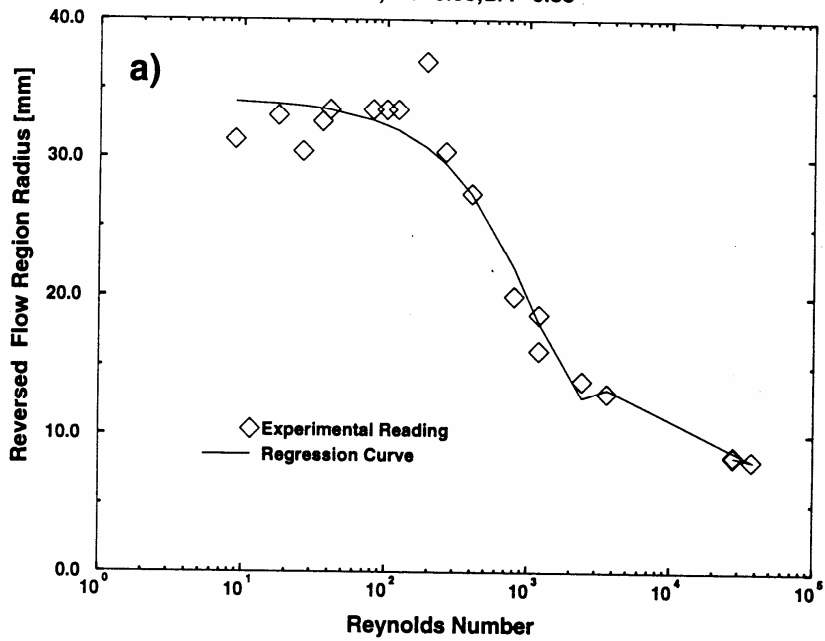


**Variation of Mean Velocity in Vertical Plane at Blade Tip  
with Reynolds Number for PBT-4  
C/T=0.33;D/T=0.33**

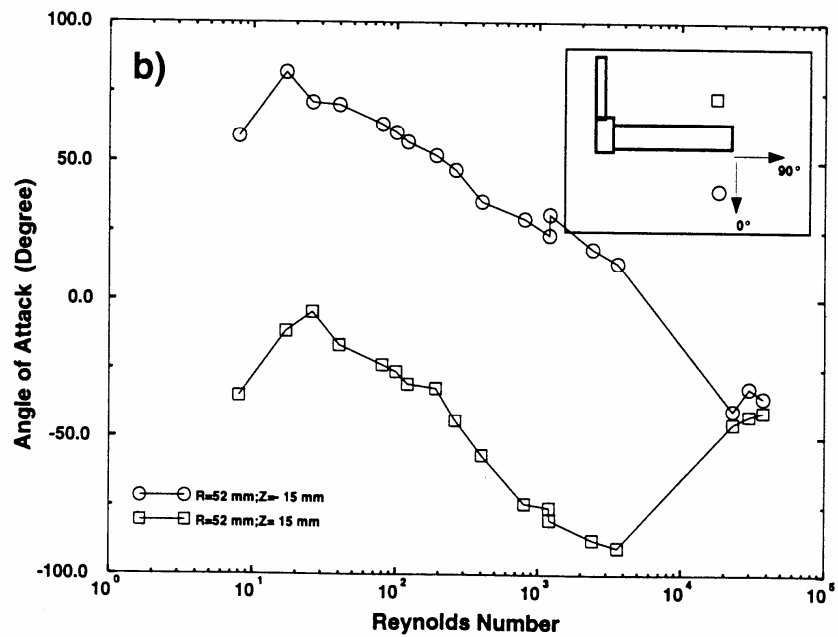
# Characterization of the Impeller Discharge Flow

Radius of Reversed (Upward) Flow Region on Lower Surface of Impeller

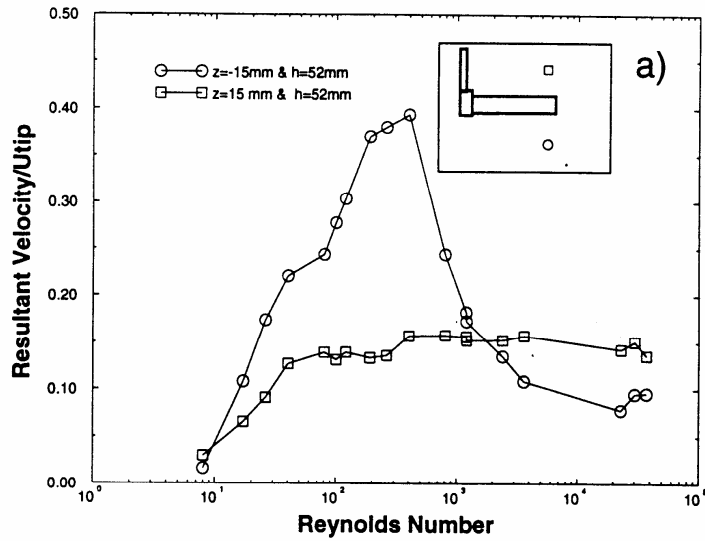
PBT-4; C/T=0.33; D/T=0.33



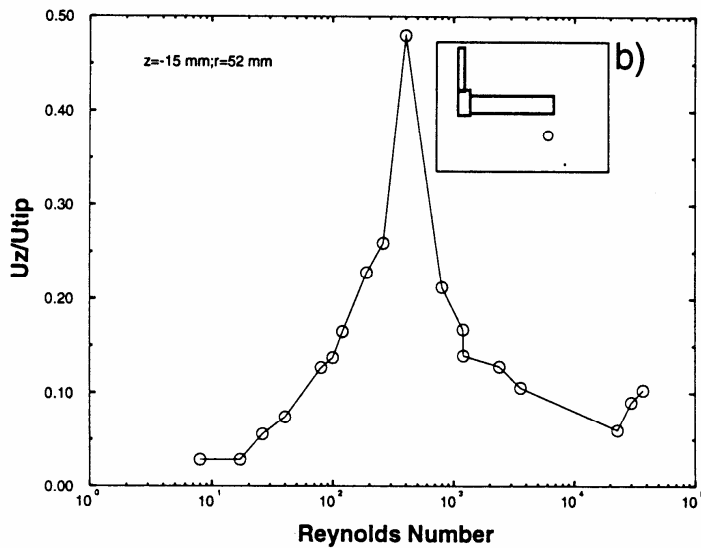
## The Evolution of Angle of Attack



### Variation of Resultant Velocity with Reynolds Number



### Variation of Axial Velocity with Reynolds Number

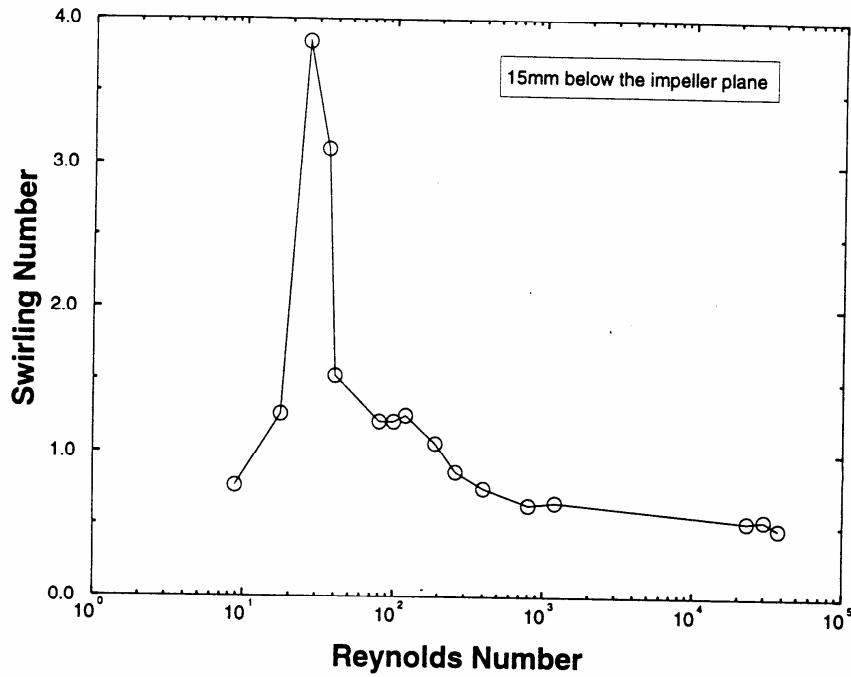


### Determination of Transition Point of Circulation Flow By Inspecting Velocity Variation at Certain Location

PBT-4; C/T=0.33; D/T=0.33

# Axial Swirling Number Vs Reynolds Number

$C/T=0.33, D/T=0.33$ , PBT -4



**Axial Swirling Number:**

$$N_s = \frac{\int_0^{D/2} U W r^2 dr}{\frac{1}{2} D \int_0^{D/2} U^2 r dr}$$

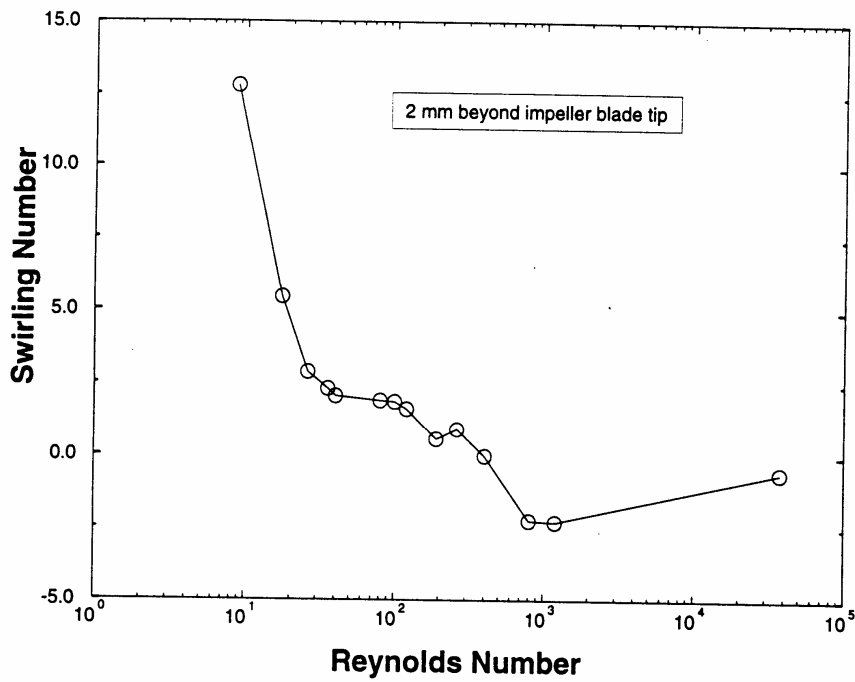
U = Mean Axial Velocity [m/s]

W = Mean Tangential Velocity [m/s]

**Integrate horizontally below blade from  
centerline to blade tip**

# Radial Swirling Number Vs Reynolds Number

$C/T=0.33, D/T=0.33$ , PBT -4



**Radial Swirling Number:**

$$N_s = \frac{\int_{B^-}^{B^+} W V R^2 dz}{D \int_{B^-}^{B^+} V^2 R dz}$$

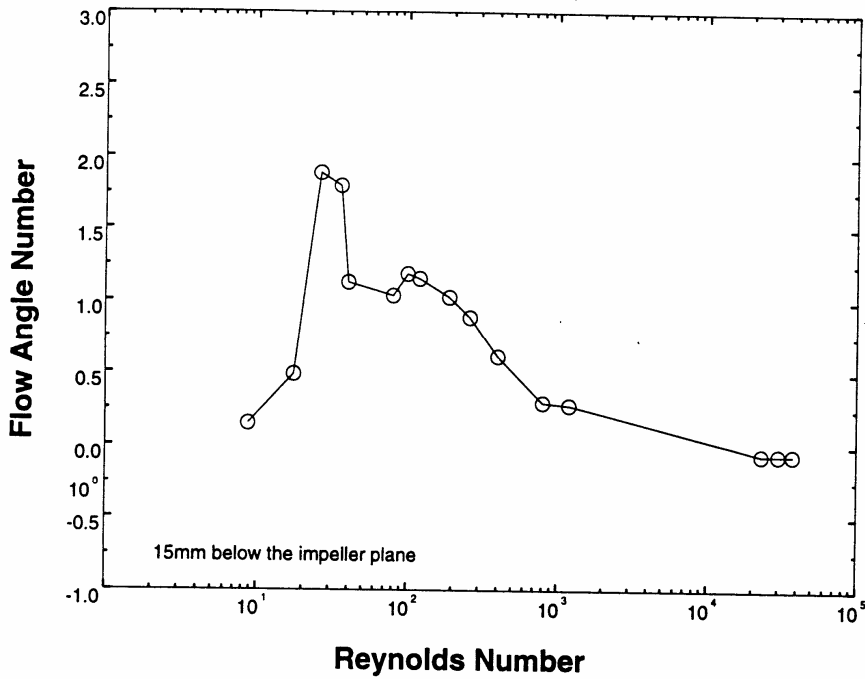
$V$  = Mean Radial Velocity [m/s]

$W$  = Mean Tangential Velocity [m/s]

**Integrate vertically from top to bottom of blade**

# Axial Flow Angle Number Vs Reynolds Number

$C/T=0.33, D/T=0.33, \text{PBT -4}$



**Flow Angle Number:**

$$N_A = \frac{\int_0^{D/2} U V r^2 dr}{1/2 D \int_0^{D/2} U^2 r dr}$$

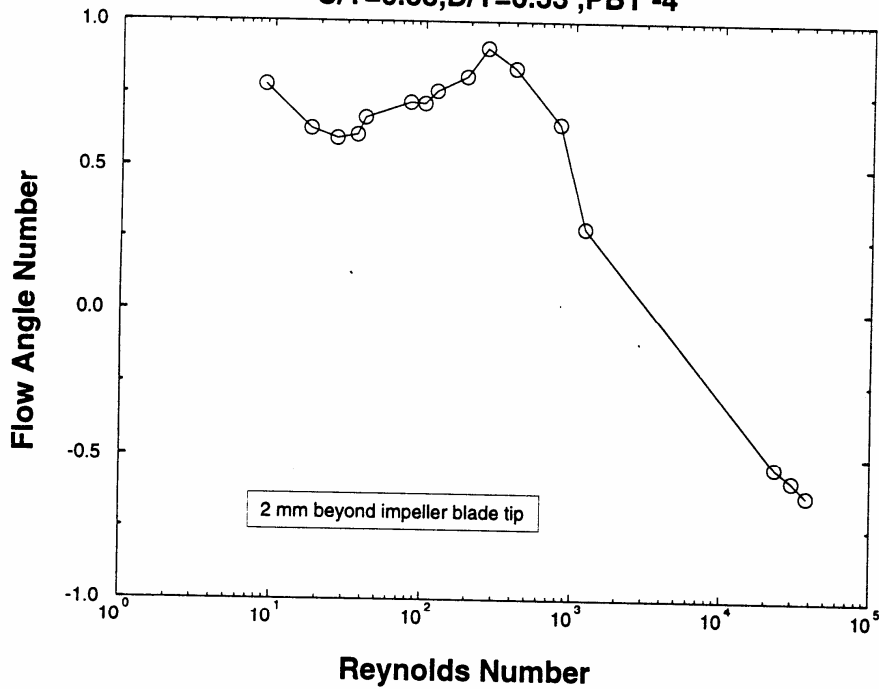
U = Mean Axial Velocity [m/s]

V = Mean Radial Velocity [m/s]

**Integrate horizontally below blade from centerline to blade tip**

# Radial Flow Angle Number Vs Reynolds Number

C/T=0.33,D/T=0.33 ,PBT -4



## Radial Flow Angle Number:

$$N_A = \frac{\int_{B^-}^{B^+} U V R^2 dz}{D \int_{B^-}^{B^+} V^2 R dz}$$

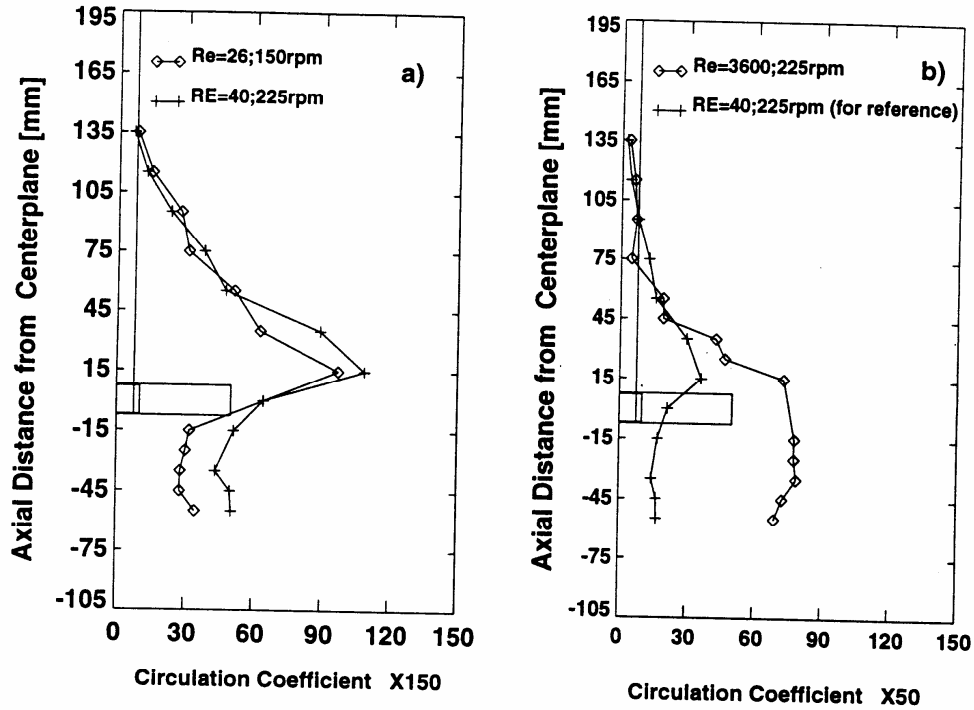
U = Mean Axial Velocity [m/s]

V = Mean Radial Velocity [m/s]

**Integrate vertically from top to bottom of blade**

## Axial Circulation Coefficient Profiles

pbt-4 D=10 cm Turbine; C/T=0.33; D/T=0.33



**Circulation Capacity:**

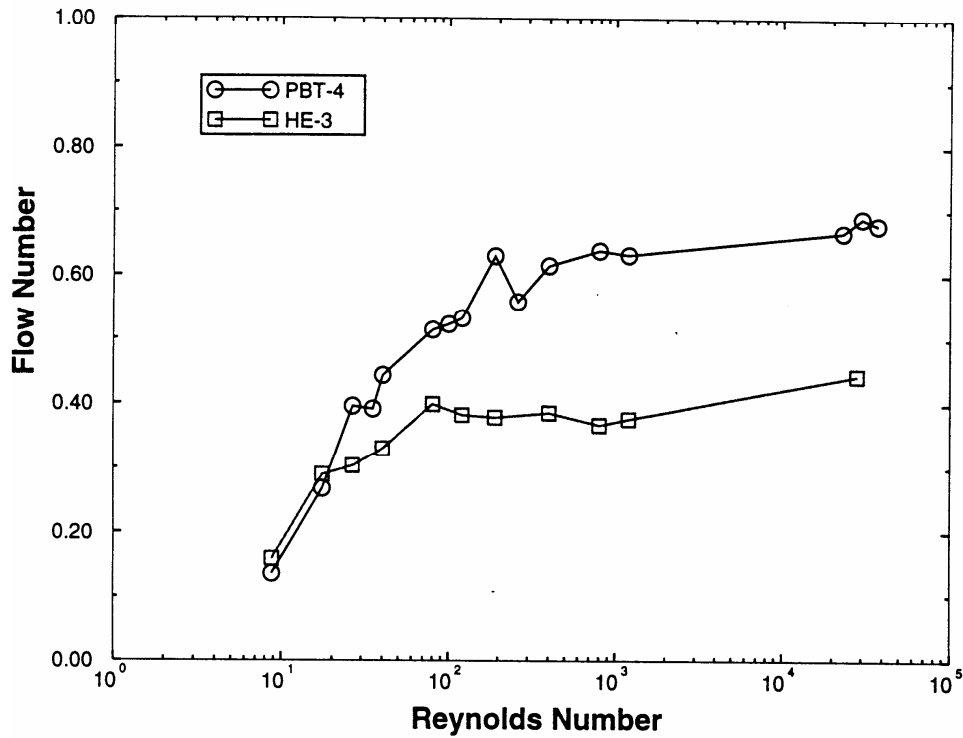
$$Q_c(z) = \int_j 2 \pi r U(r,z) dr$$

**Circulation Coefficient:**

$$N_{Ac} = \frac{Q_c(z)}{N D^3}$$

# Flow Number Vs Reynolds Number

C/T=0.33,D/T=0.33,PBT-4 & HE-3

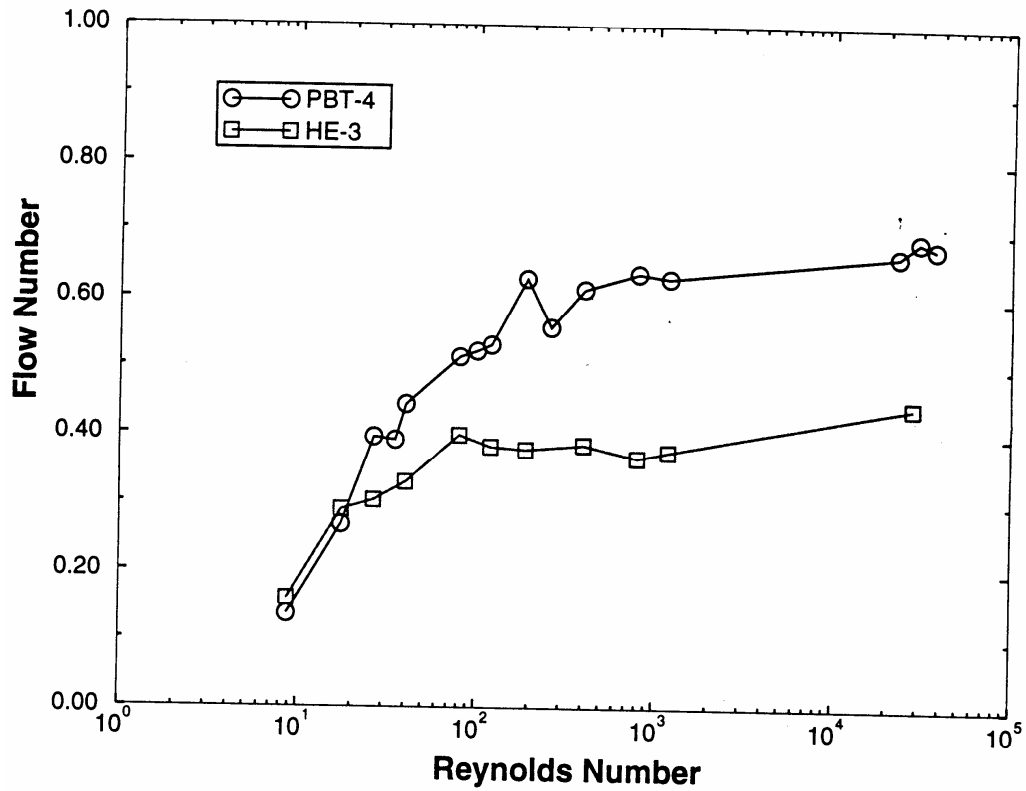


**Flow Capacity:  $Fq = 1/2(\text{Flow}_{in} + \text{Flow}_{out})$**

**Flow Number:  $Flp = \frac{Fq}{ND^3}$**

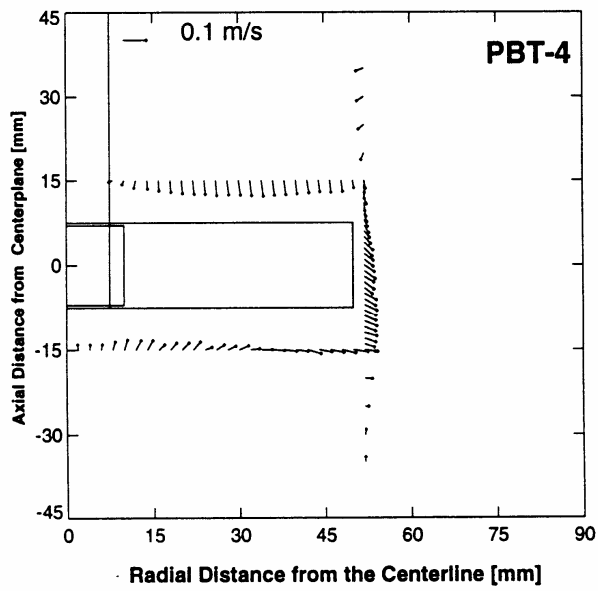
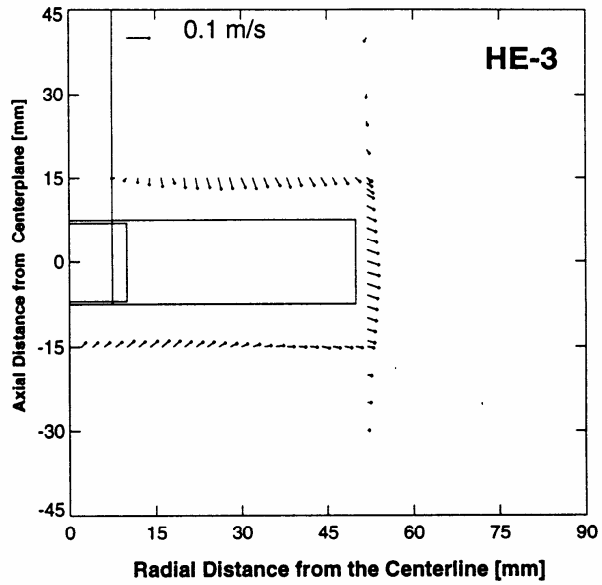
# Flow Number Vs Reynolds Number

C/T=0.33,D/T=0.33,PBT-4 & HE-3



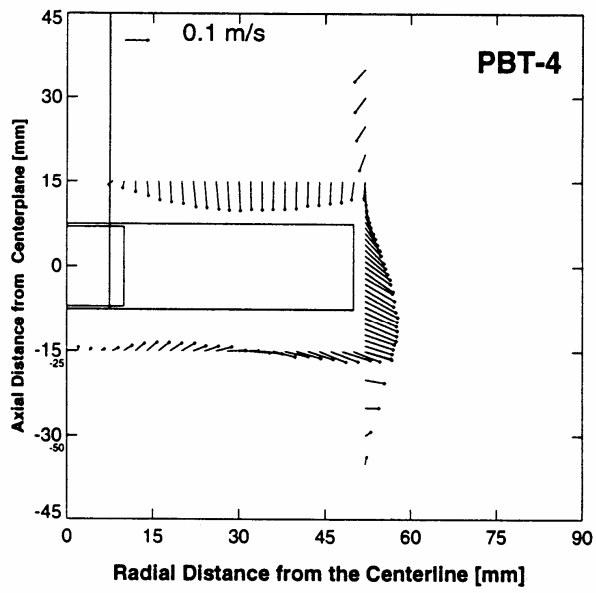
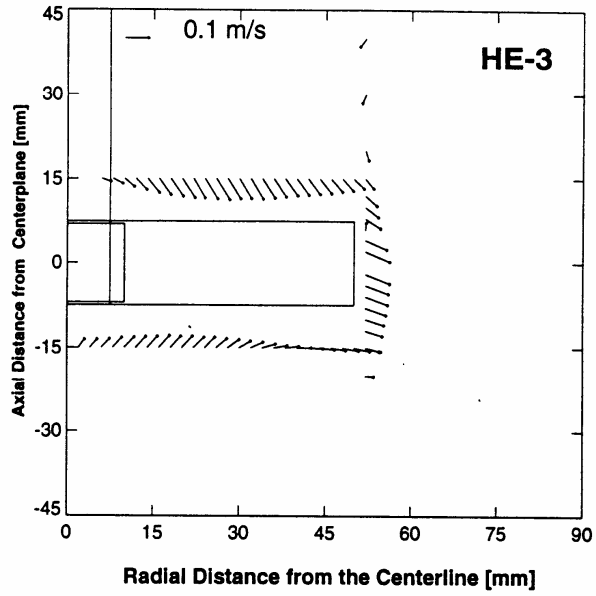
Flow Capacity:  $Fq = 1/2 (\text{Flow in} + \text{Flow out})$

$$\text{Flow Number : } Fl_p = \frac{Fq}{ND^3}$$



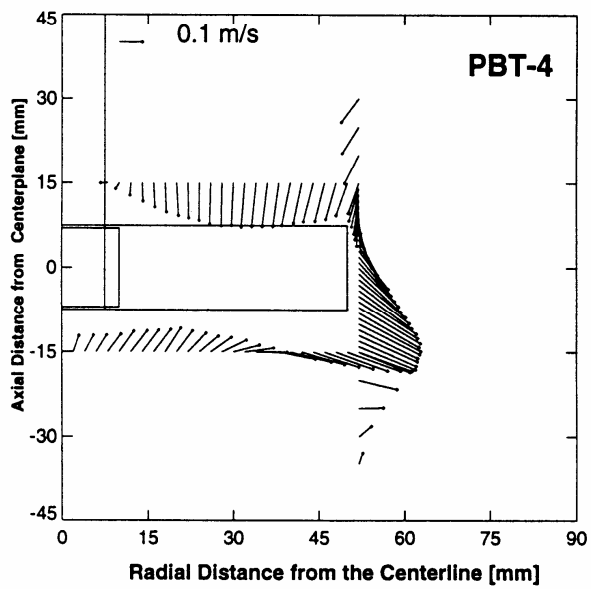
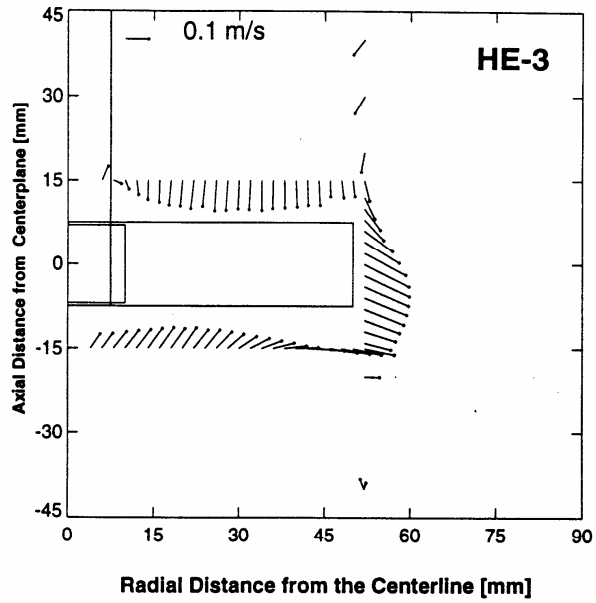
### Flow Field Around an Impeller Blade ( $N_{Re}=17.5$ )

100 rpm  $D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$



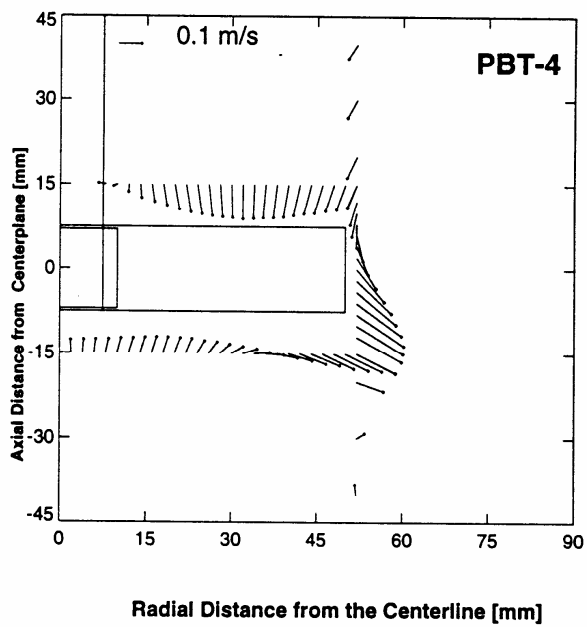
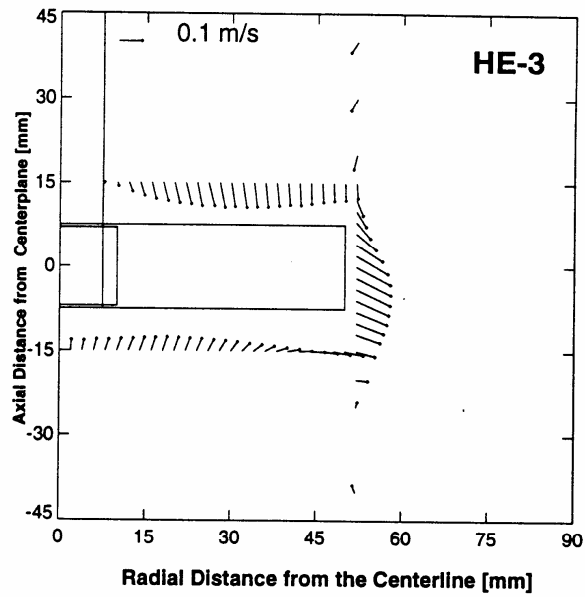
## Flow Field Around an Impeller Blade ( $N_{Re}=26$ )

150 rpm  $D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$



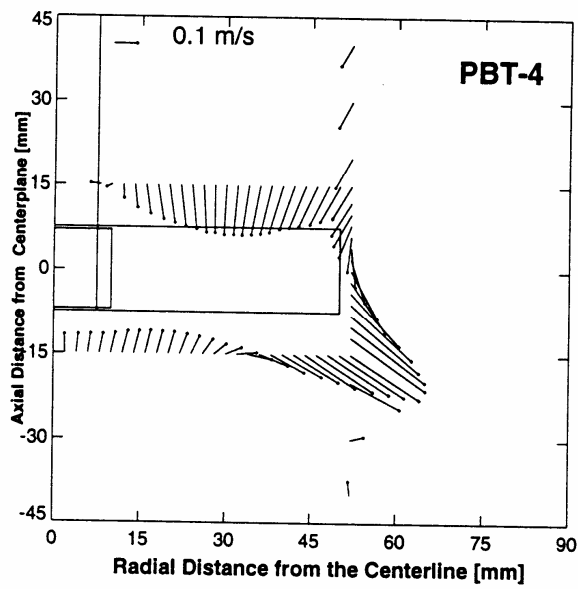
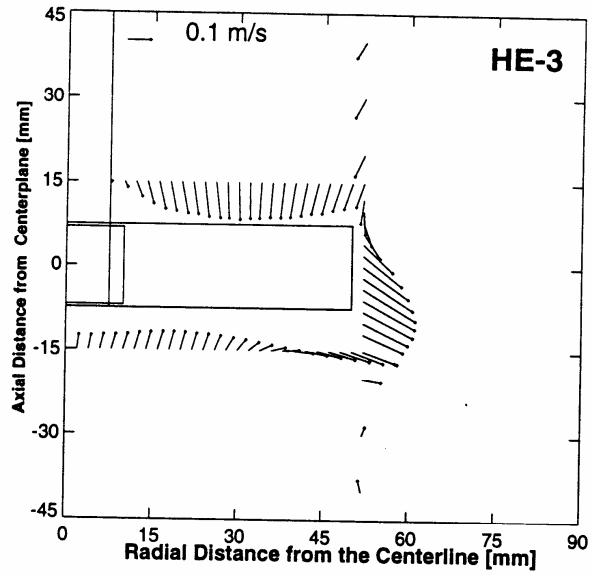
## Flow Field Around an Impeller Blade ( $N_{Re}=40$ )

225 rpm  $D=10\text{cm}$  ;  $C/T=0.33$  ;  $D/T=0.33$

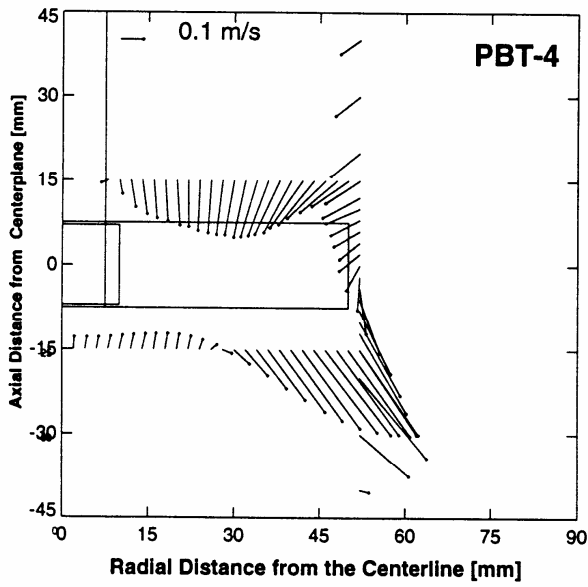
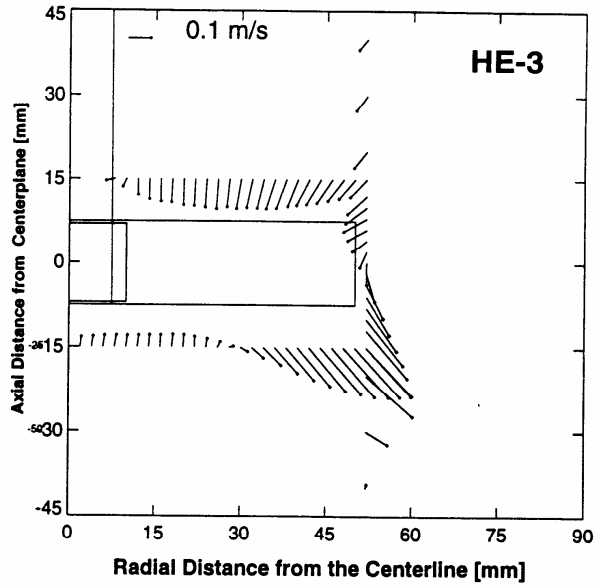


## Flow Field Around an Impeller Blade ( $N_{Re}=80$ )

150 rpm  $D=10\text{cm}$  ;  $C/T=0.33$  ;  $D/T=0.33$

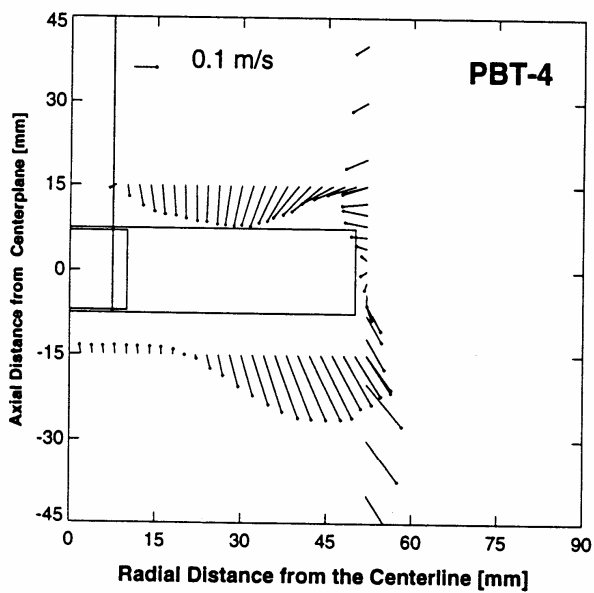
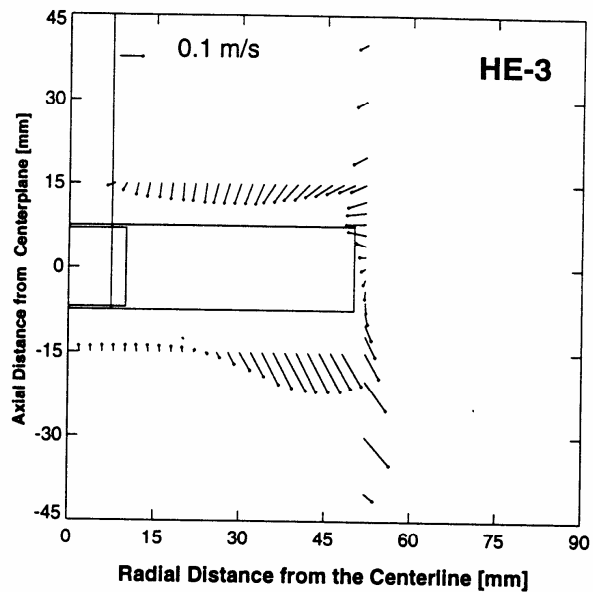


**Flow Field Around an Impeller Blade ( $N_{Re}=120$ )**  
 225 rpm  $D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$



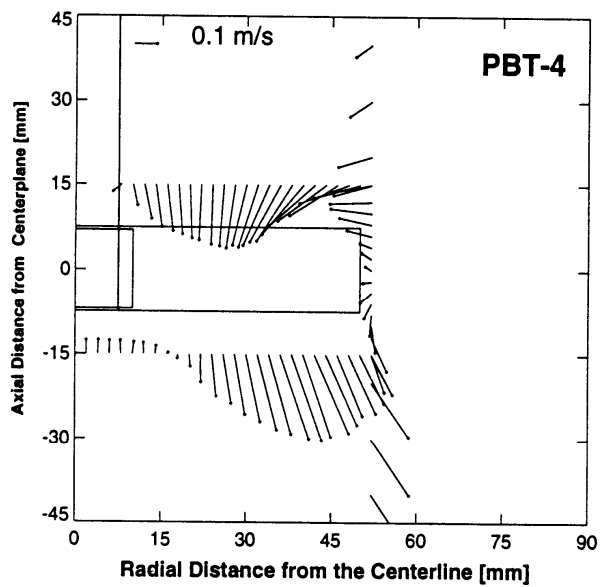
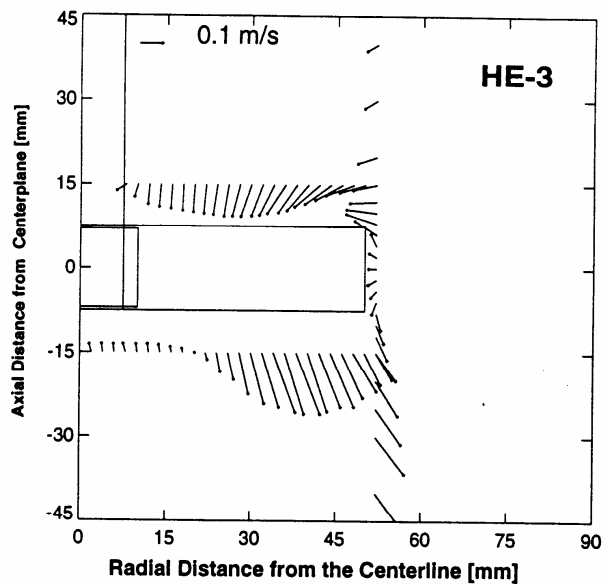
### Flow Field Around an Impeller Blade ( $N_{Re}=400$ )

225 rpm  $D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$



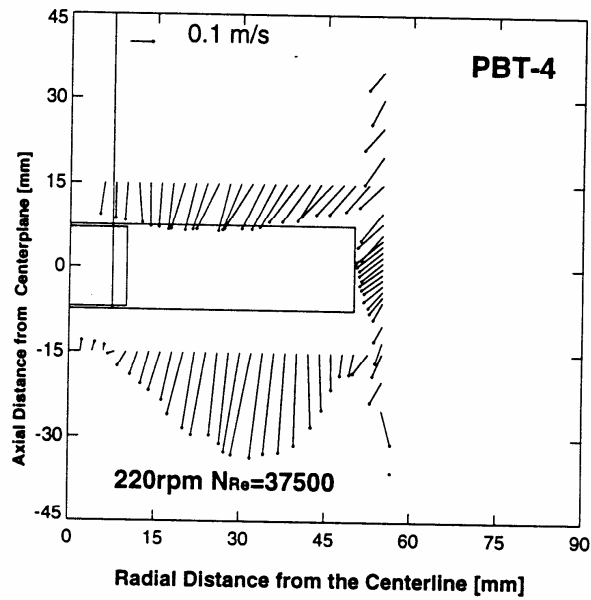
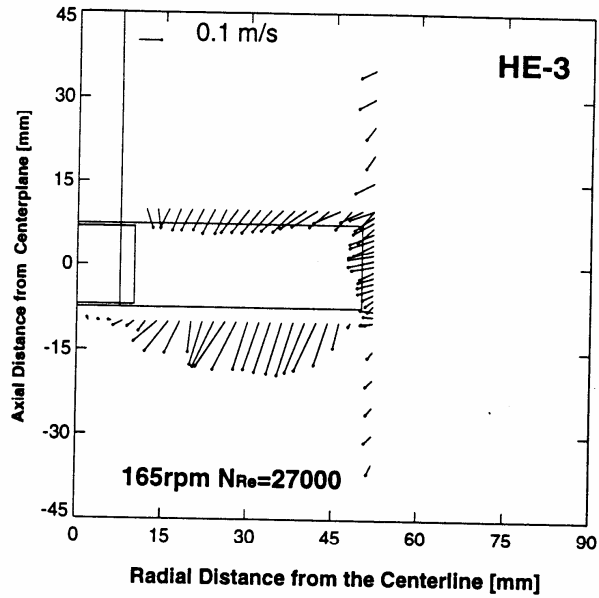
### Flow Field Around an Impeller Blade ( $N_{Re}=800$ )

150 rpm  $D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$



### Flow Field Around an Impeller Blade ( $N_{Re}=1200$ )

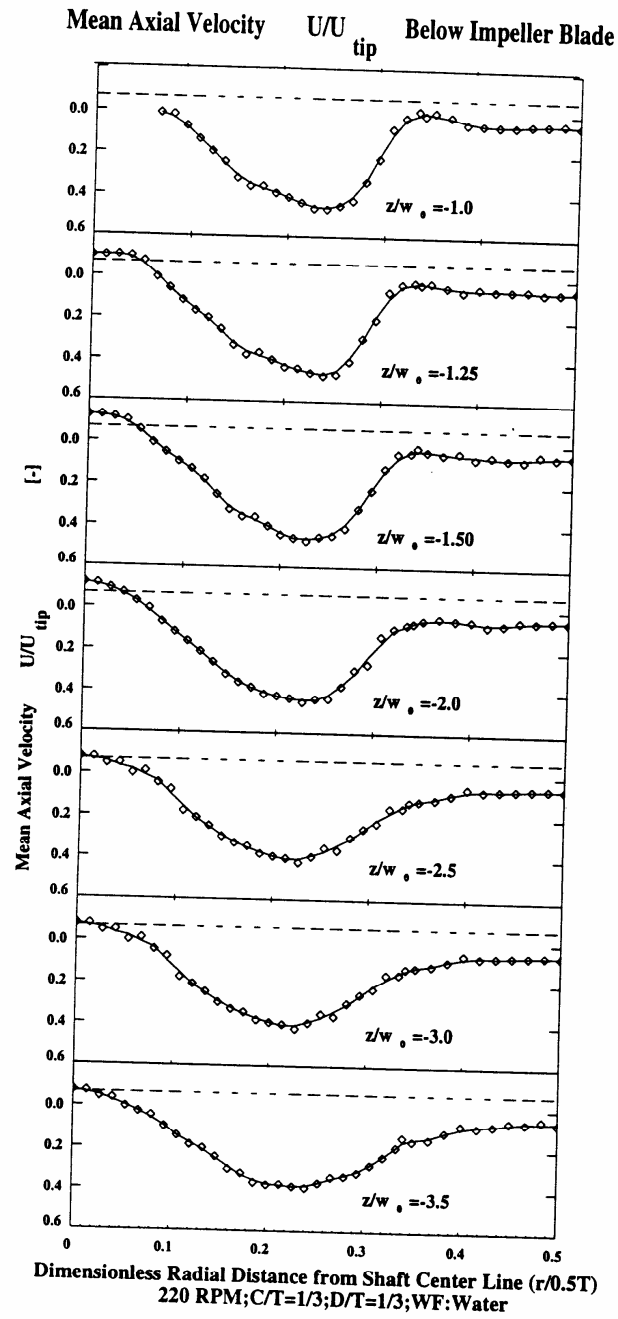
225 rpm  $D=10\text{cm}$  ;  $C/T=0.33$  ;  $D/T=0.33$



**Flow Field Around an Impeller Blade**  
 (Fully Turbulent Flow)

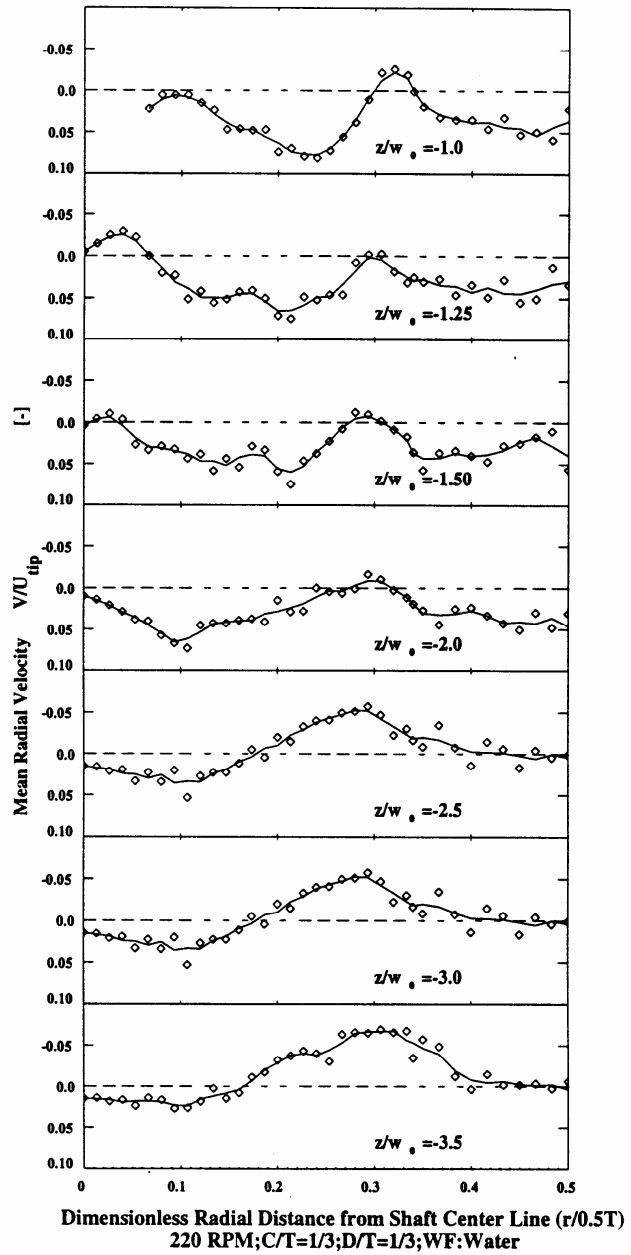
$D=10\text{cm}$  ;  $C/T=0.33$ ;  $D/T=0.33$

# (1) Turbulent Flow : $NRe = 37,500$ : PBT-4



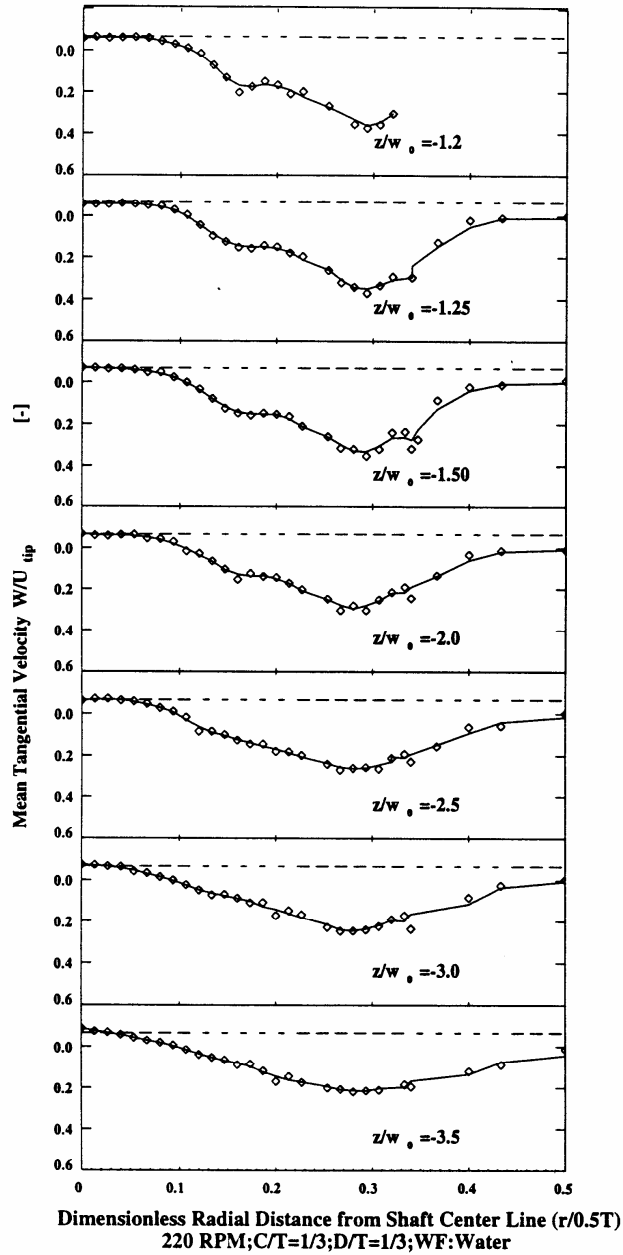
## (2) Turbulent Flow : $NRe = 37,500$ : PBT-4

Mean Radial Velocity  $V/U_{tip}$  Below Impeller Blade



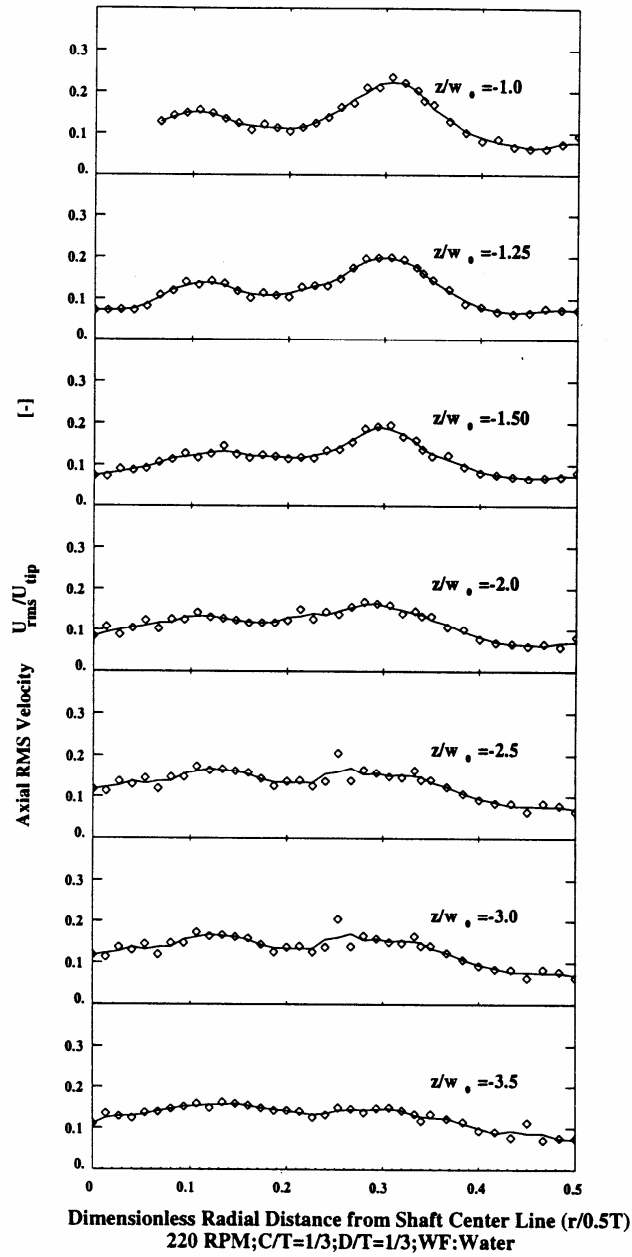
### (3) Turbulent Flow : $NRe = 37,500$ : PBT-4

Mean Tangential Velocity  $W/U_{tip}$  Below Impeller Blade



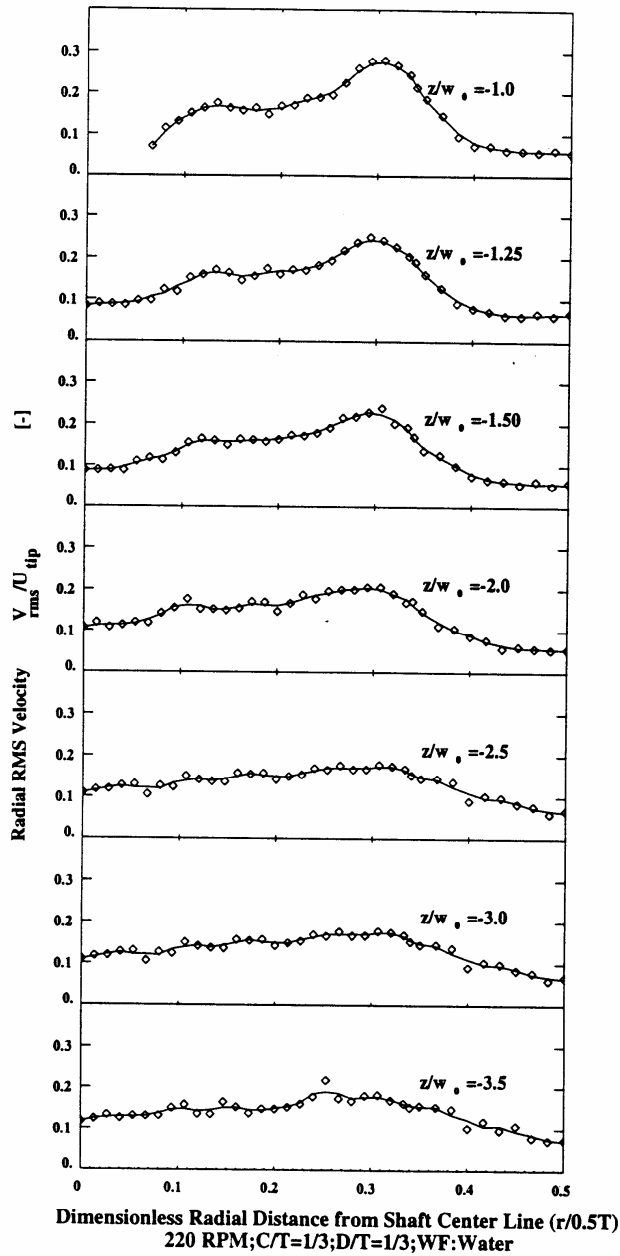
#### (4) Turbulent Flow : $N_{Re} = 37,500$ : PBT-4

Axial RMS Velocity  $U_{rms}/U_{tip}$  Below Impeller Blade



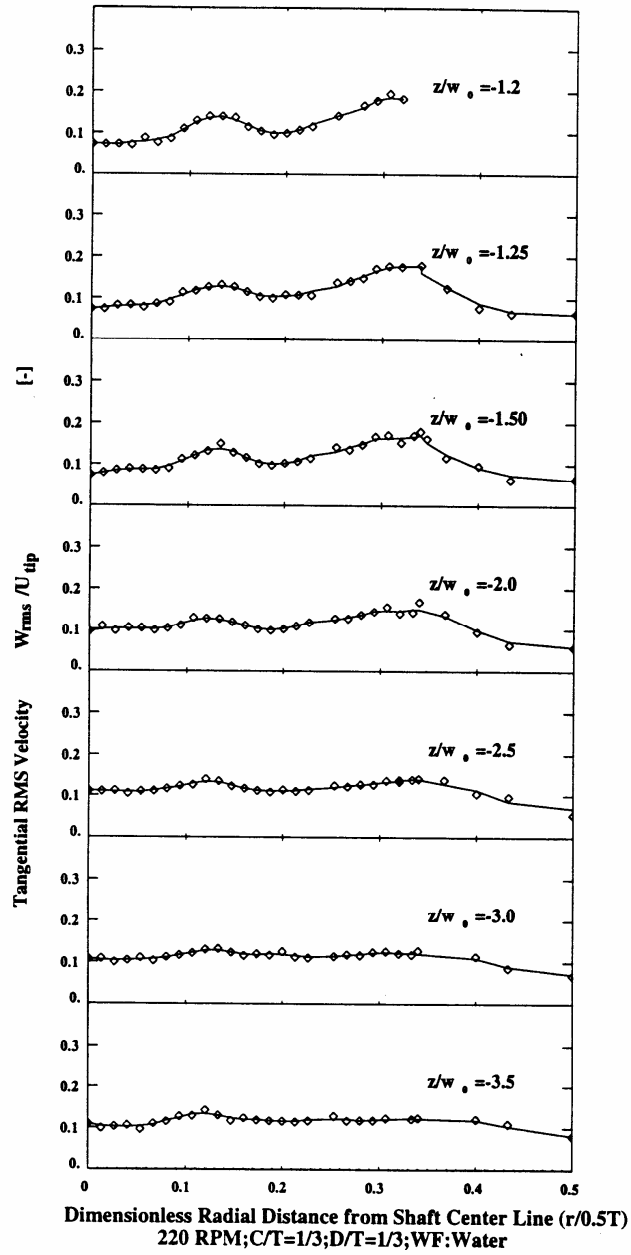
### (5) Turbulent Flow : $N_{Re} = 37,500$ : PBT-4

Radial RMS Velocity  $V_{rms} / U_{tip}$  Below Impeller Blade



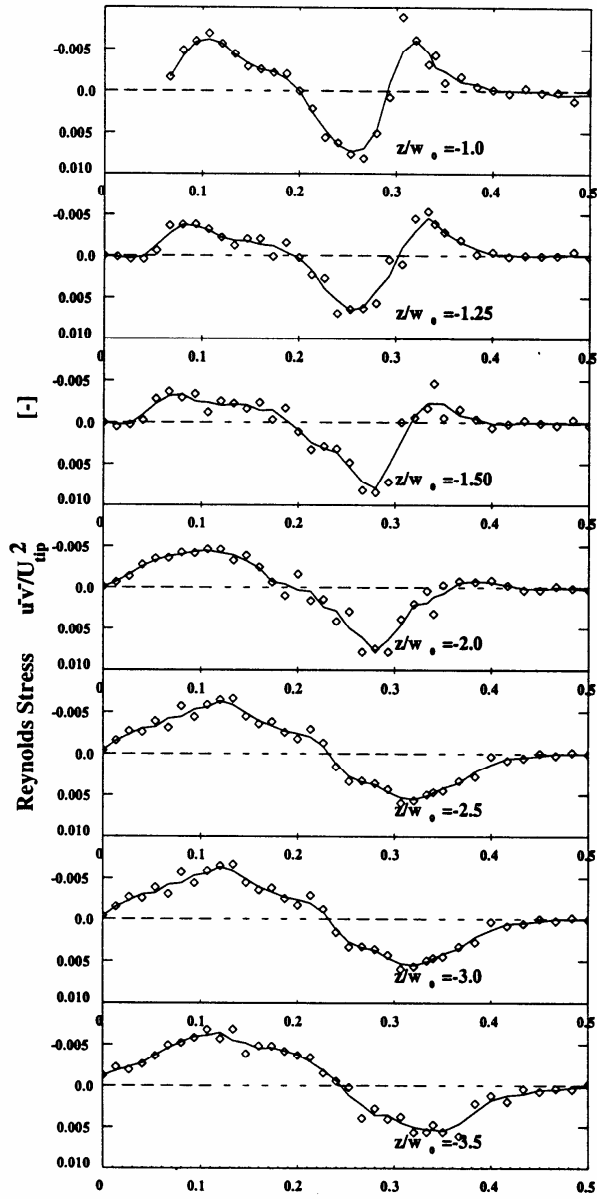
## (6) Turbulent Flow : $N_{Re} = 37,500$ : PBT-4

Tangential RMS Velocity  $W_{rms} / U_{tip}$  Below Impeller Blade



(7) Turbulent Flow :  $N_{Re} = 37,500$  : PBT-4

Reynolds Stress  $\bar{u}v/U_{tip}^2$  Below Impeller Blade



Dimensionless Radial Distance from Shaft Center Line ( $r/0.5T$ )  
220 RPM;  $C/T=1/3$ ;  $D/T=1/3$ ; WF: Water

**(8) Turbulent Flow : NRe = 37,500 : PBT-4**

Reynolds Stress  $u'w'/U_{tip}^2$  Below Impeller Blade

