FLOW FIELD AND HEAT TRANSFER IN A MODEL GAS TURBINE DISK CAVITY

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OBJECTIVE

The objective is to understand the turbulent flow field and heat transfer in gas turbine disk cavities. The main issue is the potential for hot gas ingress from the main gas path into disk cavities, particularly the first-stage disk cavity, and its effect on the rotor disk thermo-mechanical state and durability.

TASKS AND PRESENT STATUS

1. Measurement of Local Convective Heat Transfer Coefficient and Cooling Effectiveness on Rotor Disk:
   - Method – Thermochromic Liquid Crystal
   - Status – Completed*

2. Static Pressure Distribution Measurement in Main Gas Path (Circumferential) and Disk Cavity:
   - Method - Differential Pressure Transducer/Scanivalve
   - Status – Completed*

3. Measurement of Velocity Field in Disk Cavity:
   - Method - Particle Image Velocimetry
   - Status - Completed*

TASKS AND PRESENT STATUS

4. CFD Simulation:
   - Method - Fluent/UNS
   - Status - 2D Completed*, 3D Continuing

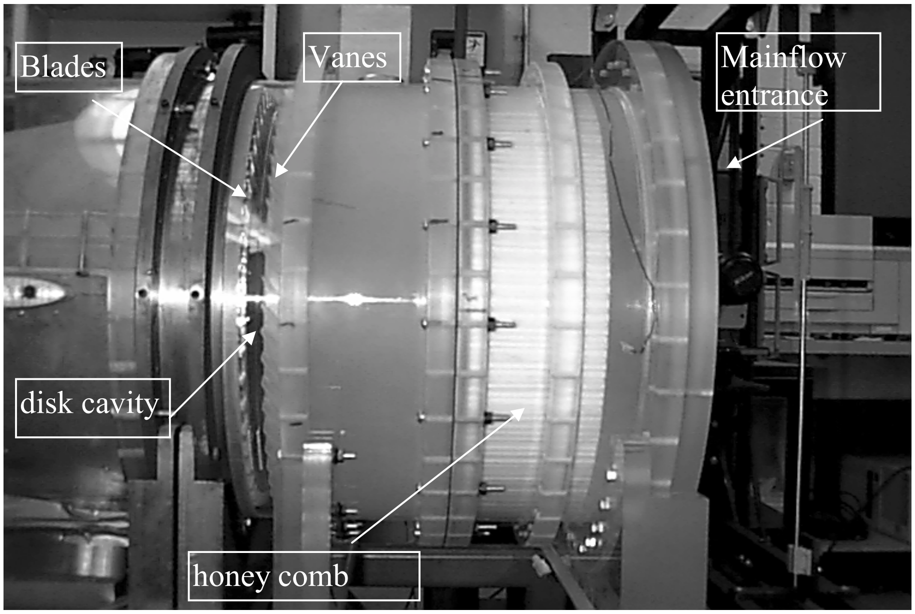
5. Gas Ingress Study:
   - Method - Laser Sheet Flow Visualization
   - Status - Completed*
   - Method - Tracer Gas (CO_2) Concentration by NDIR
   - Status - In Progress

6. Experiments with New Stator Disk and Discourager Configurations
   - Heat Transfer – Remeasurements with shaft/bearing cooling – Completed*
   - Pressure and Velocity Field – In Progress
   - Gas Ingress – In Progress

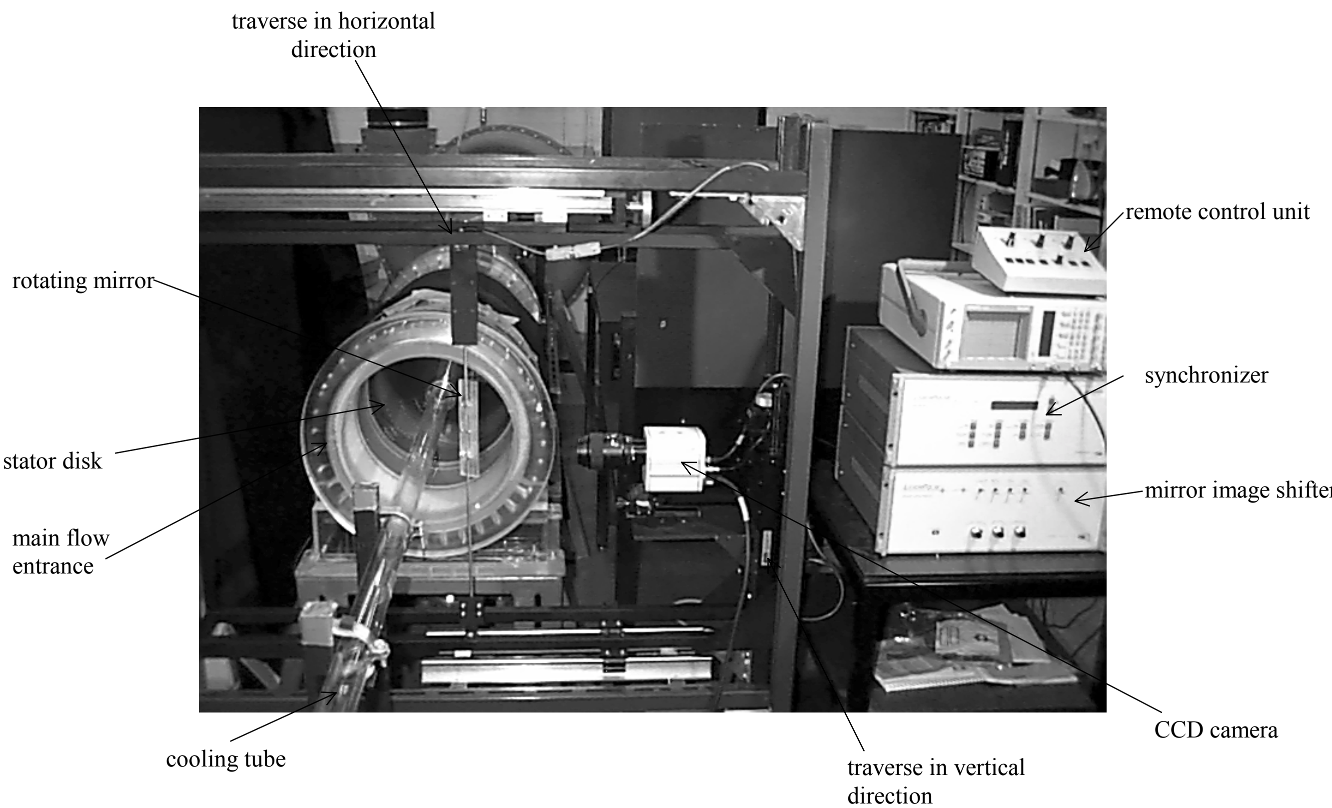
RANGES OF EXPERIMENTAL PARAMETERS

Flow Parameters	Range
Rotational Reynolds number, Re_ϕ	$5 \times 10^5 - 1.0 \times 10^6$
Main gas-path Reynolds number, Re_m	$2.6 \times 10^5 - 6.6 \times 10^5$
Main gas-path to rotor disk tip velocity ratio	to $\cong 1.0$
Secondary (cooling) air flow rate ratio, $Q_c/Q_{pumping}$	0.09 - 1.0 ($c_w \approx 700 - 8300$)

Geometric Parameters	
Cavity gap ratio, s/b	0.084 (baseline), 0.054
Rim discourager axial overlap ratio, z_a/b	0.01 (baseline); other discourager configs.
Radial discourager clearance ratio, z_r/b	0.01 (baseline), 0.02; other discourager configs.
Exit flow angle at stator vane, α	55°



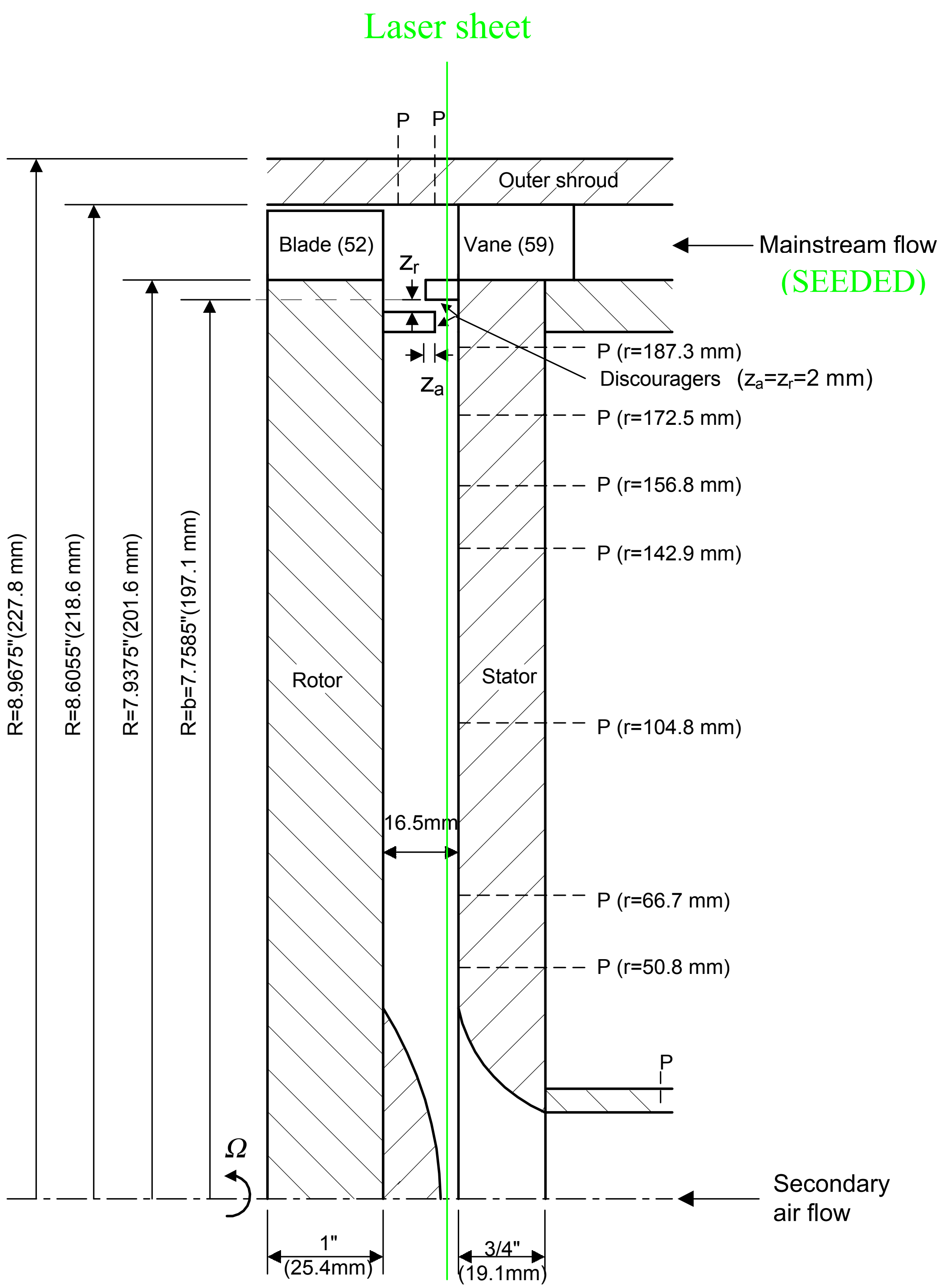
(a) inlet section



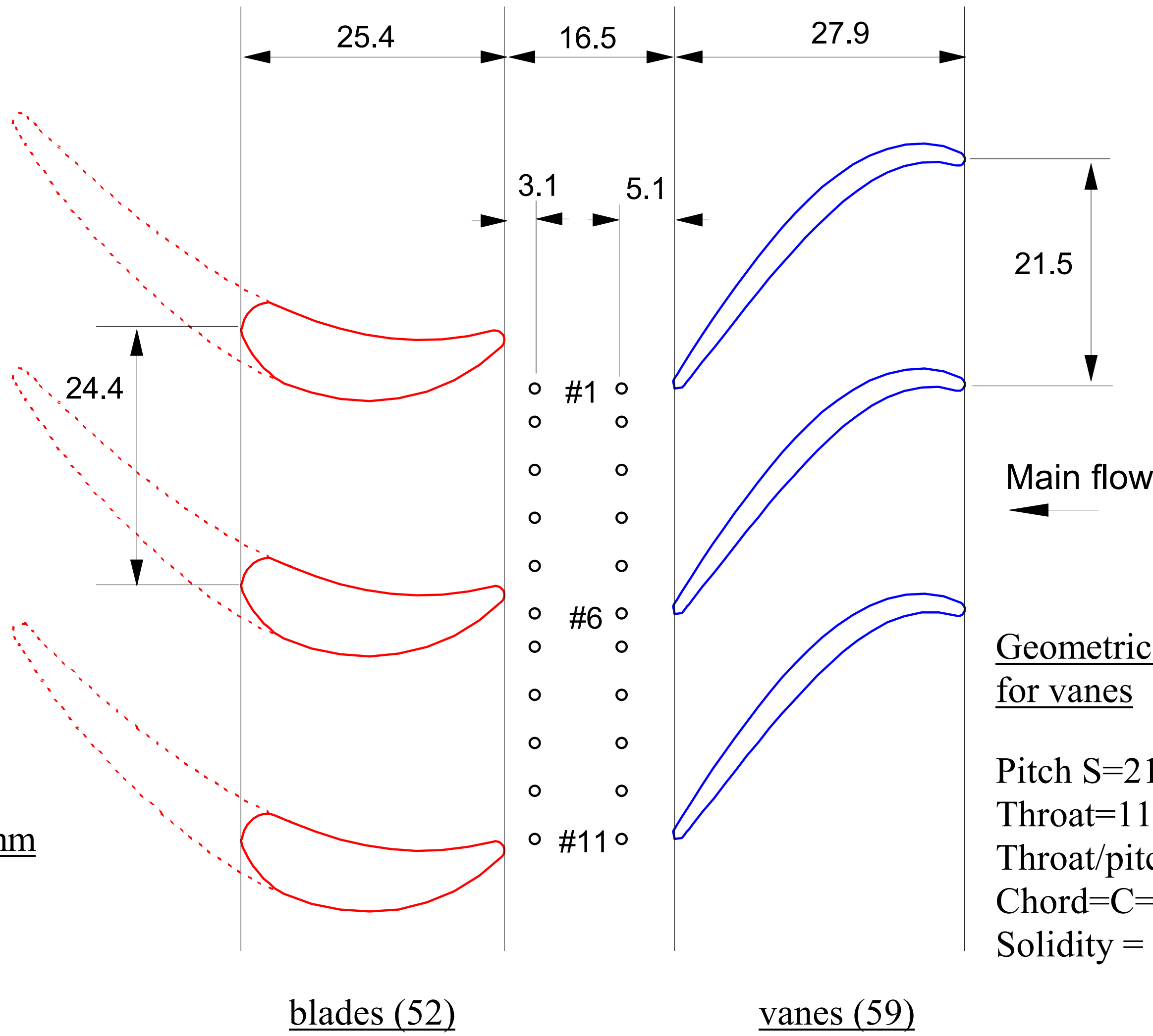
(b) the PIV set-up

THE ROTOR-STATOR DISK CAVITY RIG

THE DISK CAVITY CONFIGURATION
(Ingress Study by Laser Sheet Visualization)



SCHEMATIC OF GUIDE VANES AND BLADES



<u>All dimensions are in mm</u>

○ pressure taps

<u>Geometric parameters for vanes</u>

Pitch S=21.5 mm
Throat=11.86 mm
Throat/pitch=0.552
Chord=C=35.23 mm
Solidity = 1.639

NONDIMENSIONAL PARAMETERS

$$\mathrm{Re}_\phi \equiv \frac{\Omega r_0^{\,2}}{\nu} \quad , \quad \mathrm{Re}_{\phi,r} \equiv \frac{\Omega r^{\,2}}{\nu}, \quad \mathrm{Re}_m \equiv \frac{V_{main,axial} \cdot r_0}{\nu_{main}}$$

$$\beta(r) \equiv \frac{\omega(r)}{\Omega}$$

$$c_w \equiv \frac{\dot{m}_c}{\mu r_0}$$

$$Q_p \equiv 0.0697\,\pi r_0 \nu\,\mathrm{Re}_\phi^{0.8}$$ ("free disk pumping flow rate")

$$\lambda_t \equiv \frac{c_w}{\mathrm{Re}_\phi^{0.8}} = 0.219\,\frac{\dot{m}_c}{\dot{m}_p}$$

$$Nu_r \equiv \frac{h(r)r}{k_{fluid}}$$

- Disk cavity radius is r_0 or b.

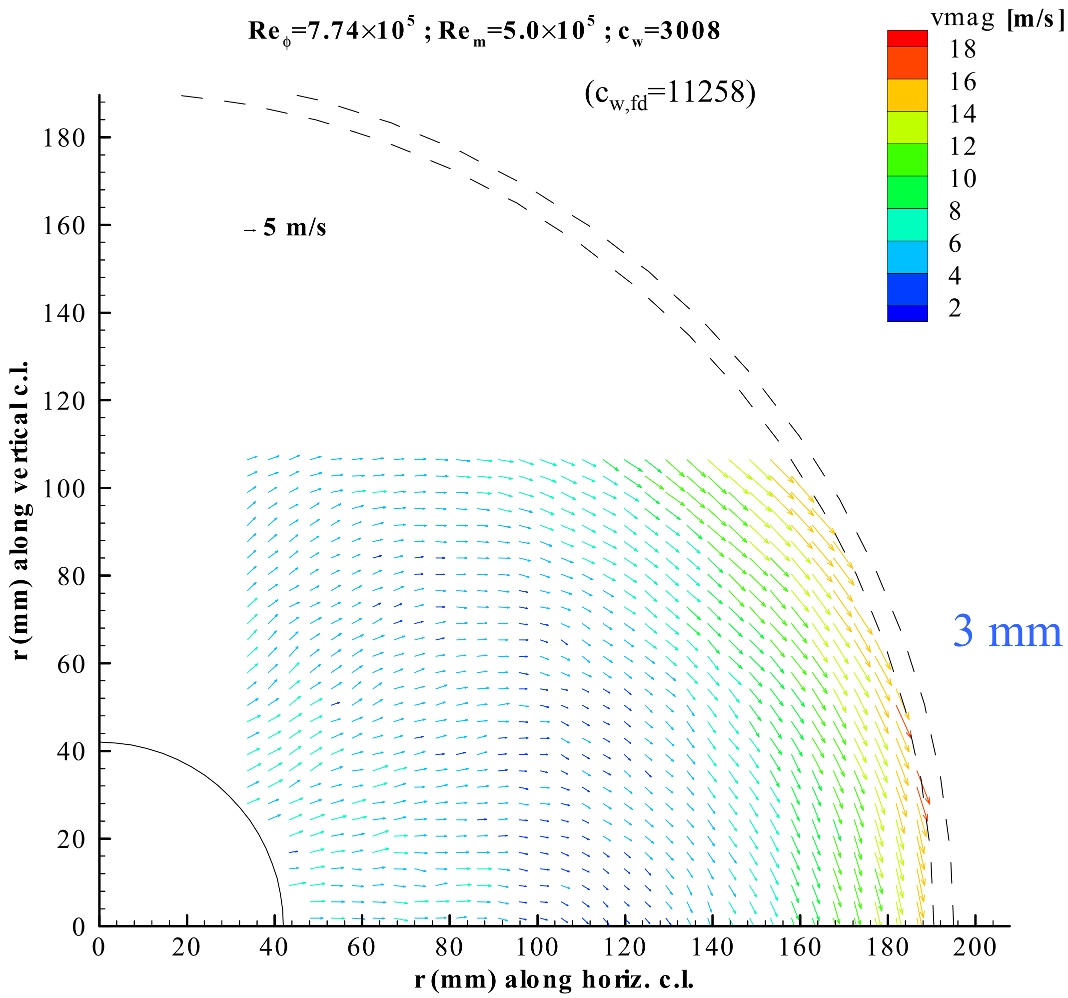
EXPERIMENTAL CONDITIONS – PIV

Expt. No.	Re_{ϕ}	Re_m	c_w	$c_{w,fd}$
1	5.16×10^5	5.0×10^5	1504	8139
2	″	″	3008	″
3	″	″	7520	″
4	7.74×10^5	″	1504	11258
5	″	″	3008	″
6	9.55×10^5	″	1504	13319
7	″	6.2×10^5	″	″

ESTIMATED UNCERTAINTIES

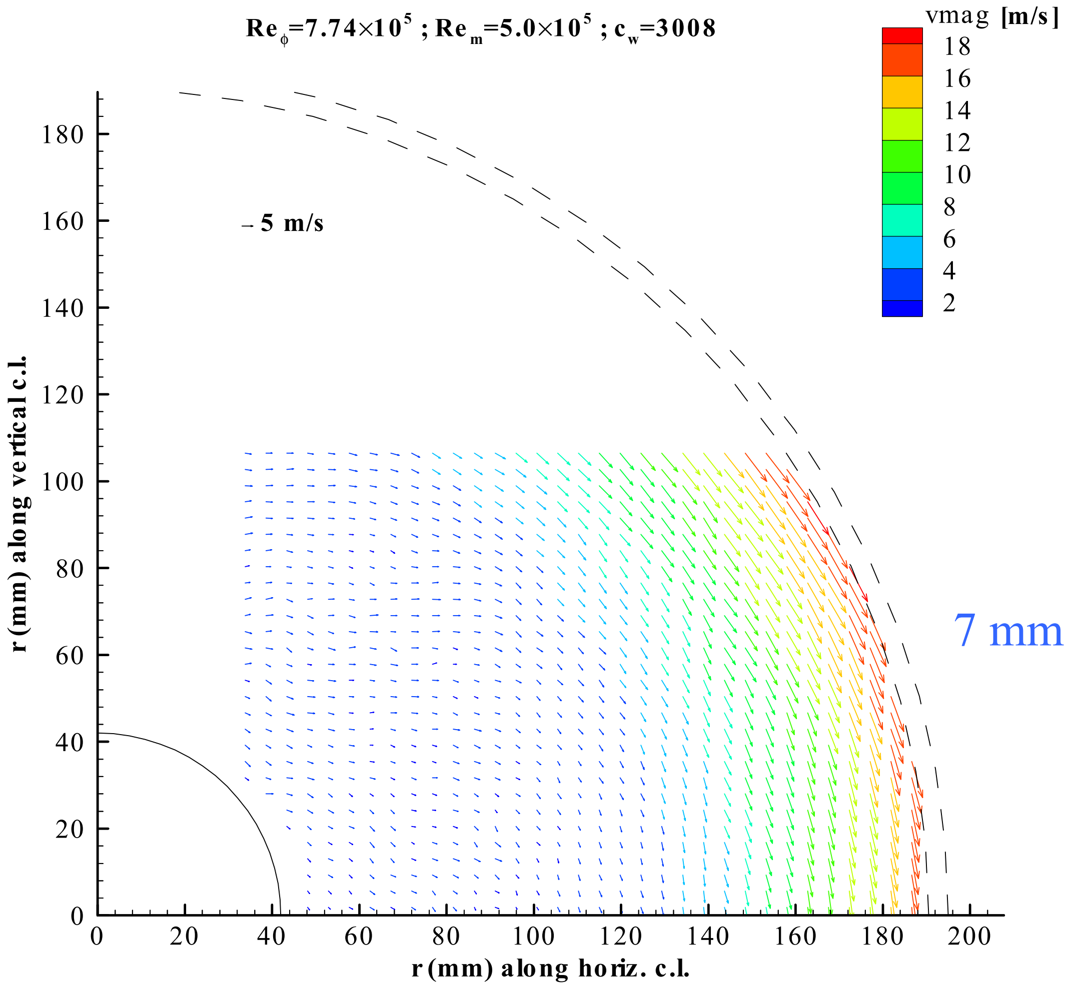
	Re_ϕ	Re_m	c_w	V_r	V_ϕ	p
Uncertainty	± 2 %	± 3 %	± 5 %	± 5 %	± 5 %	± 1 %

FLUID MEAN VELOCITY FIELD – PIV



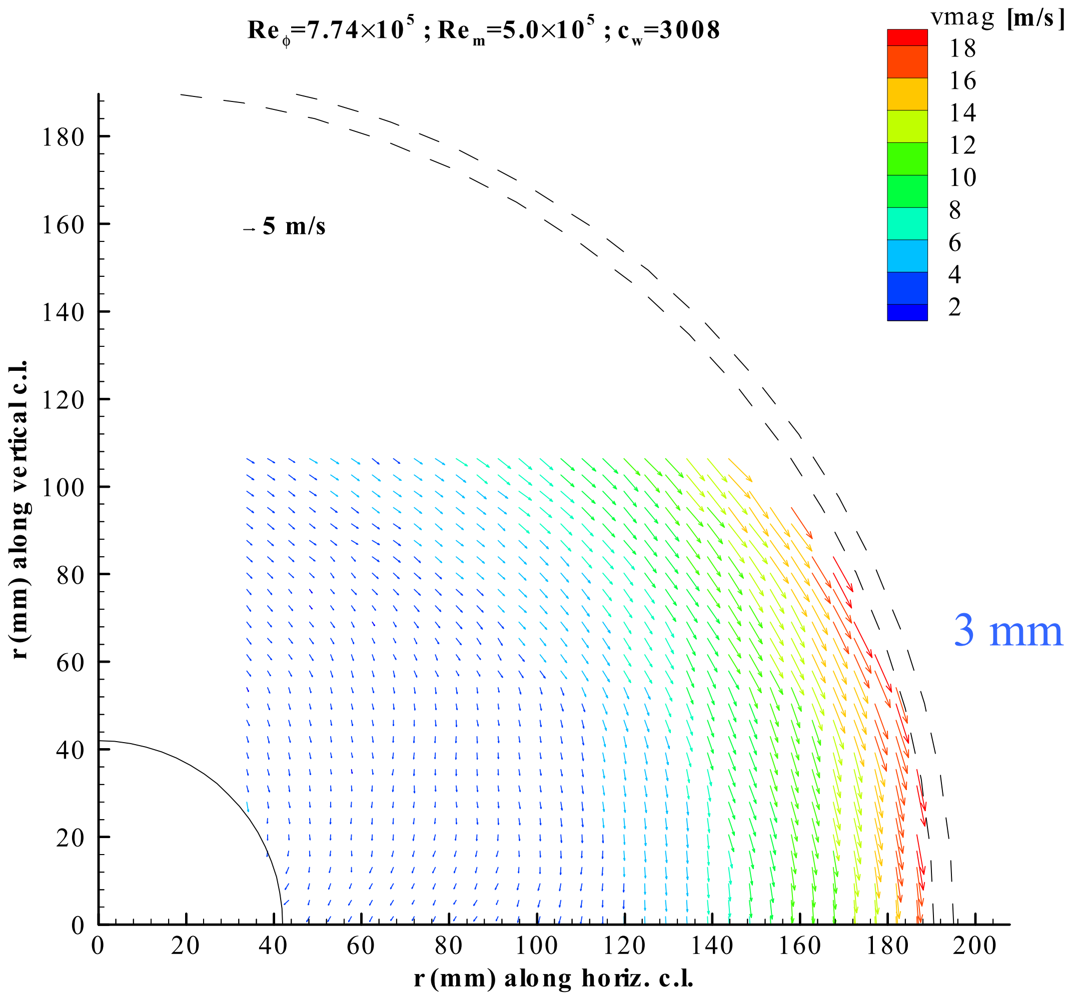
3 mm from the rotor disk

FLUID MEAN VELOCITY FIELD – PIV



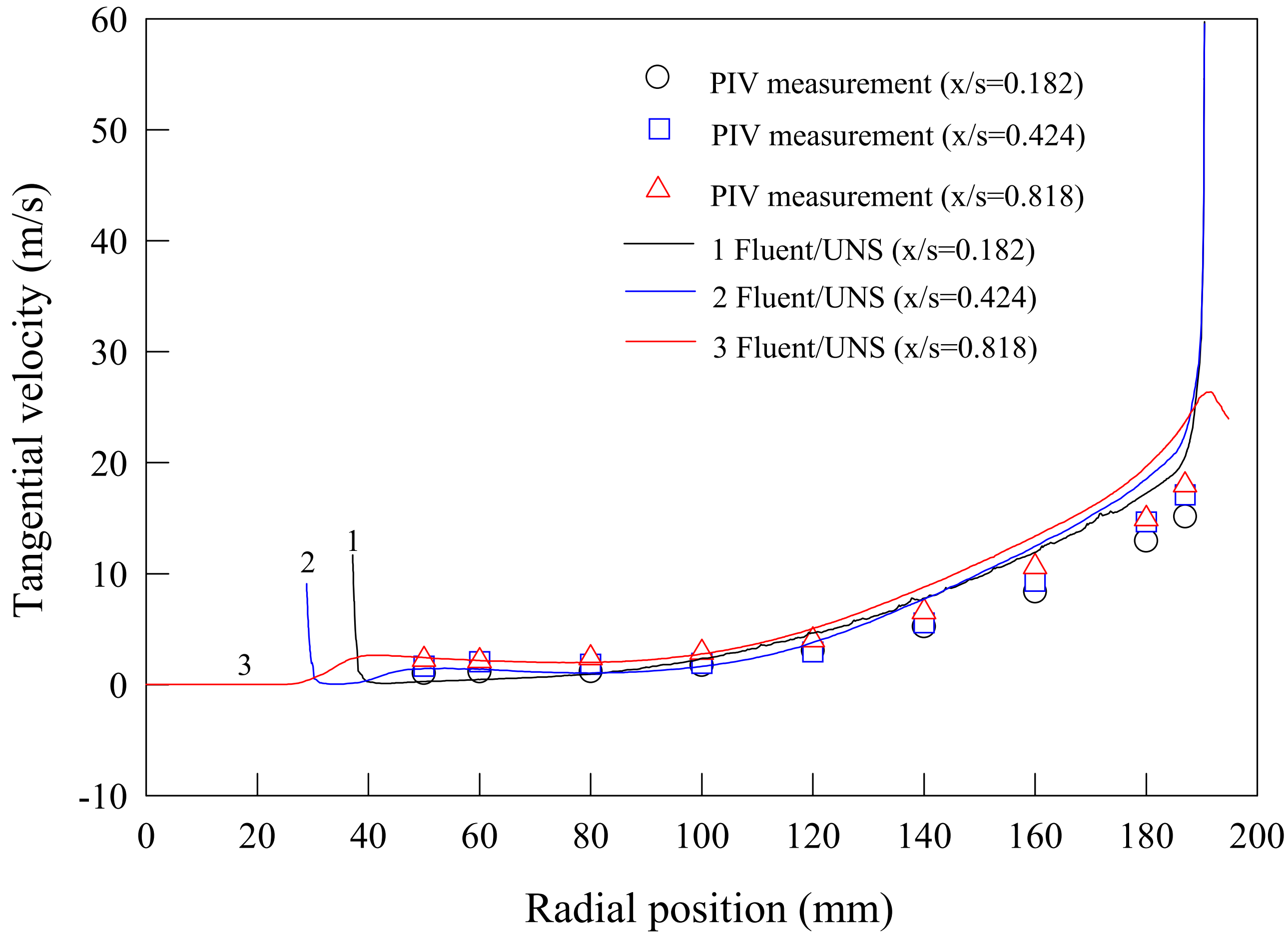
7 mm from the rotor disk

FLUID MEAN VELOCITY FIELD – PIV



3 mm from the stator disk

FLUID TANGENTIAL VELOCITY

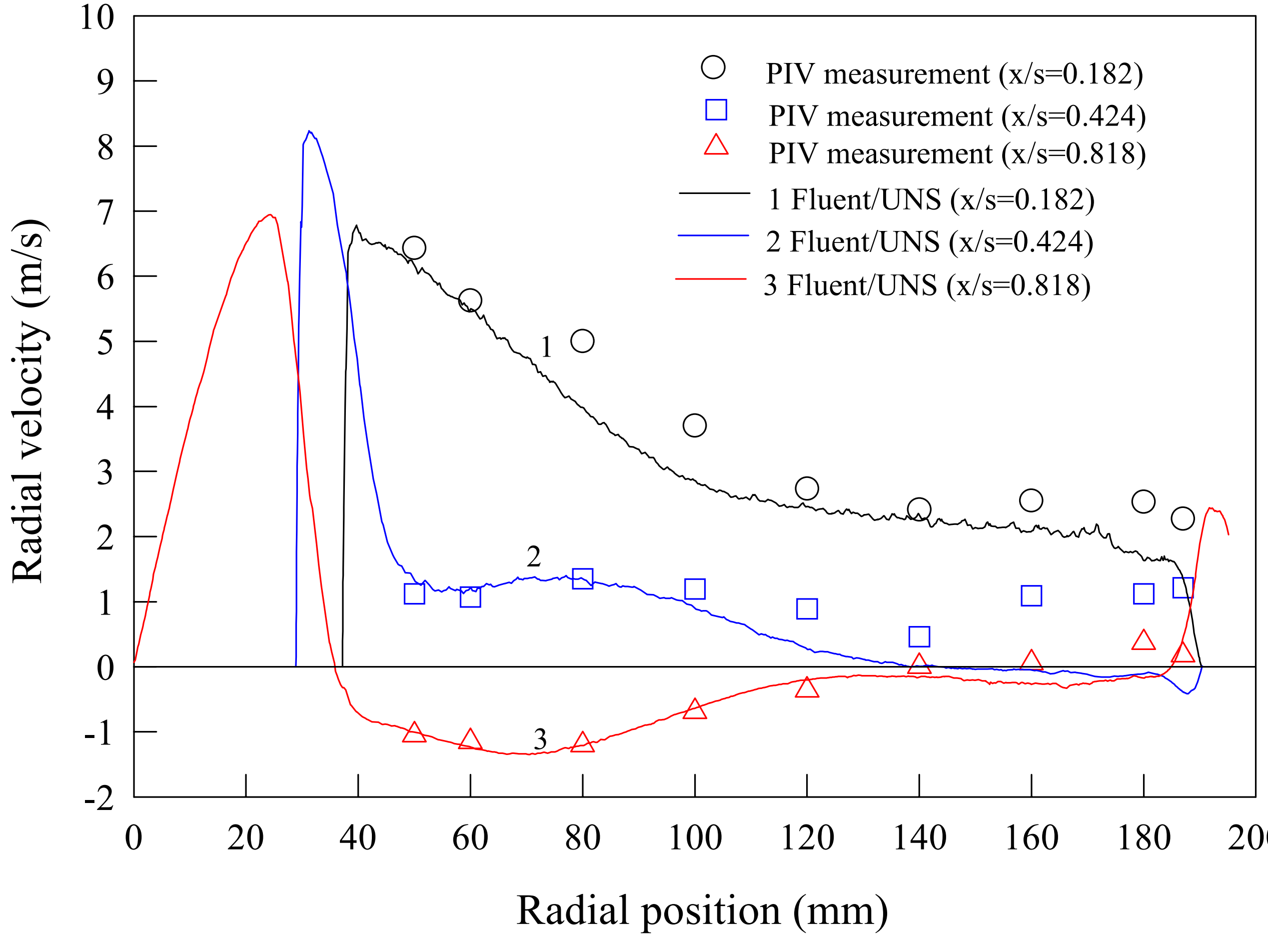


$Re_\phi = 7.74 \times 10^5$

$Re_m = 5.0 \times 10^5$

$c_w = 3008$

FLUID RADIAL VELOCITY



$Re_{\phi}=7.74\times10^5$

$Re_m=5.0\times10^5$

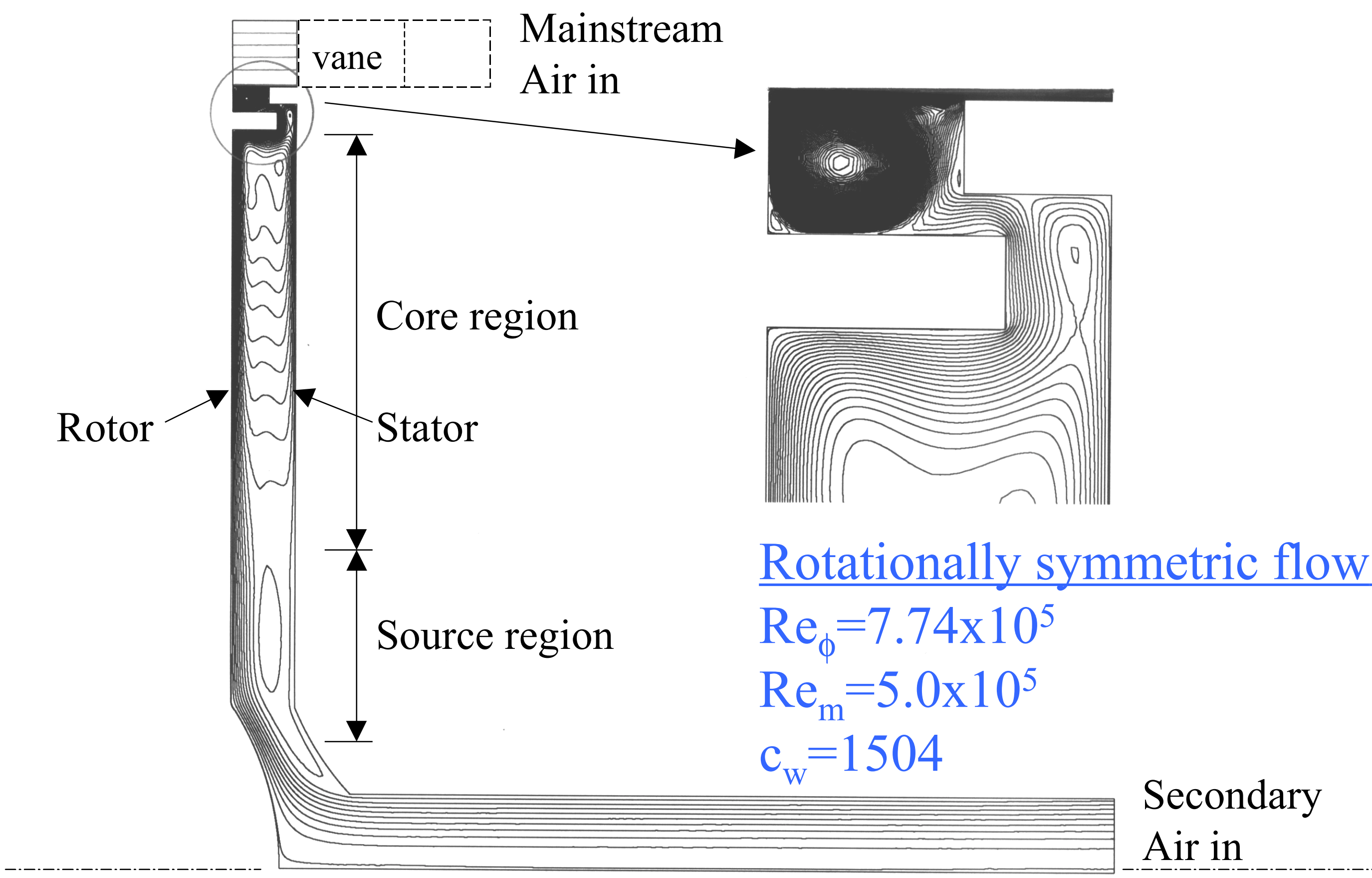
$c_w=3008$

COMPUTATIONAL TOOL

- Commercial CFD Code FLUENT/UNS
  - Two-Layer Description of Flow Domain for Rotationally Symmetric 2D Calculations
  - Wall Function for 3D Calculations
  - Turbulence Model:

    Renormalization Group (RNG) k-ε model

COMPUTED STREAMLINES



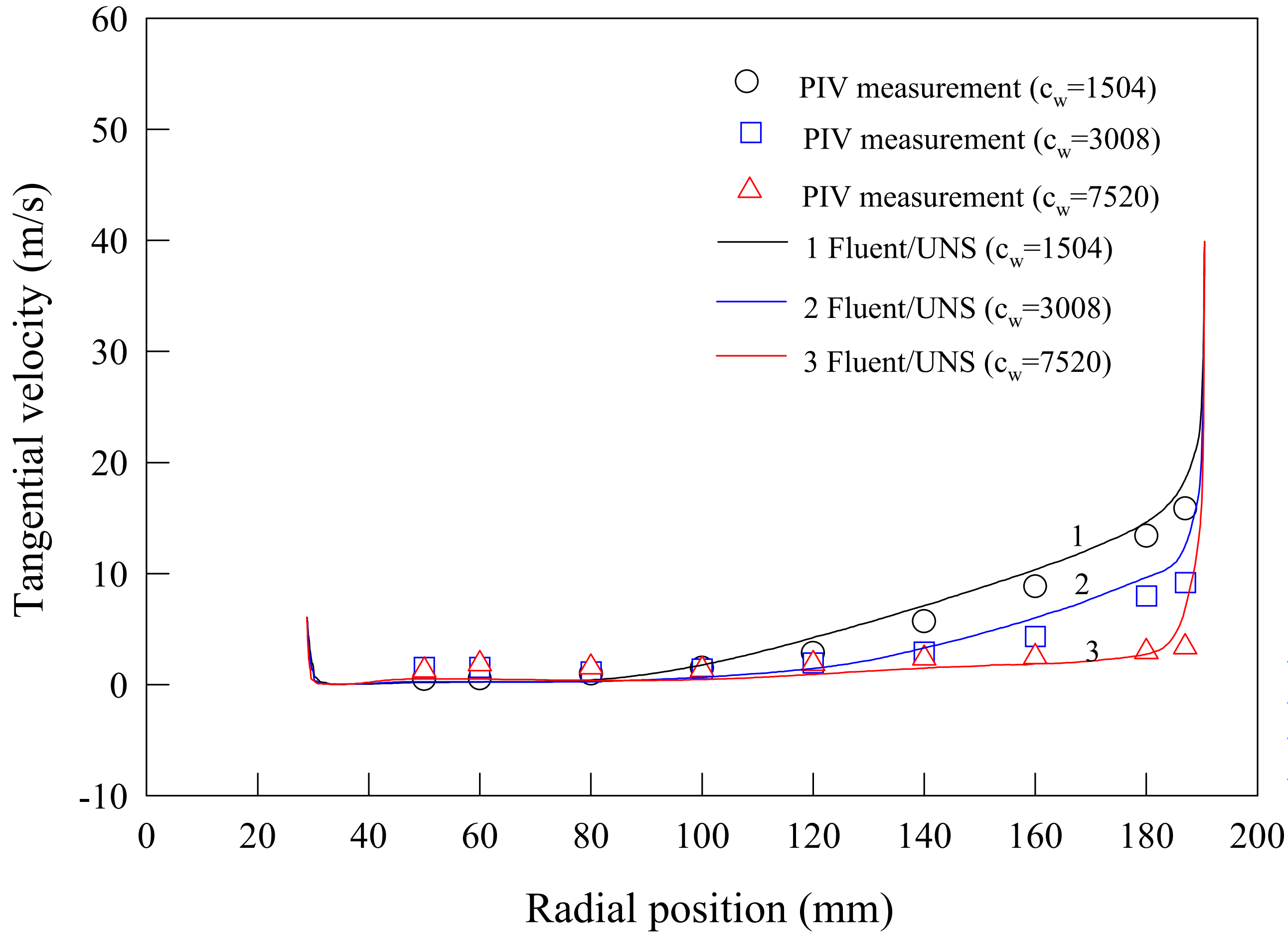
<u>Rotationally symmetric flow calc.</u>

$Re_{\phi}=7.74x10^5$

$Re_m=5.0x10^5$

$c_w=1504$

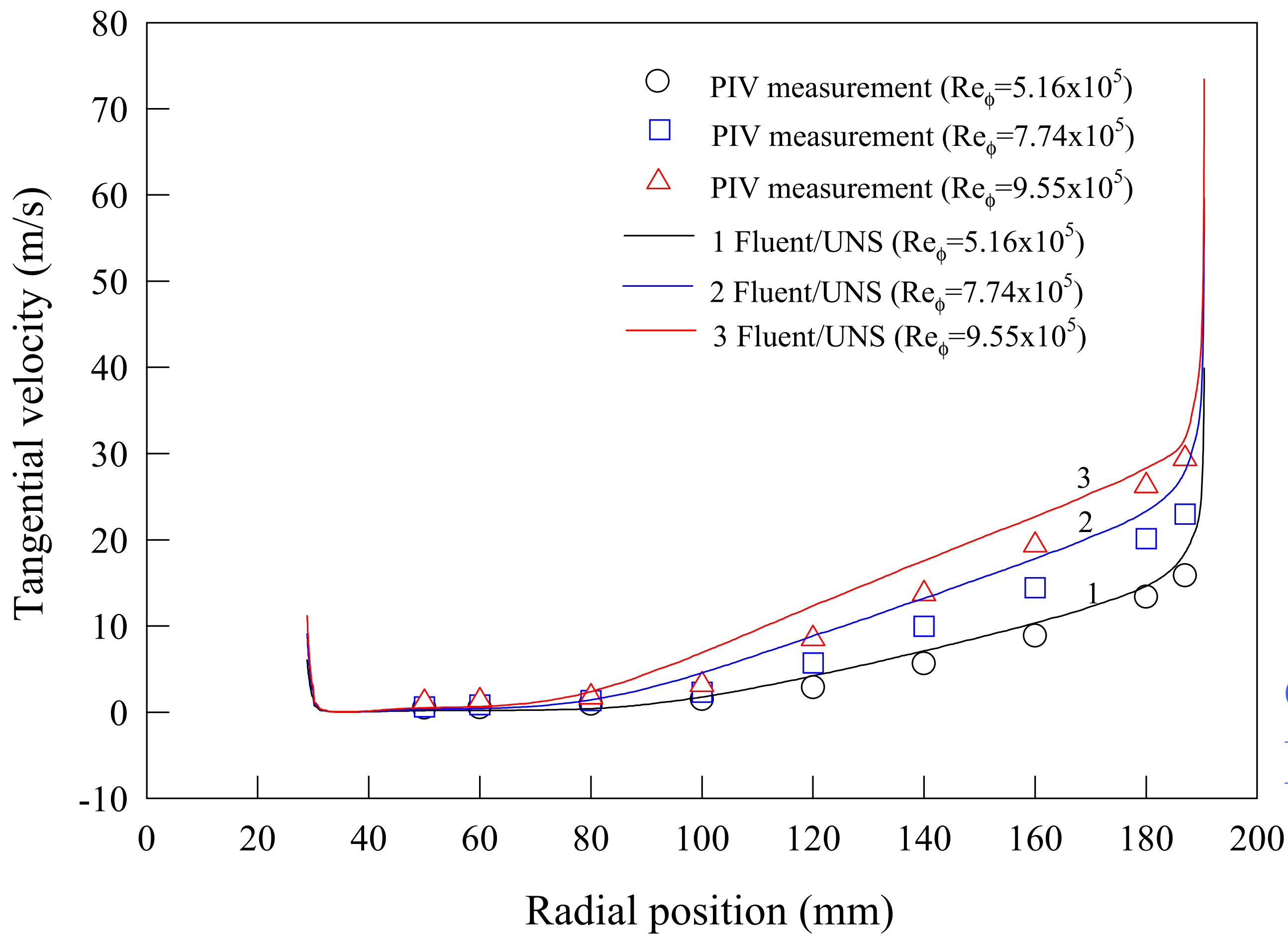
EFFECT OF c_w ON TANGENTIAL VELOCITY



$Re_\phi=5.16\text{x}10^5$

$Re_m=5.0\text{x}10^5$

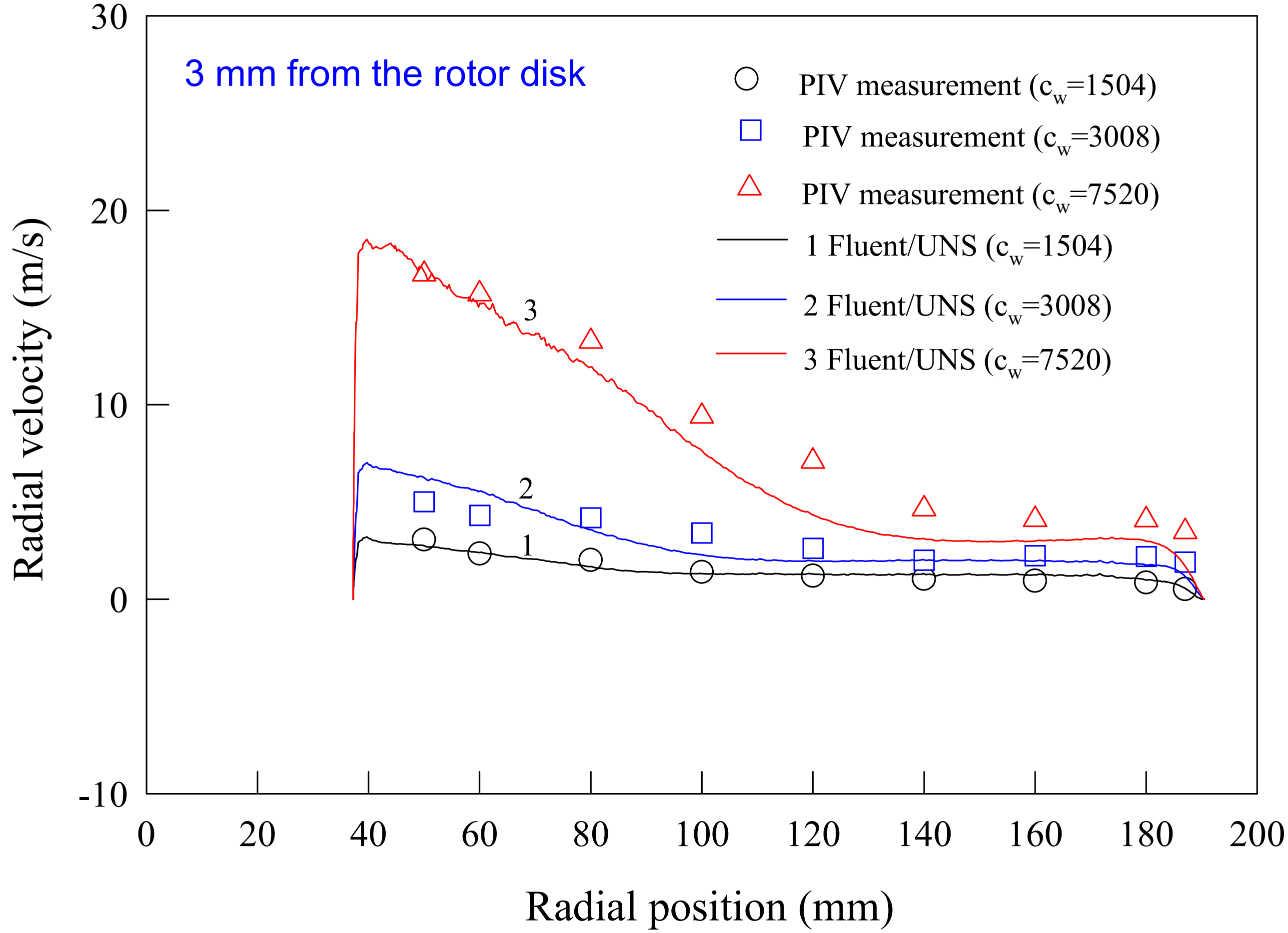
EFFECT OF Re_ϕ ON TANGENTIAL VELOCITY



c_w=1504

Re_m=5.0x10^5

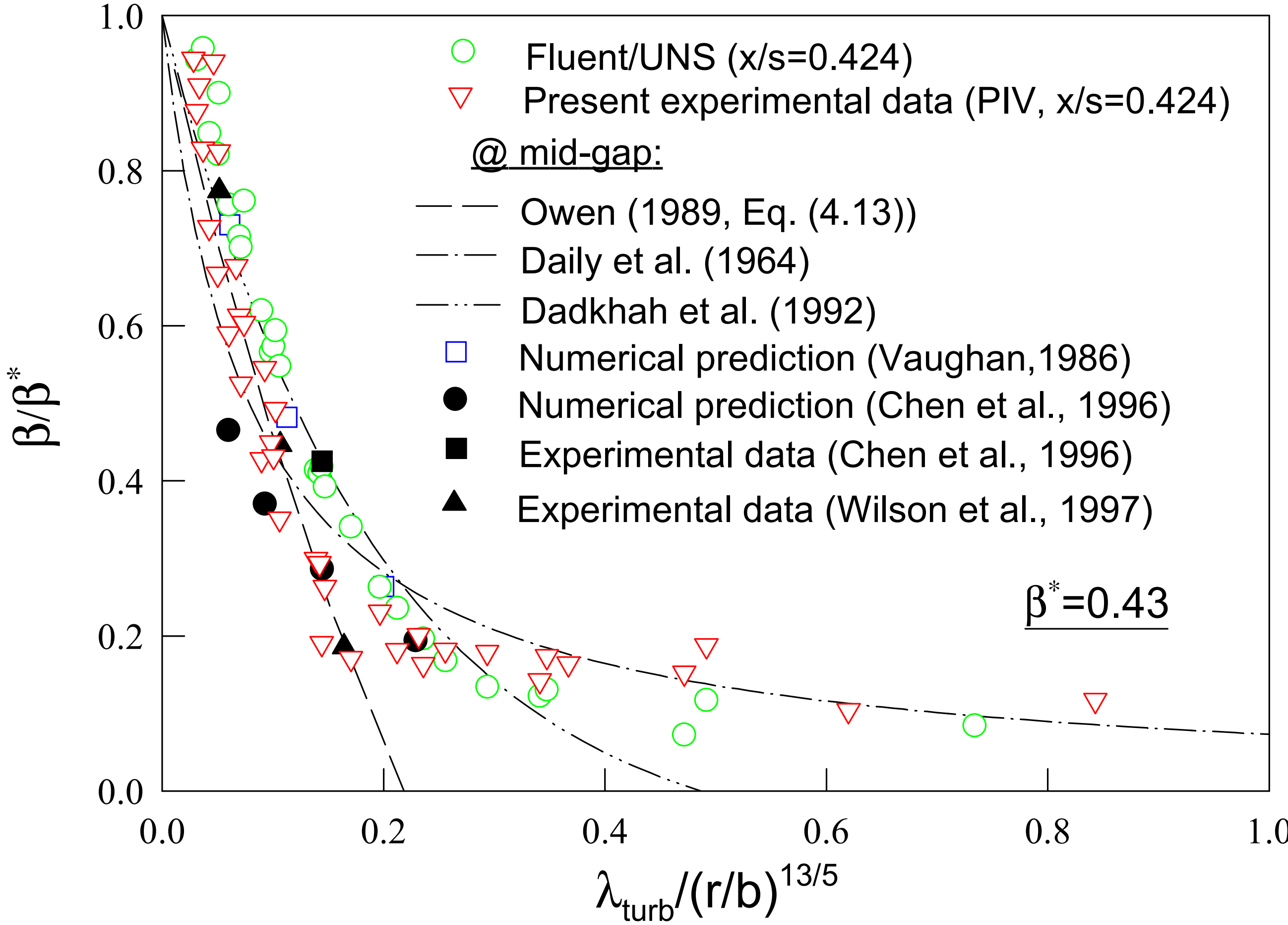
EFFECT OF c_w ON RADIAL VELOCITY



$Re_\phi=5.16\text{x}10^5$

$Re_m=5.0\text{x}10^5$

CORE FLUID ROTATION RATIO



$0.4<r/b<1$

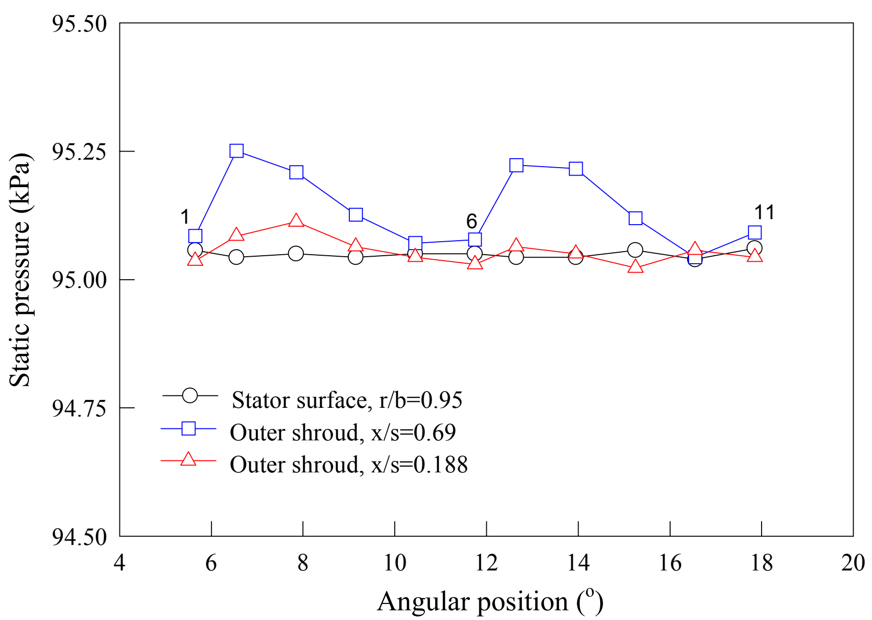
$1504 \leq c_w \leq 7520$

$5.2 \times 10^5 \leq Re_\phi \leq 9.6 \times 10^5$

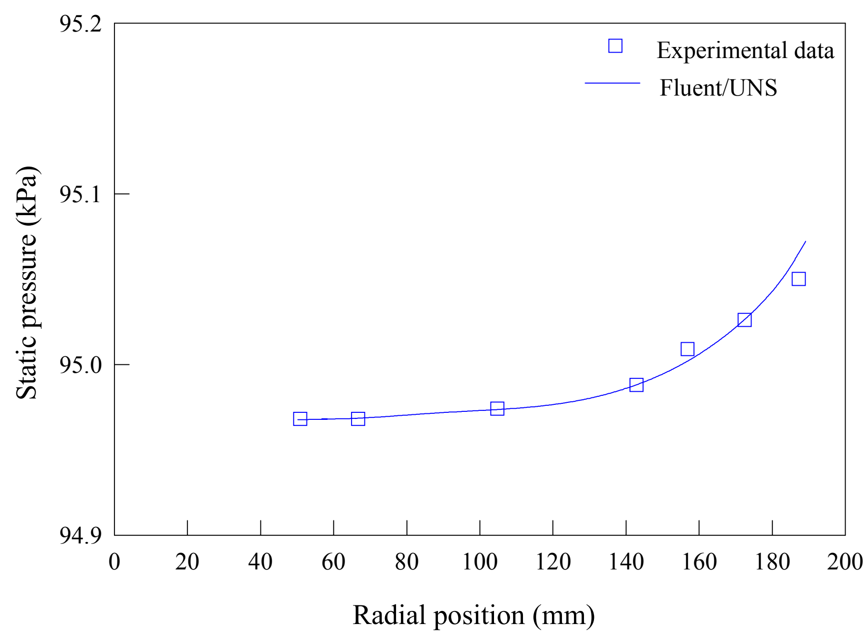
$Re_m = 5.0 \times 10^5$

STATIC PRESSURE

At Outer Shroud



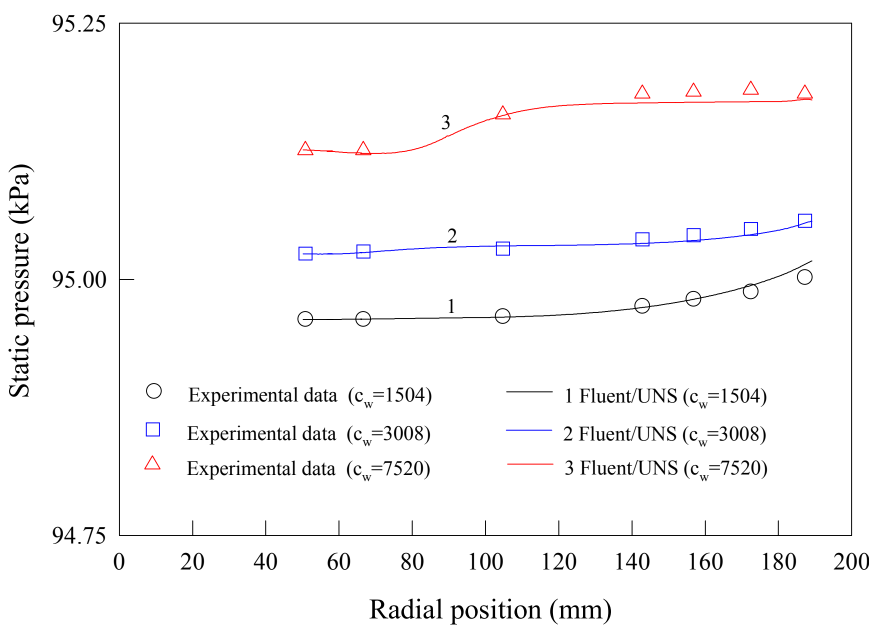
At Stator Disk Surface



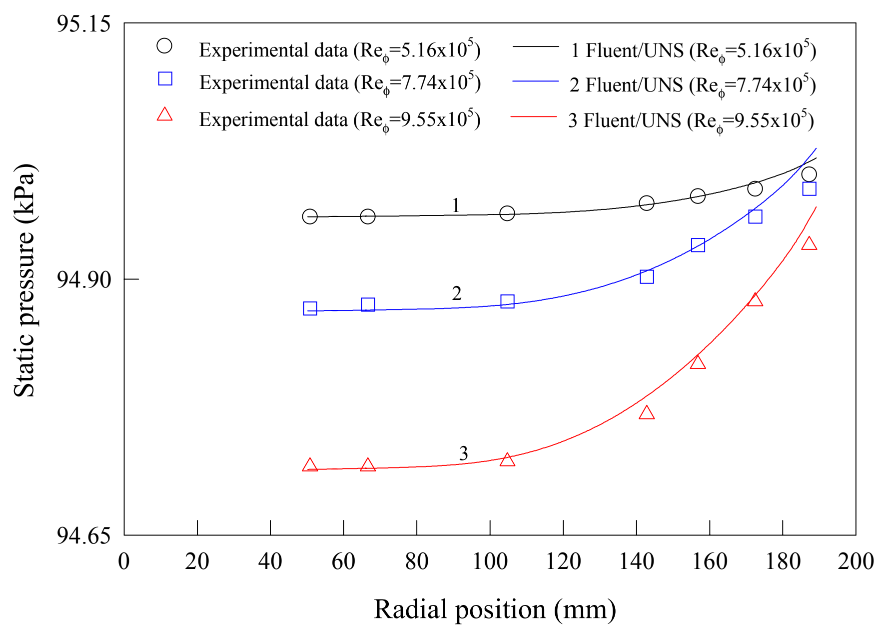
$Re_\phi = 7.74 \times 10^5$, $Re_m = 5.0 \times 10^5$, $c_w = 3008$, $p_{atm} = 97.84$ kPa

STATIC PRESSURE

Effect of c_w for $Re_\phi=5.16x10^5$



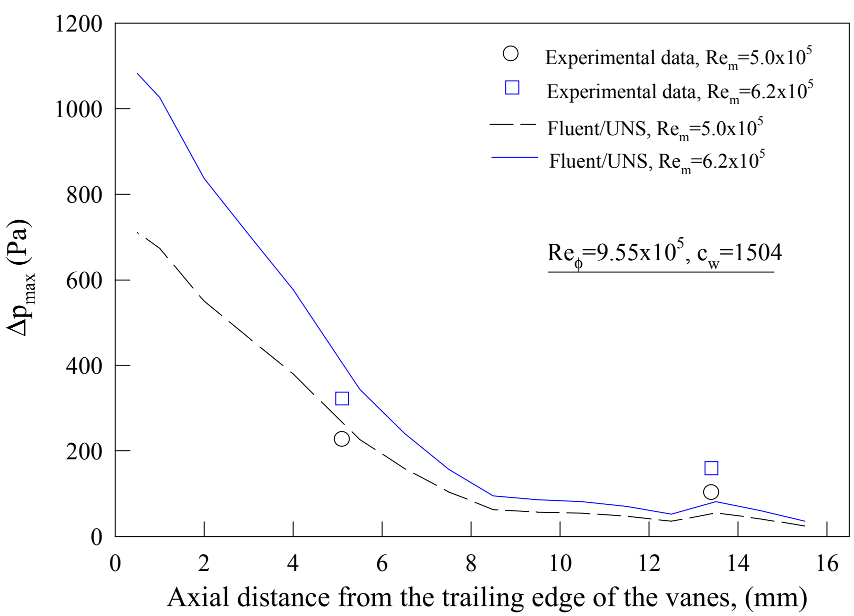
Effect of Re_ϕ for $c_w=1504$



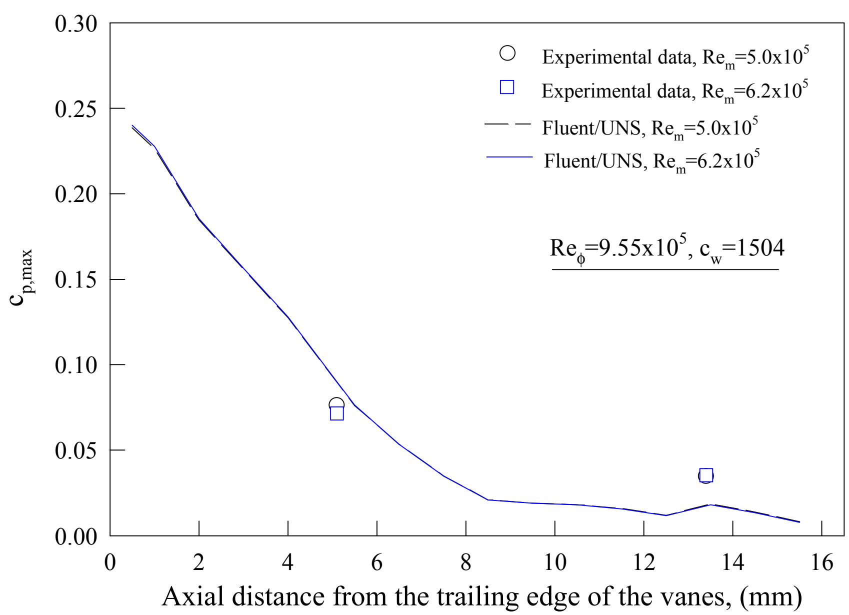
$Re_m=5.0x10^5$, $p_{atm}=97.84$ kPa

PRESSURE ASYMMETRY

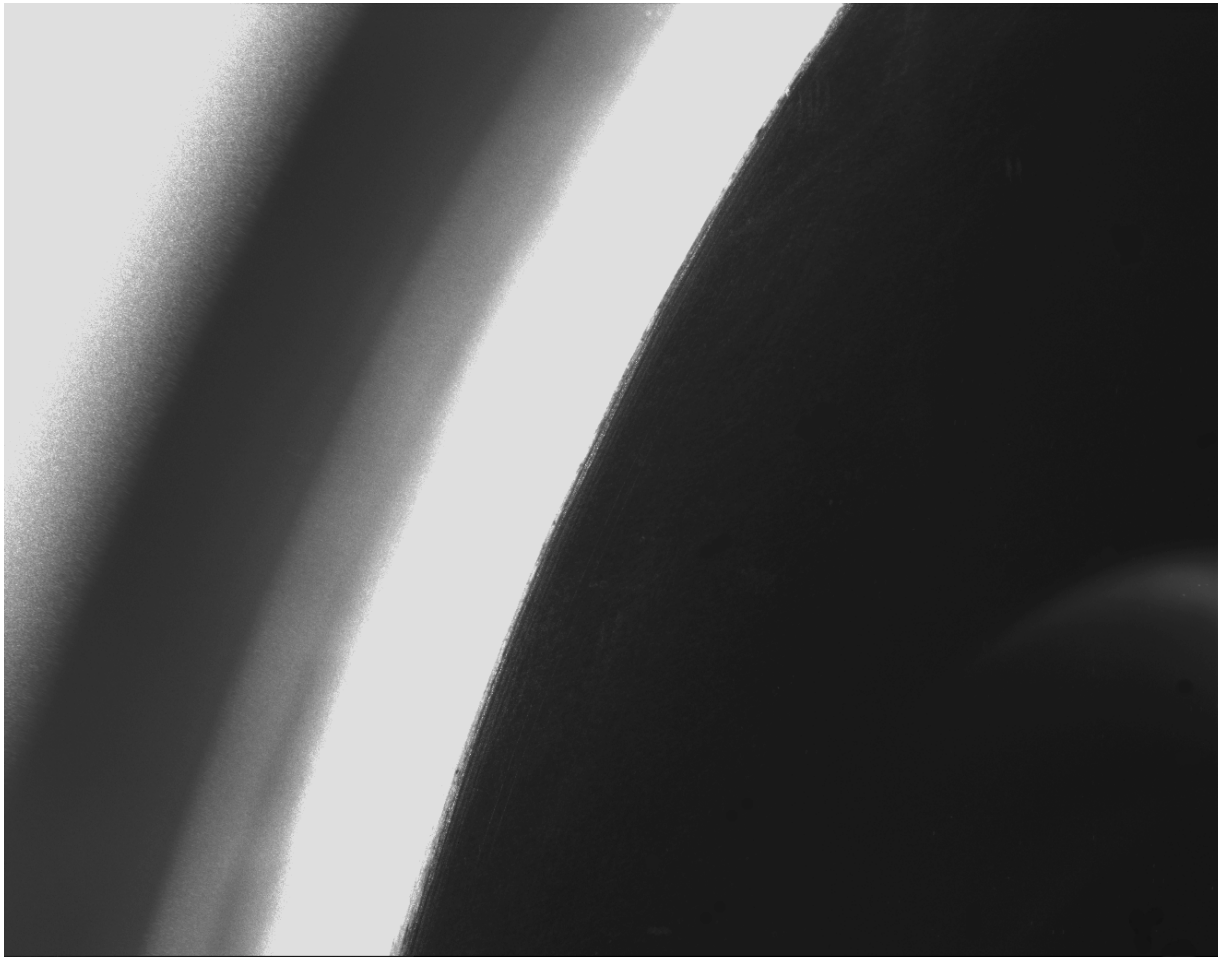
Effect of Re_m on Δp_{max}



Effect of Re_m on $c_{p,max}$



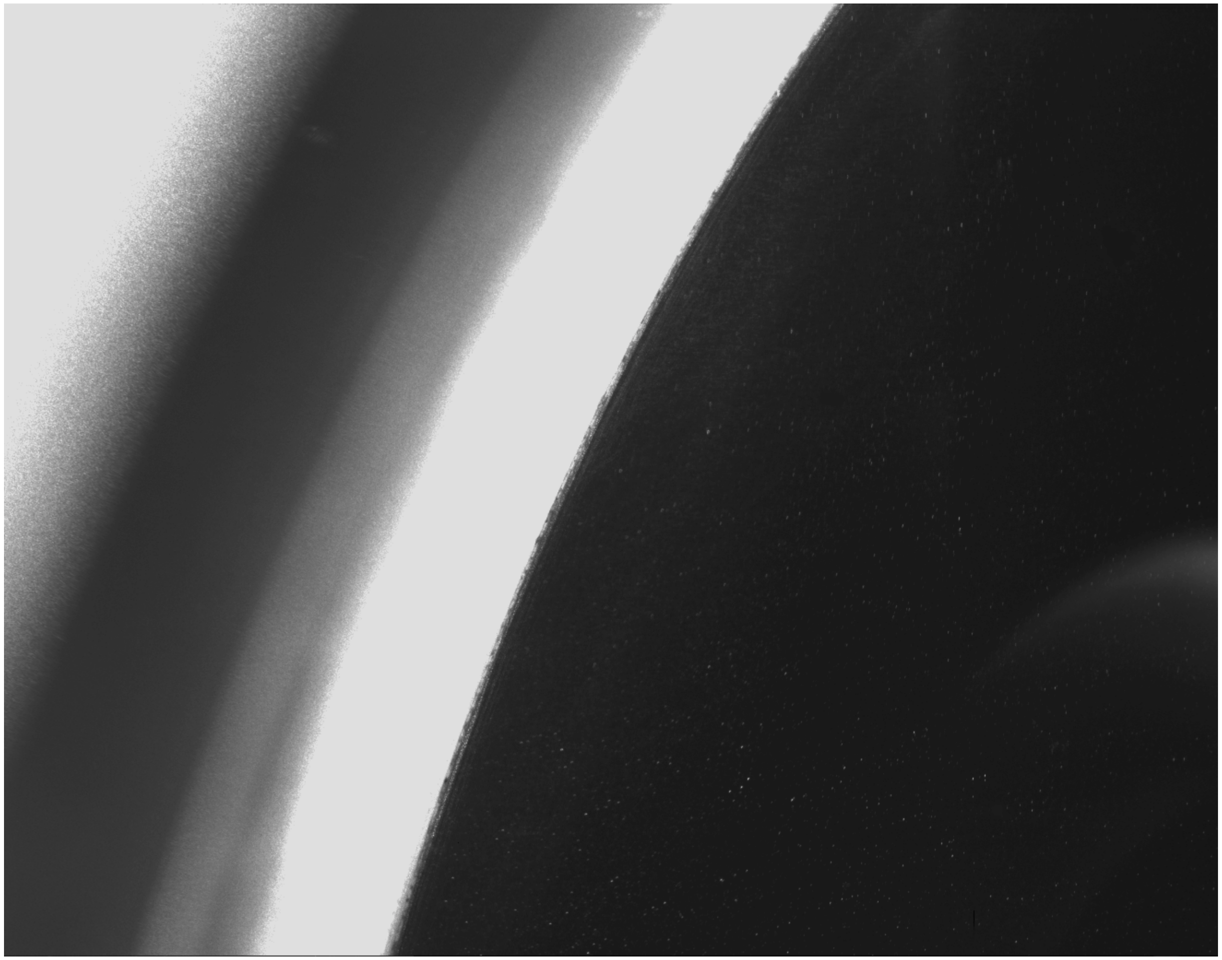
INGRESS – FLOW VISUALIZATION



No Ingress

$Re_\phi=5.16x10^5$
$Re_m=5.0x10^5$
$c_w=4512$

INGRESS – FLOW VISUALIZATION

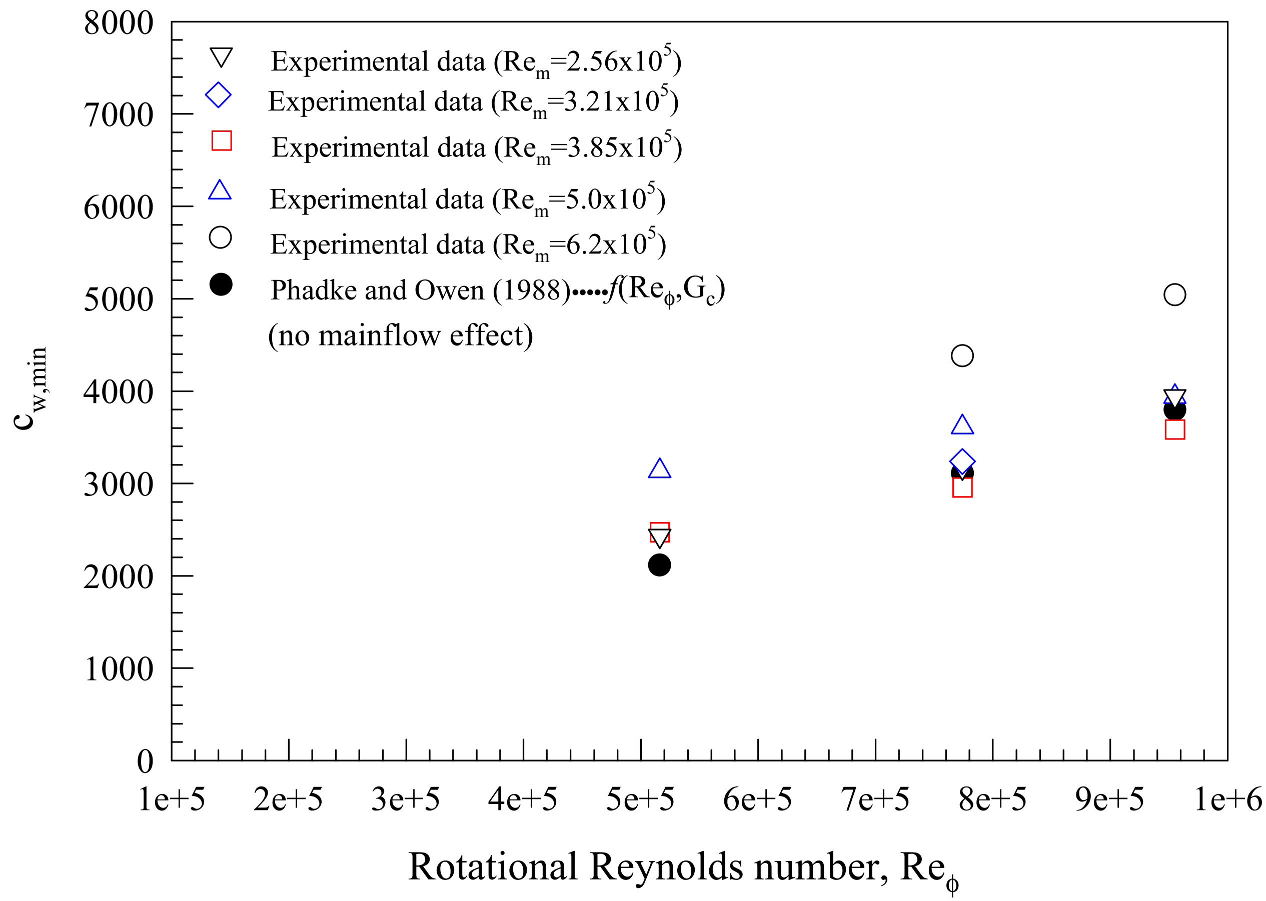


Ingress

Re_ϕ=5.16x10^5
Re_m=5.0x10^5
c_w=752

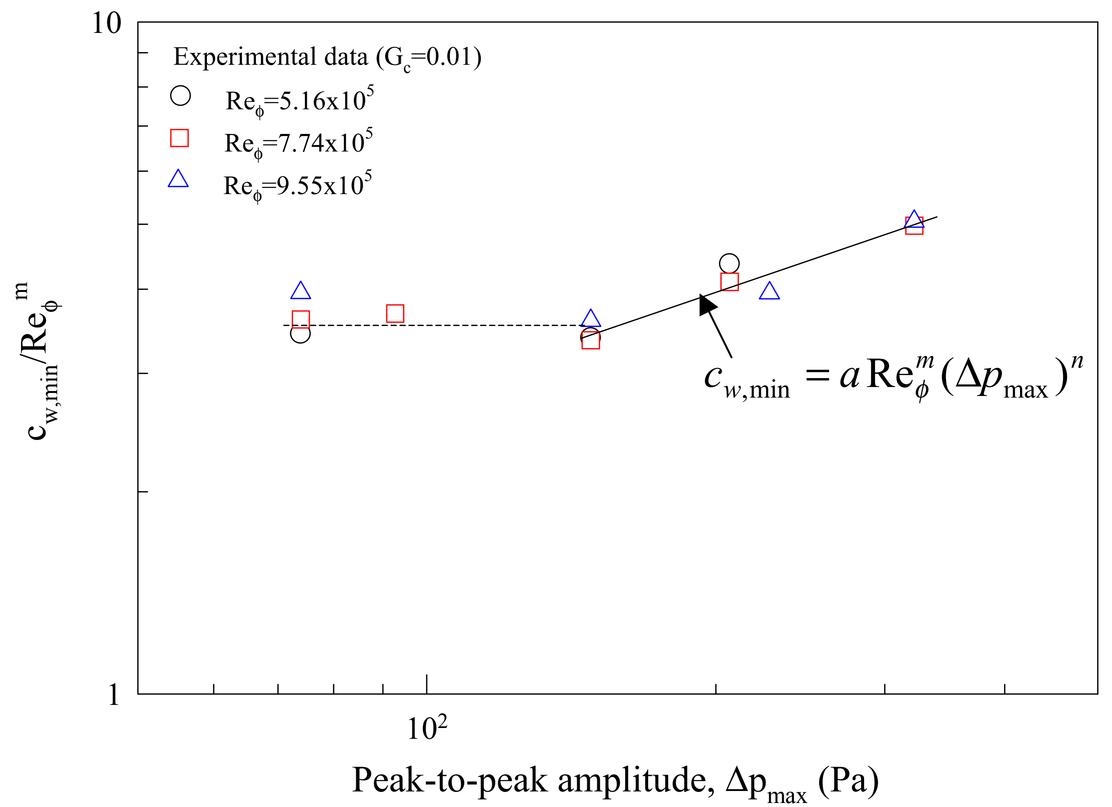
INGRESS – FLOW VISUALIZATION

Effect of Re_ϕ and Re_m on $c_{w,min}$

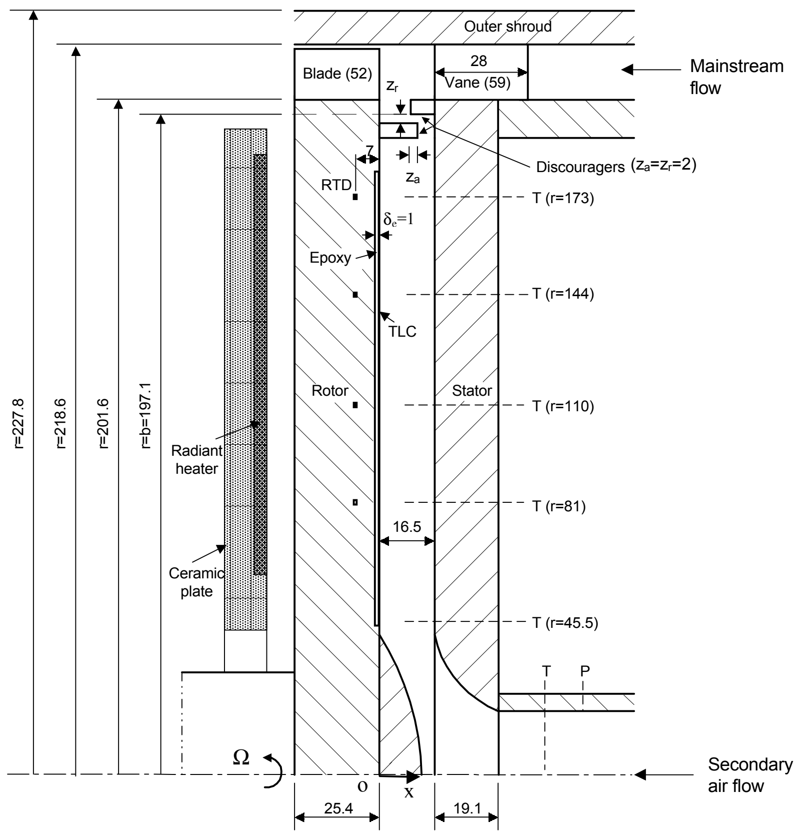


INGRESS – CORRELATION

Minimum Secondary Flow Rates for Preventing Ingress



HEAT TRANSFER TESTS



All dimensions in mm

Definition of Heat Transfer Coefficient On the Rotor Disk h(r):

$$h(r) = \frac{q''_{w,conv}(r)}{T_w(r) - T_{fluid\ \ core}(r)}$$

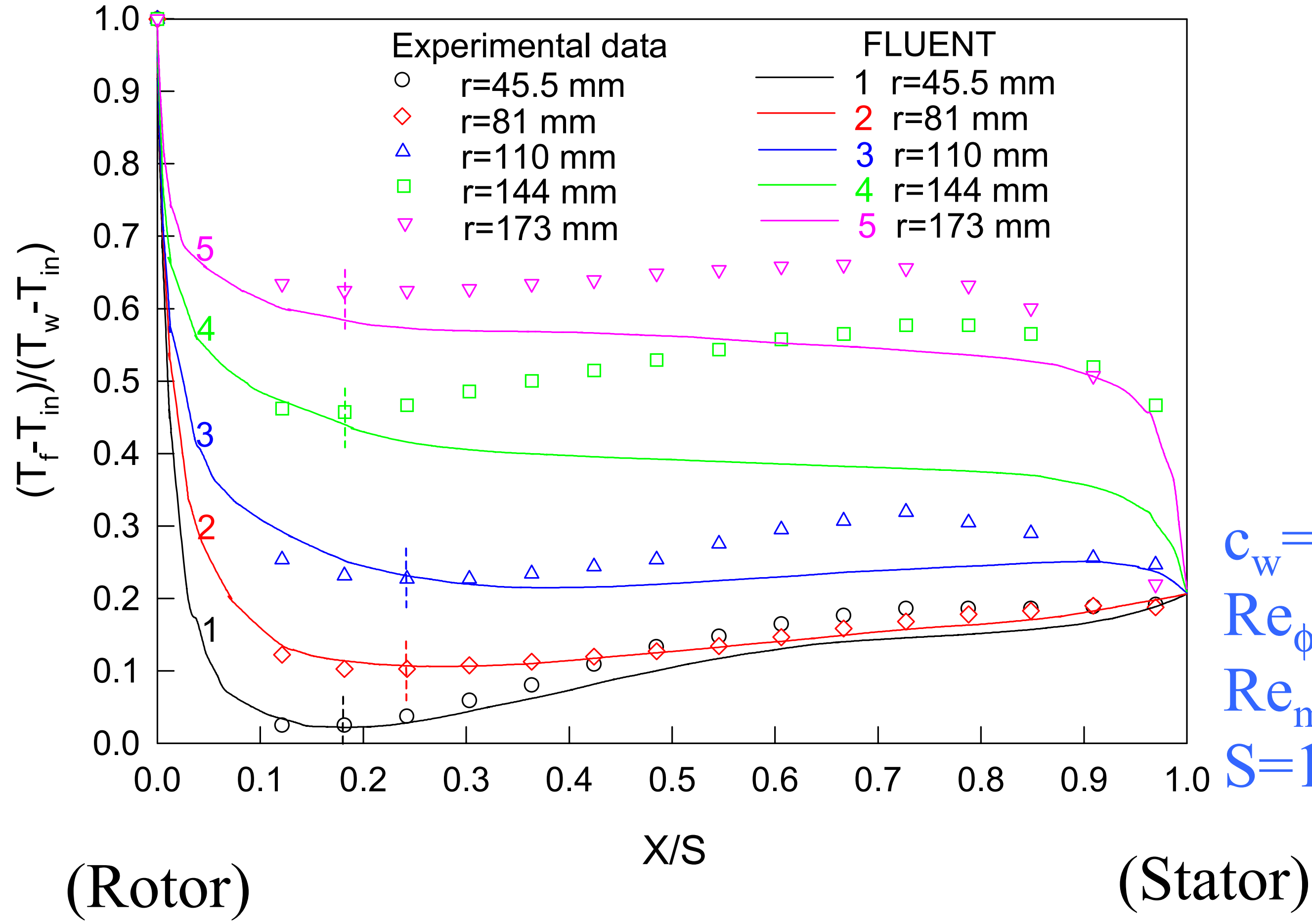
Technique used:

TLC – quasi-steady expt.

EXPERIMENTAL CONDITIONS— HEAT TRANSFER

Expt. No.	Re_ϕ	c_w	Re_m
1	4.65×10^5	1504	5.0×10^5
2	4.65×10^5	3008	5.0×10^5
3	4.65×10^5	7520	5.0×10^5
4	7.0×10^5	1504	5.0×10^5
5	7.0×10^5	3008	5.0×10^5
6	7.0×10^5	7520	5.0×10^5
7	8.6×10^5	1504	5.0×10^5
8	8.6×10^5	3008	5.0×10^5
9	8.6×10^5	7520	5.0×10^5

DISTRIBUTION OF FLUID TEMPERATURE IN THE DISK CAVITY



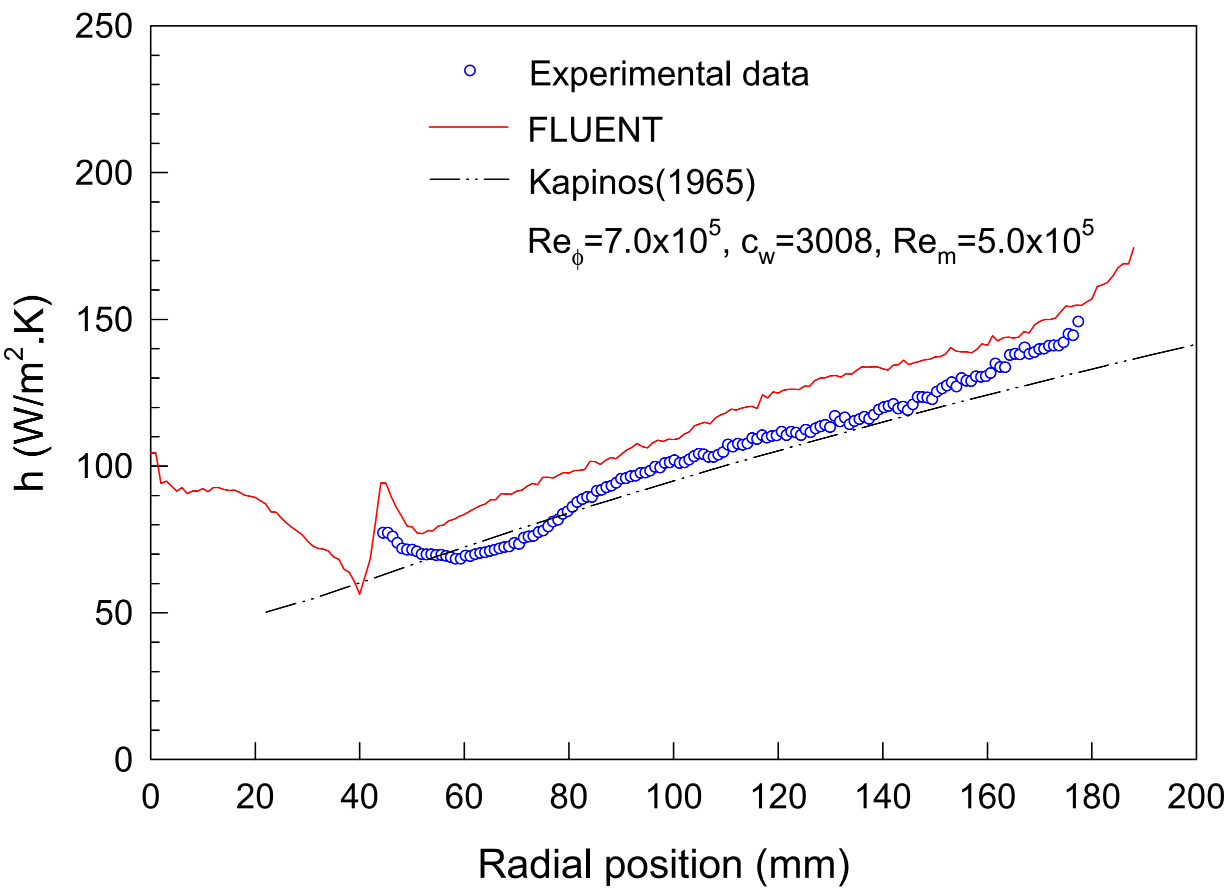
$c_w=3008$

$Re_\phi=7.0\text{x}10^5$

$Re_m=5.0\text{x}10^5$

$S=16.5$ mm

RADIAL VARIATION OF HEAT TRANSFER COEFFICIENT ON ROTOR DISK

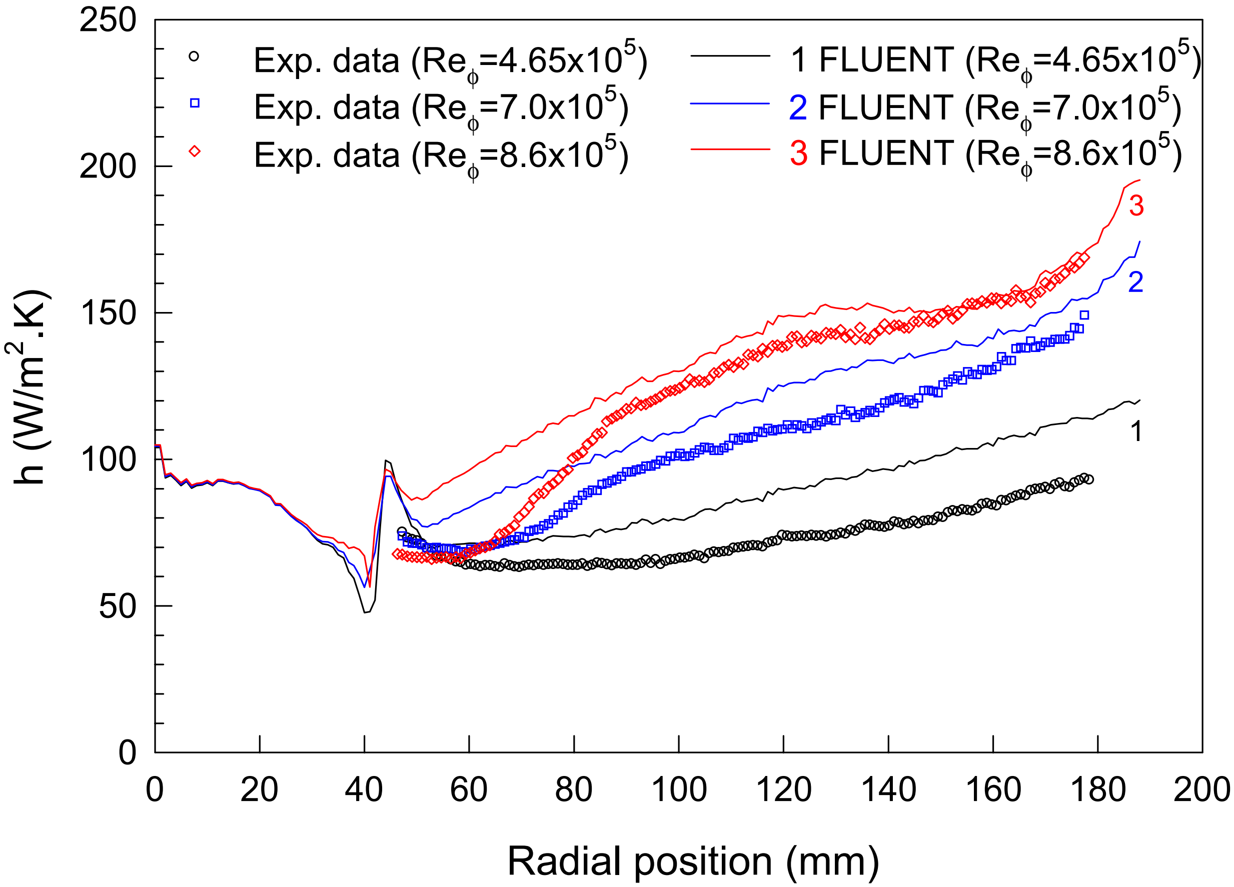


$c_w=3008$

$Re_\phi=7.0x10^5$

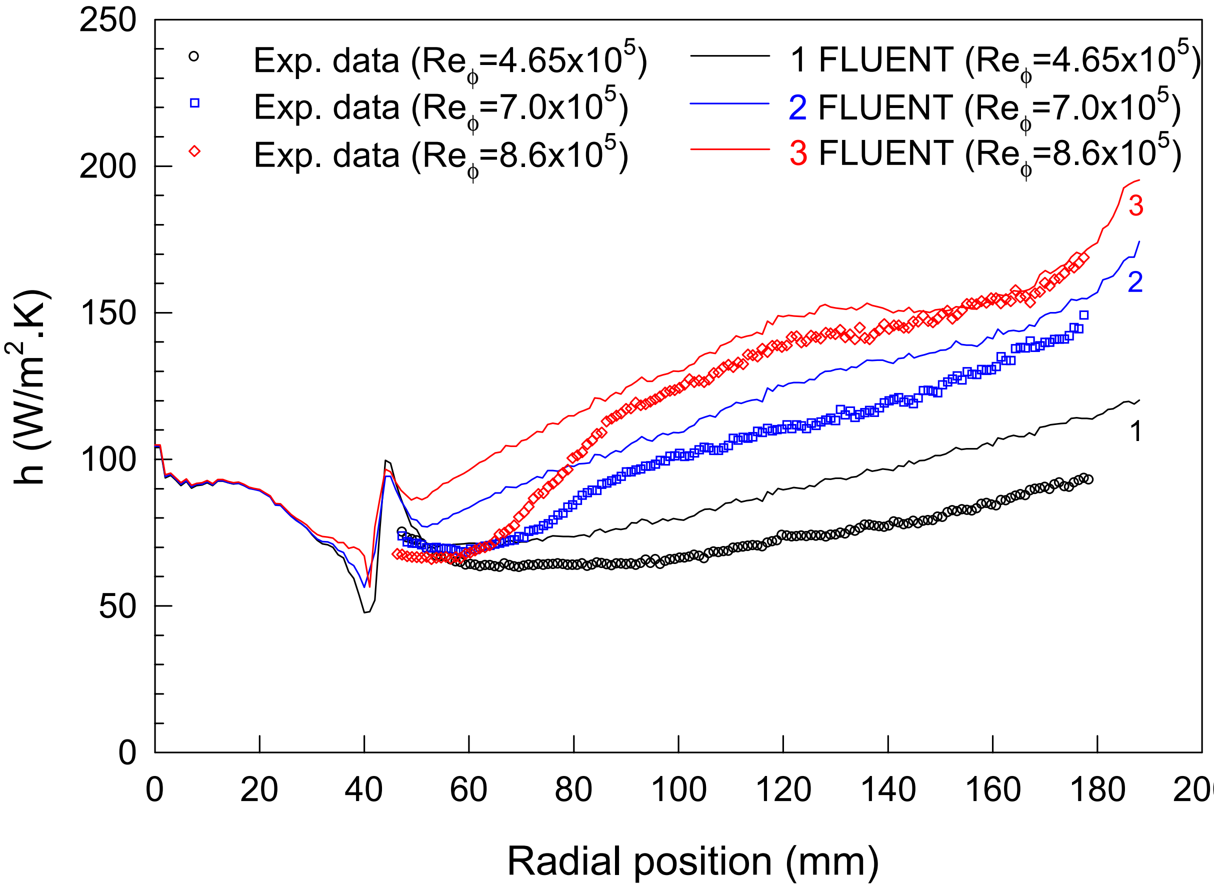
$Re_m=5.0x10^5$

EFFECT OF ROTATIONAL REYNOLDS NUMBER ON THE HEAT TRANSFER COEFFICIENT



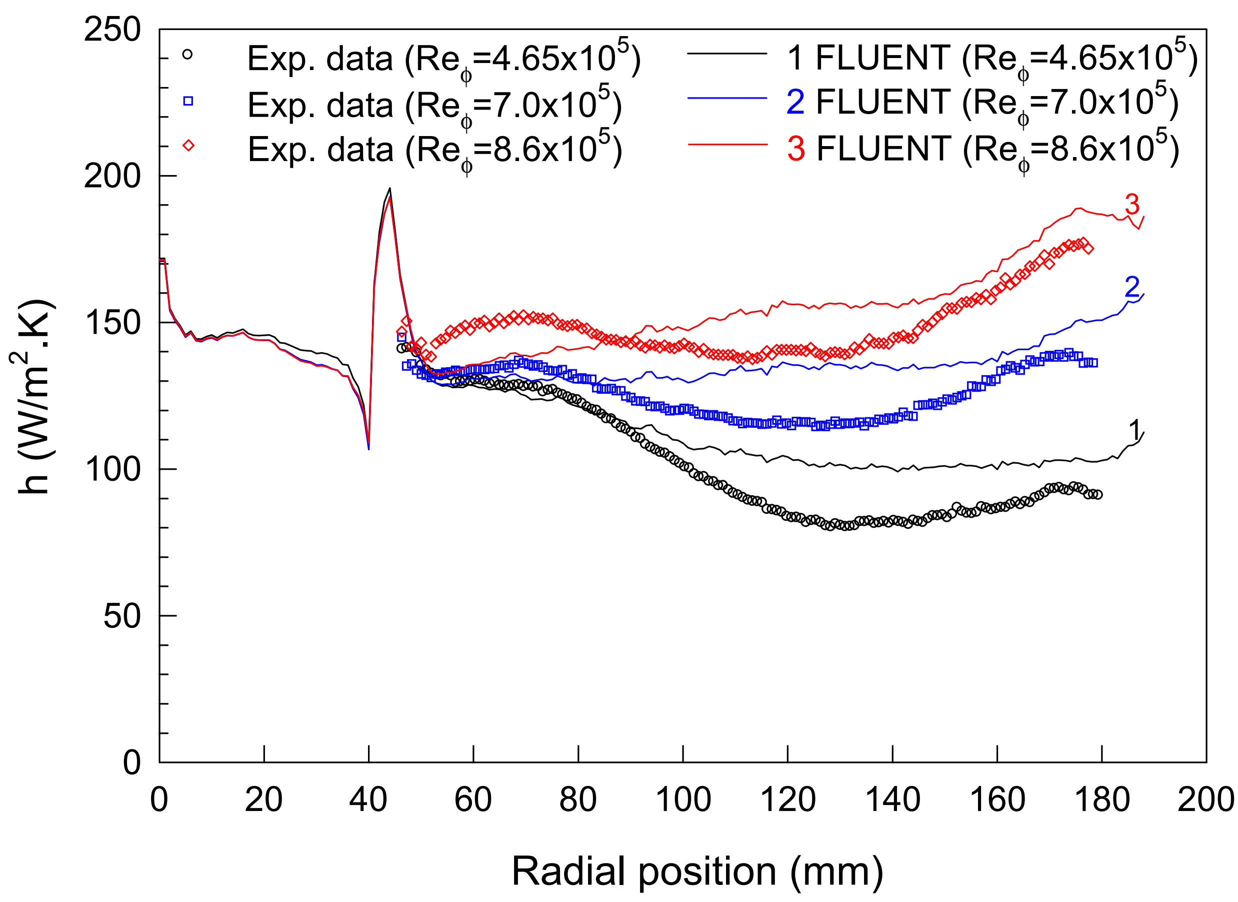
c_w=1504

EFFECT OF ROTATIONAL REYNOLDS NUMBER ON THE HEAT TRANSFER COEFFICIENT



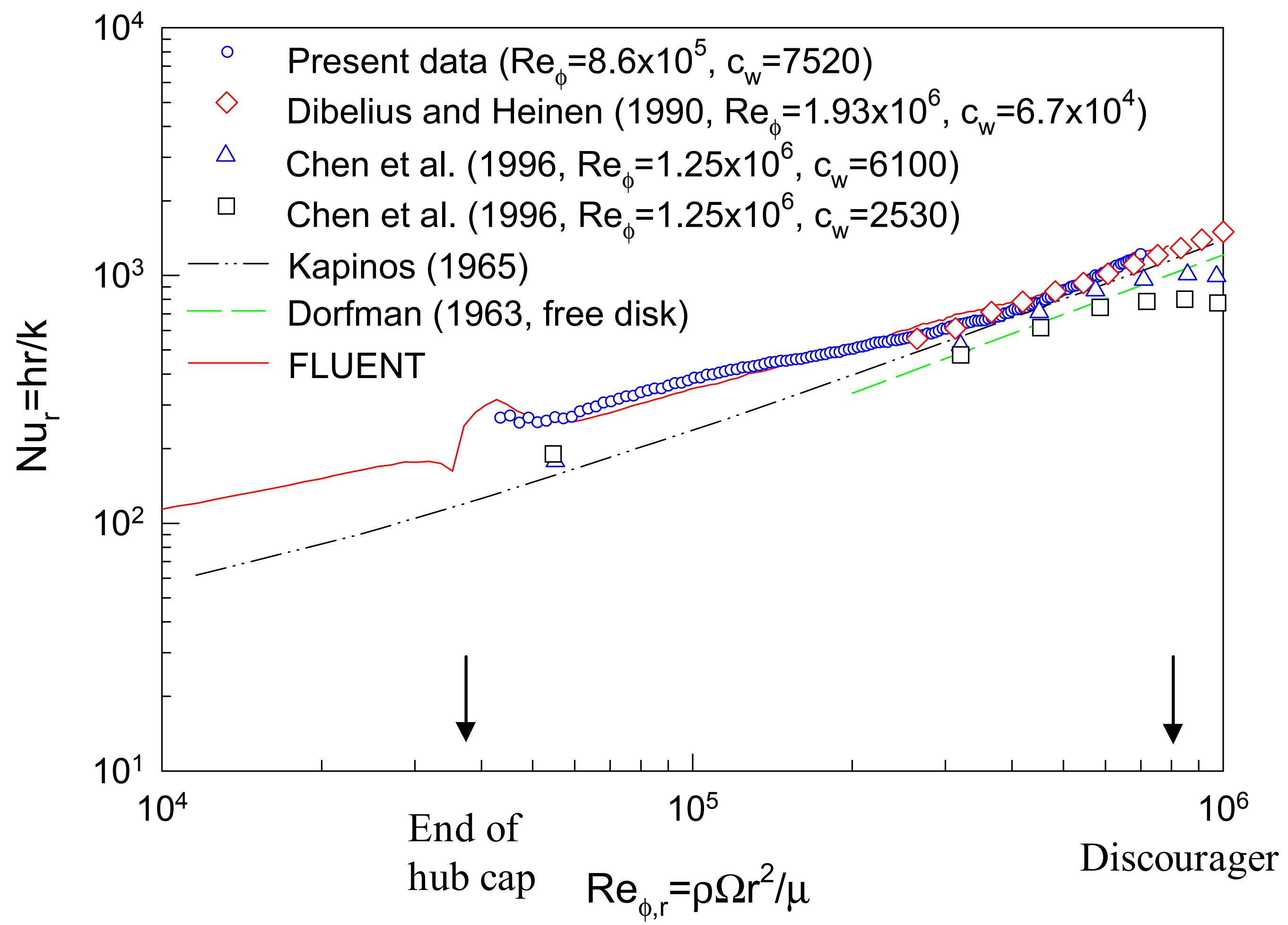
c_w=3008

EFFECT OF ROTATIONAL REYNOLDS NUMBER ON THE HEAT TRANSFER COEFFICIENT

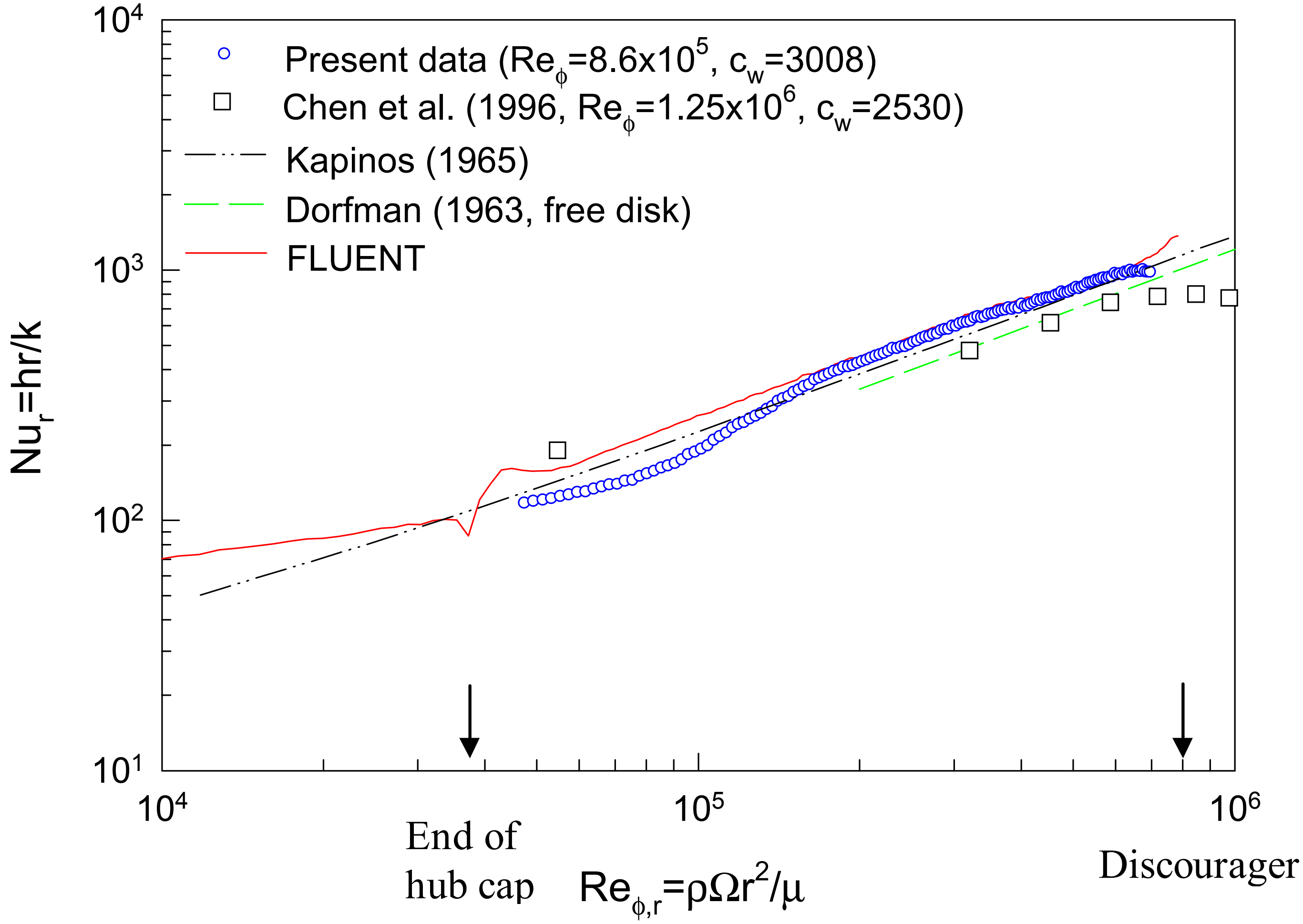


c_w=7520

COMPARISON OF PRESENT STUDY WITH PREVIOUS EXPTS. & CFD



COMPARISON OF PRESENT STUDY WITH PREVIOUS EXPTS. & CFD



CONCLUDING REMARKS

- Two Identifiable Flow Regions in the Rotor–Stator Cavity:

(1) Source Region — Core Fluid Rotation is minimal,
Strong Radial Outflow Near the Rotor Disk,
Weaker Radial Inflow Near the Stator Disk,
Region Increases in Radial Extent with c_w
& Decreases Slightly with Re_ϕ

(2) Core Region — Flow Dominated by Tangential Velocity
(Except when c_w is high, e.g., $\approx c_{w,fd}$)

CONCLUDING REMARKS (Contd.)

- CFD

  — FLUENT / UNS: Rotationally Symmetric (2D) Near-Wall Calculations Provided Reasonable Results Except for Ingress

  3D Simulation (so far only with wall function) Was Better for Ingress Simulation; Near-wall Calculation in Progress

- Laser Sheet Visualization Provided Quantitative Information on Initiation of Ingress. An empirical correlation has been developed for the $c_{w,minimum}$.

CONCLUDING REMARKS (Contd.)

- Circumferentially Periodic (Following the Vane Pitch) Static Pressure Distribution in the Mainstream Path:

  — Peak-to-Peak Amplitude ~ (Mainstream Flow Rate)^2

  — $c_{p,max} \approx 0.25$ at the Vane Exit Plane & Decays Rapidly Downstream

- Cavity Pressure Field:

  — No Circumferential Pressure Asymmetry Found, Even Near the Rim

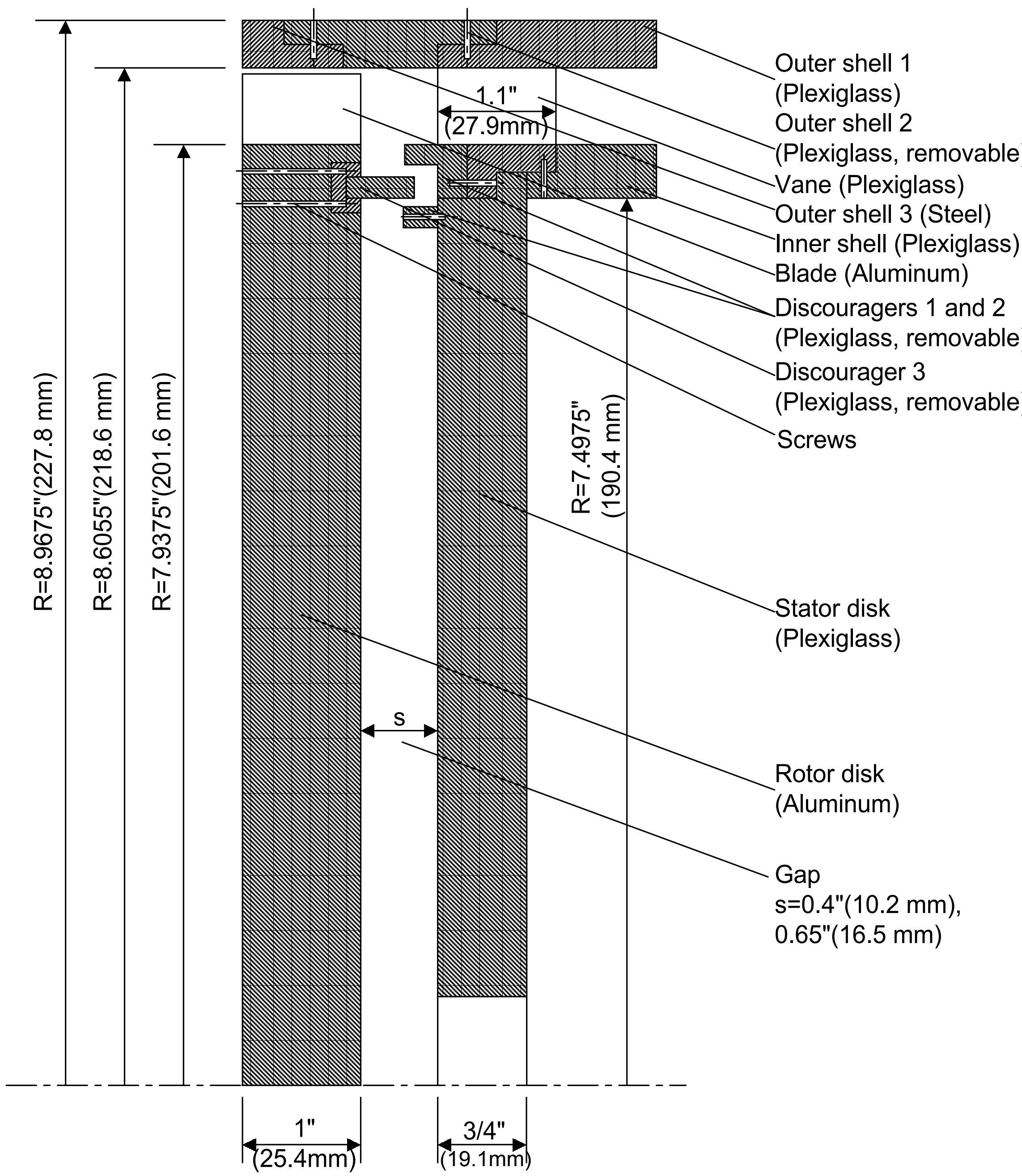
  — Adverse Radial Pressure Gradient When c_w is Small (Facilitates Ingress)

CONCLUDING REMARKS (Contd.)

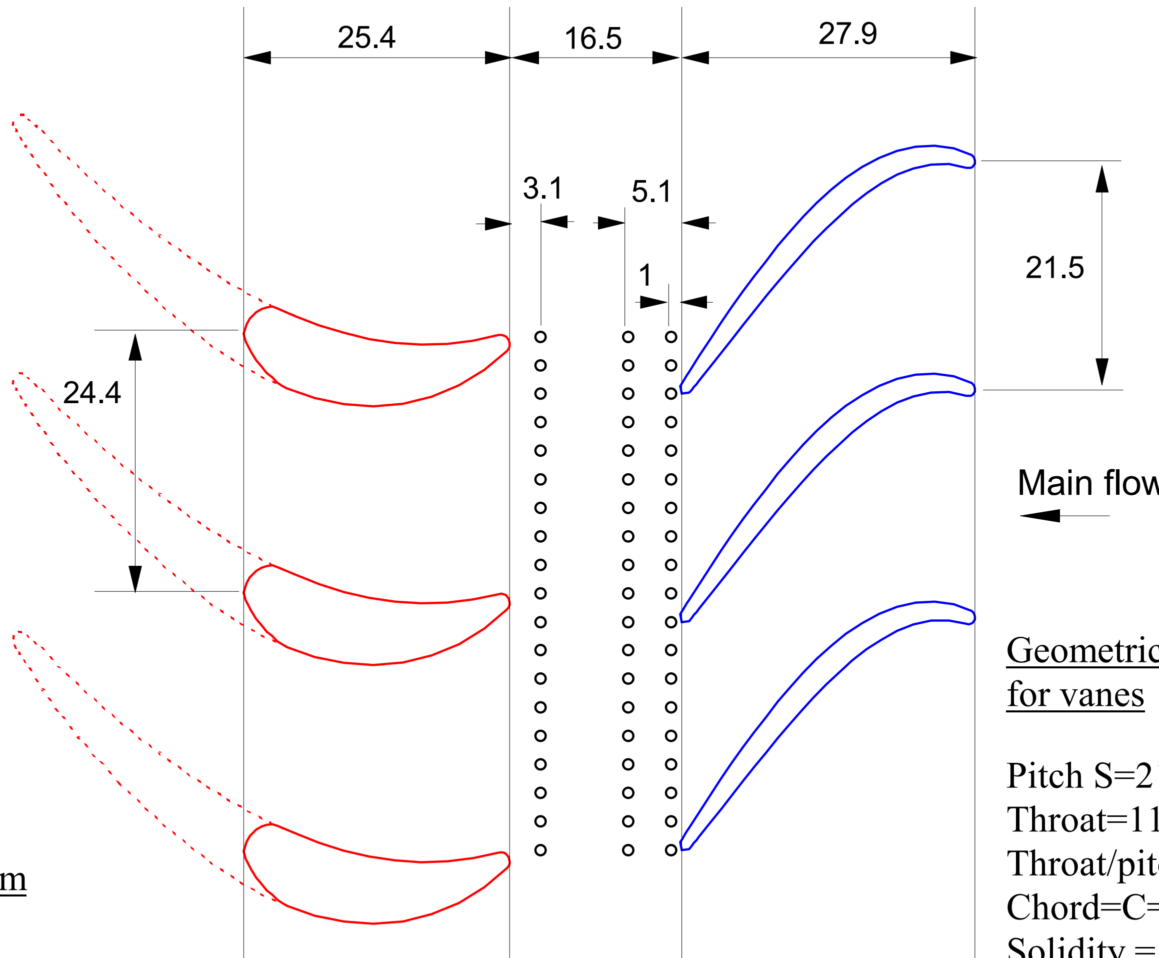
- Convective Heat Transfer Coefficient Distribution on the Rotor Disk:

  - Proper choice of reference fluid temperature in defining h is important.
  - h is influenced by: the local rotational Reynolds number $Re_{\phi,r}$, secondary air entry location in the cavity, and secondary air flow rate.
  - For secondary air injection at the hub, a simple empirical Nusselt number correlation is unable to represent the measurements from the hub to the rim. We have developed a correlation for the rotationally dominated region (typically, radially outboard) of the disk.

THE NEW DISK CAVITY CONFIGURATION



GUIDE VANES AND BLADES WITH NEW PRESSURE PORTS



blades (52)

vanes (59)

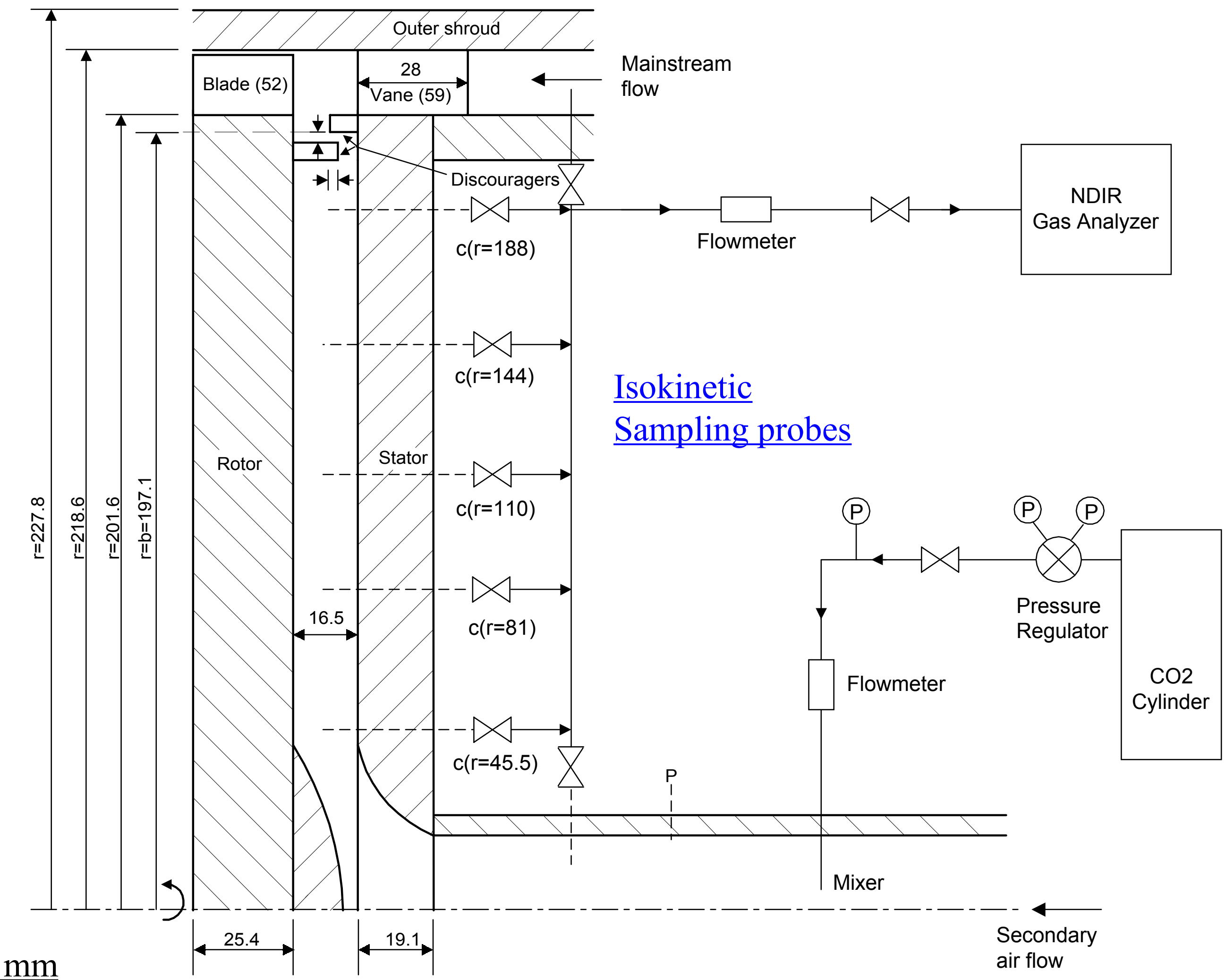
All dimensions are in mm

○ pressure taps

Geometric parameters for vanes

Pitch S=21.5 mm
Throat=11.86 mm
Throat/pitch=0.552
Chord=C=35.23 mm
Solidity = 1.639

SCHEMATIC DIAGRAM OF TRACER GAS CONCENTRATION MEASUREMENT



All dimensions in mm