Secondary Air System Component Modelling For Engine Performance Simulations

A. Alexiou & K. Mathioudakis

Laboratory of Thermal Turbomachines
National Technical University of Athens

Paper Objectives

- **Describe an object-oriented approach for modelling Secondary Air Systems**

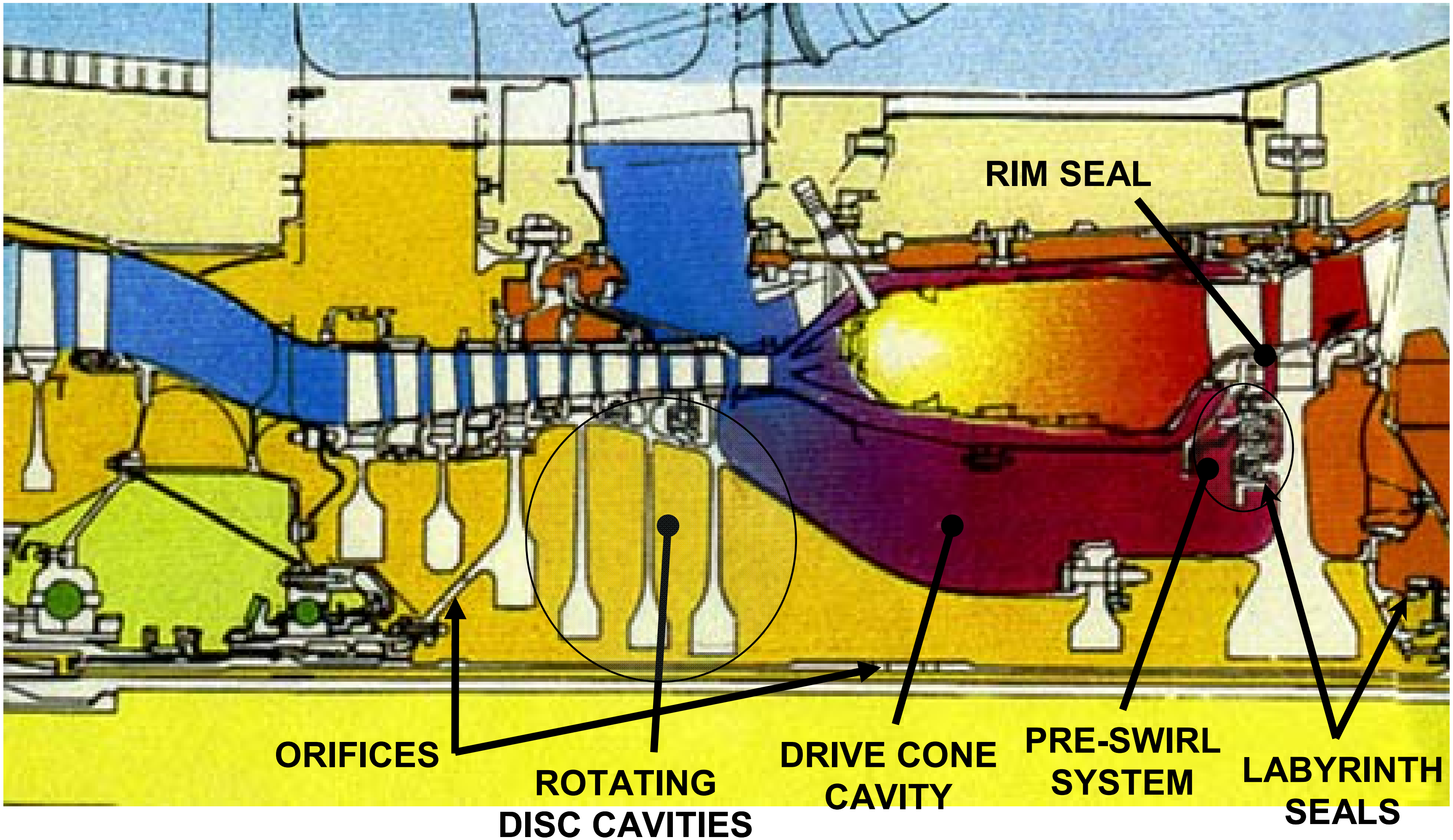
- **Present the detailed modelling of some typical Secondary Air System components**

- **Validate the modelling against publicly available experimental and/or computational results**

- **Demonstrate the integration of such components in a whole engine performance model**

Contents

Secondary Air System Schematic



Secondary Air System Modelling: Current Approach

Engine Performance Model

↑

Values for Bleeds & Returns for particular engine running conditions

Dedicated Air System Model

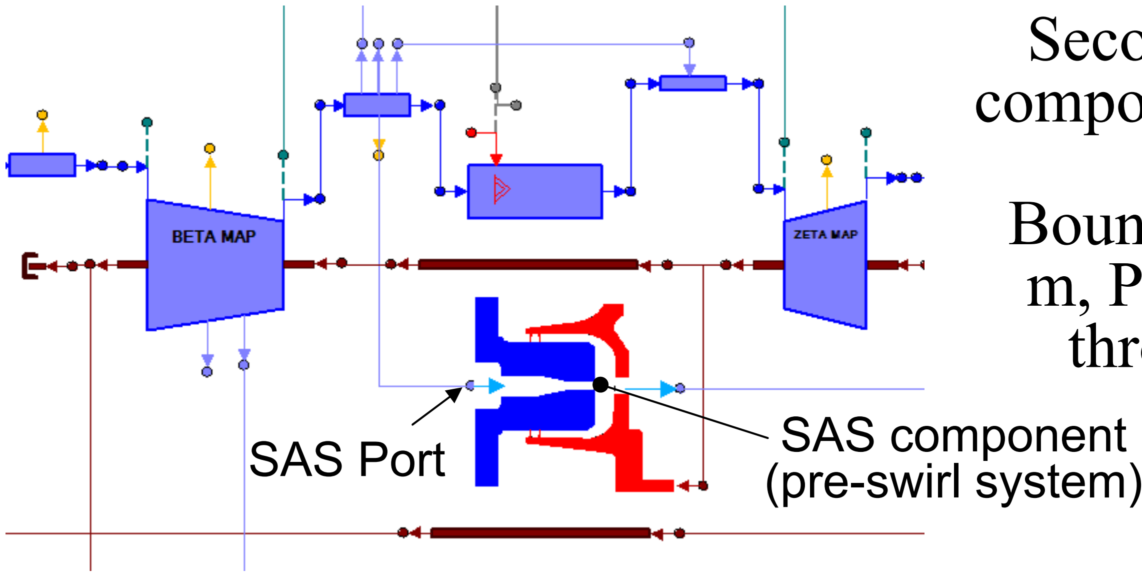
<u>Disadvantages</u>

❑ The Secondary Air System is a “black box” for the performance engineer.

❑ The Air System designer cannot assess autonomously the system performance as part of the whole engine model.

❑ Increased scope for error during data exchange.

Secondary Air System Modelling: Proposed Approach



Secondary Air System (SAS) components directly integrated in engine model.
Boundary conditions (IN/OUT m, Pt, Tt, Vφ) communicated through appropriate Ports.

Advantages

- ❑ Individual components or entire air systems can be integrated transparently in whole engine performance models.
- ❑ Different air system design configurations can be constructed and compared in a generic, flexible and intuitive manner.
- ❑ Component changes visible during model exchanging.

Contents

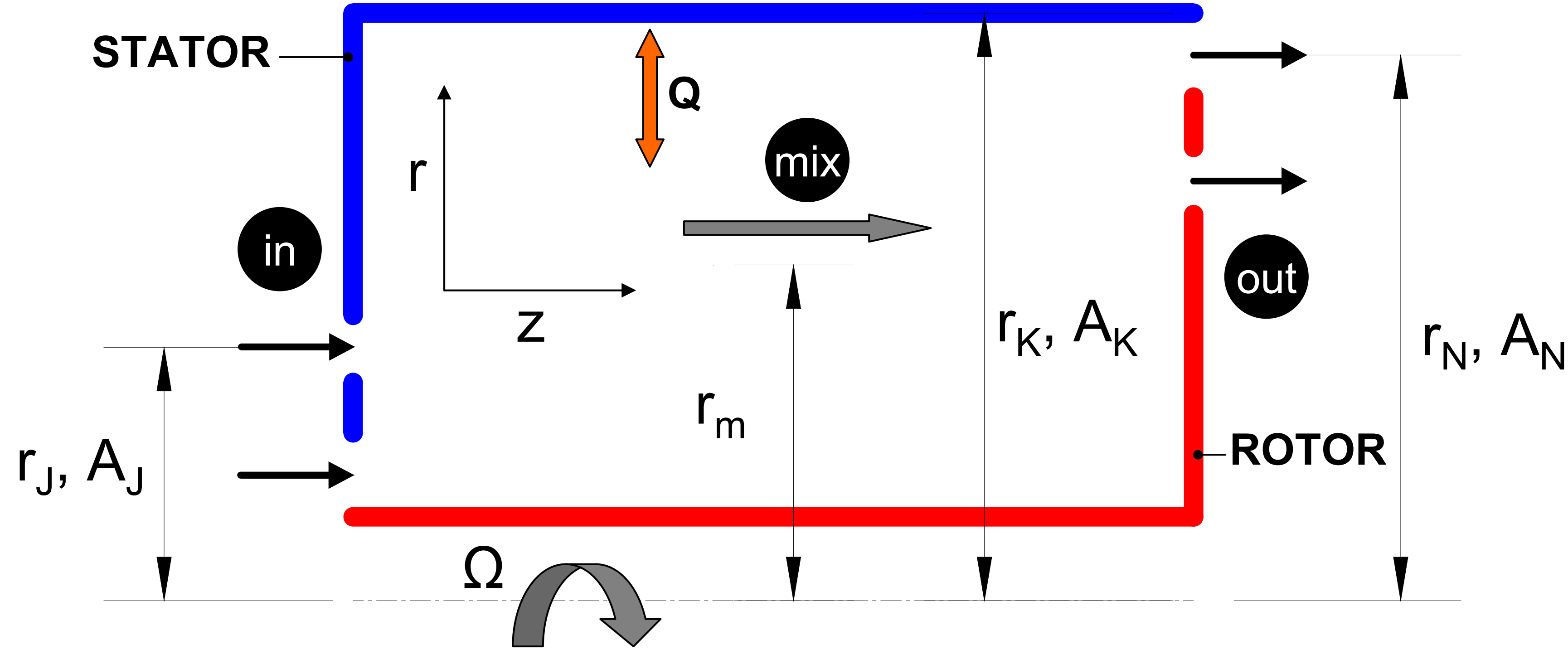
Component Models

Using the advantages of object-oriented modelling (such as encapsulation, inheritance, abstraction aggregation and polymorphism), it is possible to create secondary air system models for a variety of engine configurations using three main components: **generic**, **orifice** and **labyrinth seal**.

For a specified component geometry, the inlet flow conditions (m, Pt, Tt, Vφ) are linked to the outflow ones through the conservation equations for mass flow, energy, axial and angular momentum.

The component's performance can be calculated for any valid combination of input/output variables and component characteristics.

Generic Component Model



- Arbitrary geometry (discs, cones, cylinders)
- **J** Input flows and **N** output flows
- Fully mixed flow
- Work and heat transfer from surrounding **K** surfaces
- SAS examples: pre-swirl system chamber, compressor inter-disc cavities, drive-cone cavity

Generic Component Equations (I)

Angular Momentum Conservation Equation $\rightarrow V_{\varphi,mix}$

$$\dot{m}_{mix} \cdot r_m \cdot V_{\phi,mix} - \sum_{j=1}^{J} \left(\dot{m}_{in,j} \cdot r_{in,j} \cdot V_{\phi,in,j} \right) = \sum_{k=1}^{K} M_k$$

Moment exerted by fluid on each surrounding surface, M_k (from drag force equation):

$$M_k = 0.5 \cdot C_{m,k} \cdot r_k \cdot A_k \cdot \rho_{mix} \cdot \left| \Omega \cdot r_k - V_{\phi,mix} \right| \cdot \left(\Omega \cdot r_k - V_{\phi,mix} \right)$$

Energy Conservation Equation $\rightarrow T_{t,mix}$

$$\dot{m}_{mix} \cdot C_{p,mix} \cdot T_{t,mix} - \sum_{j=1}^{J} \left(\dot{m}_{in,j} \cdot C_{p,j} \cdot T_{t,in,j} \right) = Q + \sum_{k=1}^{K} \Omega \cdot M_k$$

Generic Component Equations (II)

Mixing total pressure, $P_{t,mix}$

$$P_{t,mix} = P_{s,mix} \cdot \left[(1-\zeta) \cdot \left(\frac{T_{t,mix} - \left(Q / \left(\dot{m}_{mix} \cdot C_P\right)\right)}{T_{s,mix}} \right)^{\frac{\gamma}{\gamma-1}} + \zeta \right]$$

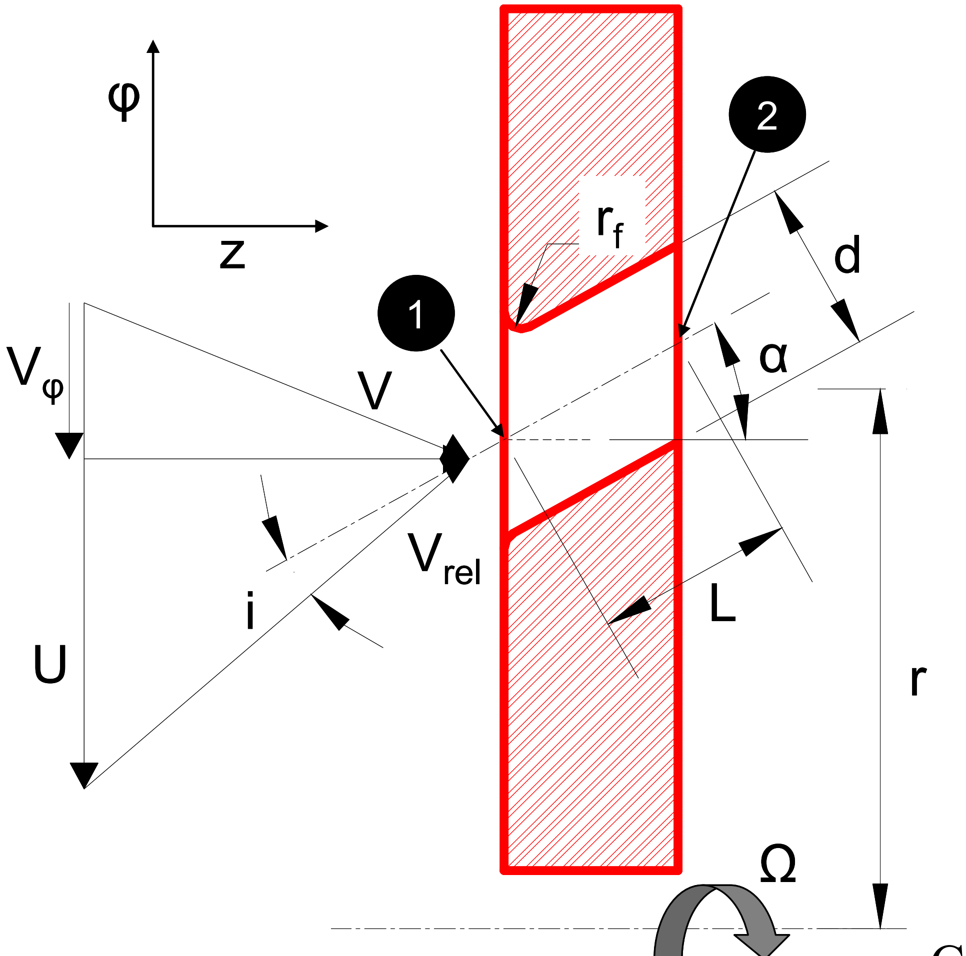
Axial momentum equation → $P_{s,mix}$:

$$P_{s,mix} = \frac{\sum_{j=1}^{J} \left(\dot{m}_{in,j} \cdot V_{z,in,j} + P_{s,in,j} \cdot A_{in,j} \right) - \dot{m}_{mix} \cdot V_{z,mix}}{A_{mix}} - \left(P_{t,mix,is} - P_{t,mix} \right)$$

Convective heat transfer, Q:

$$Q = h_{av} \cdot A_S \cdot \left(T_S - T_{ref} \right)$$

Orifice Component Model



- Axial & radial holes
- Rotating & stationary

$$C_D = \frac{\dot{m}_h}{\dot{m}_{is}}$$

Discharge Coefficient C_D corrected through correlations for:

- ✓ Hole Reynolds number
- ✓ Inlet corner radius
- ✓ Hole length
- ✓ Pressure ratio
- ✓ Incidence angle

$$C_D = 1 - f_1 \cdot f_{2,r_f/d} \cdot f_{2,L/d'} \cdot f_3 \cdot \left(1 - C_{D:Re}\right) + \Delta C_{D:i}$$

Orifice Component Equations

1-D, isentropic, compressible expansion of a perfect gas from the upstream total pressure to the downstream static pressure and considering the work transfer to the fluid:

$$\dot{m}_{is} = A_h \cdot \rho_{t,1} \cdot \left(\frac{P_{s,2}}{P_{t,1}}\right)^{\frac{1}{\gamma}} \cdot \left\{ \left(\frac{2\cdot\gamma}{\gamma-1}\right)\cdot\frac{P_{t,1}}{\rho_{t,1}}\cdot\left[1-\left(\frac{P_{s,2}}{P_{t,1}}\right)^{\frac{\gamma-1}{\gamma}}\right] + 2\cdot\Omega\cdot\left(r_2\cdot V_{\phi,2}-r_1\cdot V_{\phi,1}\right)-V_{\phi,2}^2 \right\}^{1/2}$$

Incidence Angle Definition

Axial Holes

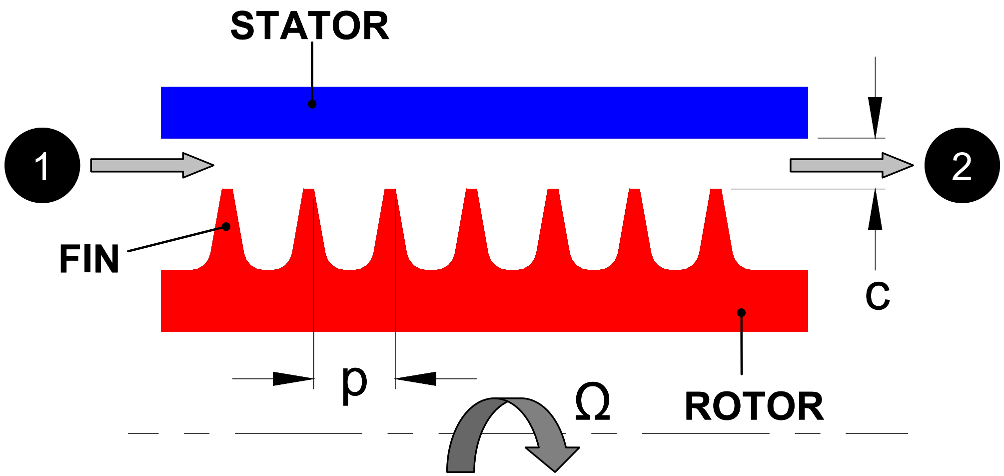
$$i = \tan^{-1}\left(\frac{U-V_{\phi,1}}{V_{is}\cdot\cos\alpha}\right)-\alpha$$

Radial Holes

$$i = \tan^{-1}\left(\frac{\sqrt{(U-V_{\phi,1})^2+V_{z,1}^2}}{V_{is}\cdot\cos\alpha}\right)-\alpha$$

Labyrinth Seal Component Model

For flow through straight, staggered and stepped labyrinth seals



$$\dot{m} = A \cdot C_D \cdot \Gamma \cdot \frac{P_{t,1}}{\sqrt{R \cdot T_{t,1}}} \cdot \sqrt{\frac{1 - PR_t^2}{n + \ln(1/PR_t)}}$$

$C_D = 0.71$ for $1.3 < c/t < 2.3$

$$\Gamma = \sqrt{\frac{1}{1 - \frac{n-1}{n} \cdot \frac{c/p}{c/p + 0.02}}}$$

Contents

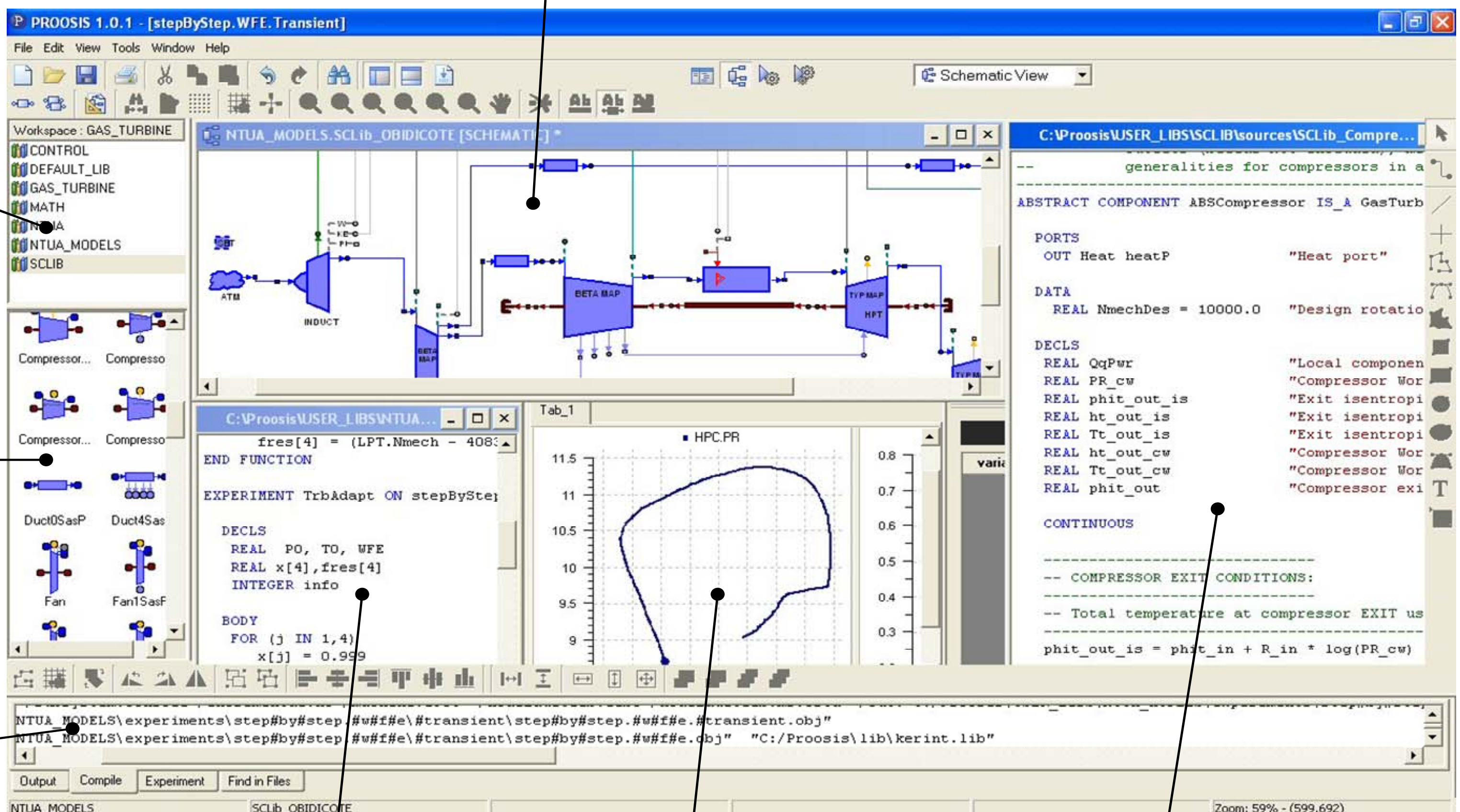
Simulation Environment Overview

Engine Diagram
(schematic view)

libraries

palette

Output
Window

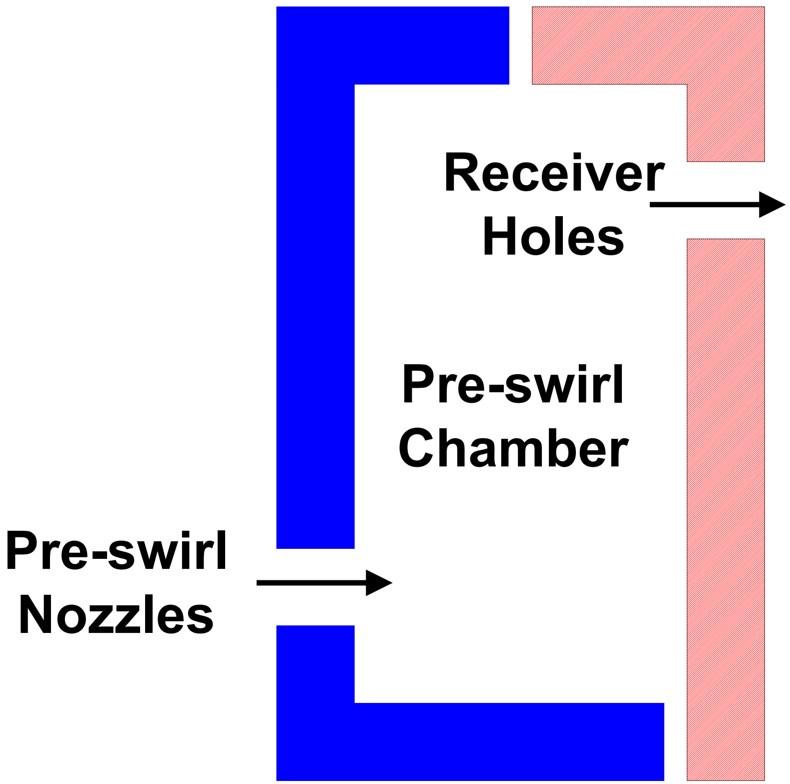


Experiment EL file
(Simulation View)

Experiment Results
(Simulation View)

Component EL file
(Code View)

Test Cases: Pre-Swirl Chamber



Adiabatic Effectiveness

$$\Theta = \frac{2 \cdot C_P \cdot \left(T_{t,PN} - T_{t,rel,RH}\right)}{\Omega^2 \cdot r_{RH}^2}$$

Relative Total Temperature

$$T_{t,rel,RH} = T_{t,mix} + \frac{\left(\Omega \cdot r_{RH}\right)^2 - 2 \cdot \Omega \cdot r_{RH} \cdot V_{\phi,mix,RH}}{2 \cdot C_P}$$

Theoretical value of Θ

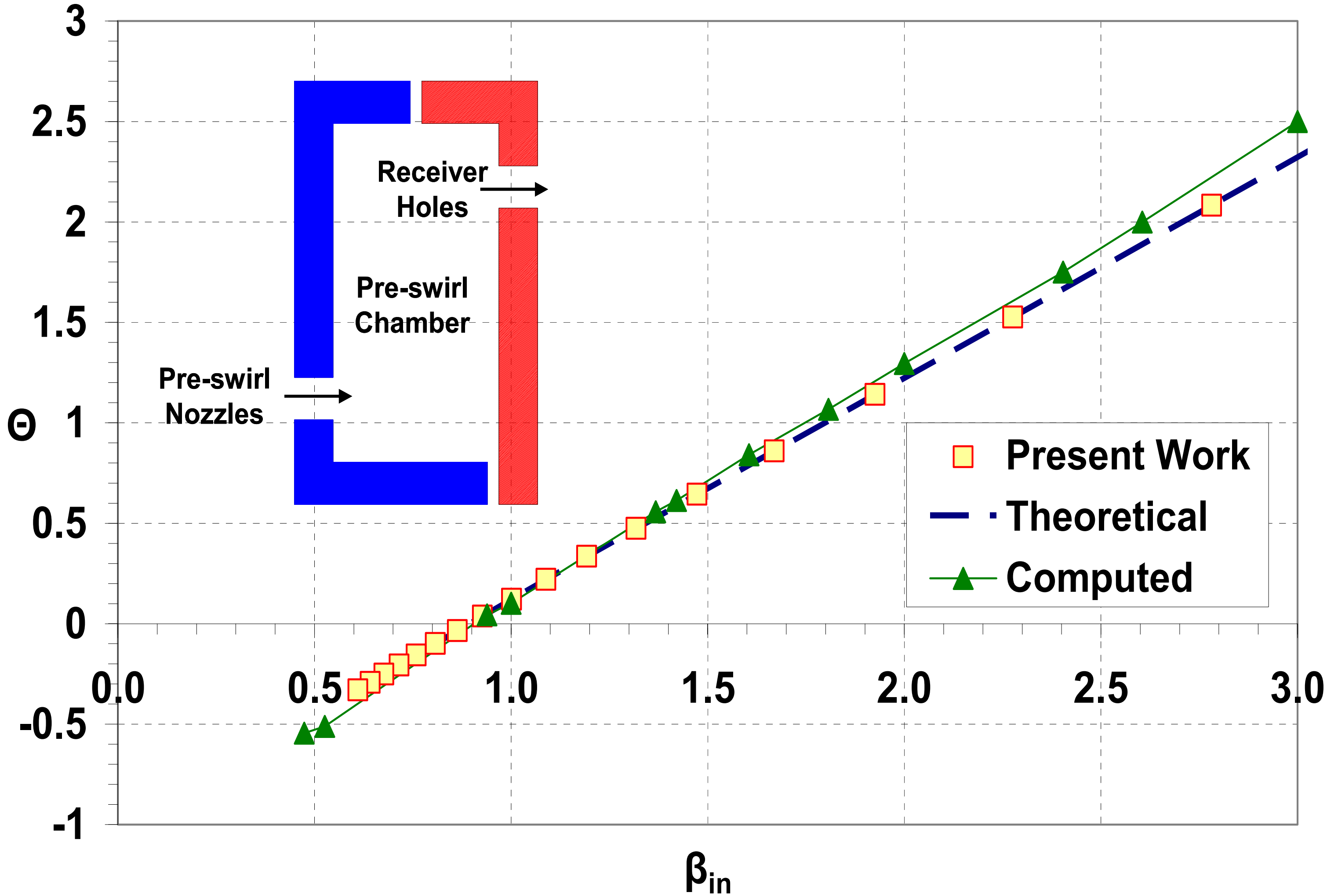
$$\Theta = 2 \cdot \beta_{in} \cdot \left(\frac{r_{PN}}{r_{RH}}\right)^2 - 1 - \frac{2 \cdot M_S}{\dot{m} \cdot \Omega \cdot r_{RH}^2}$$

Inlet Swirl ratio

$$\beta_{in} = \frac{V_{\phi,in}}{\Omega \cdot r_{PN}}$$

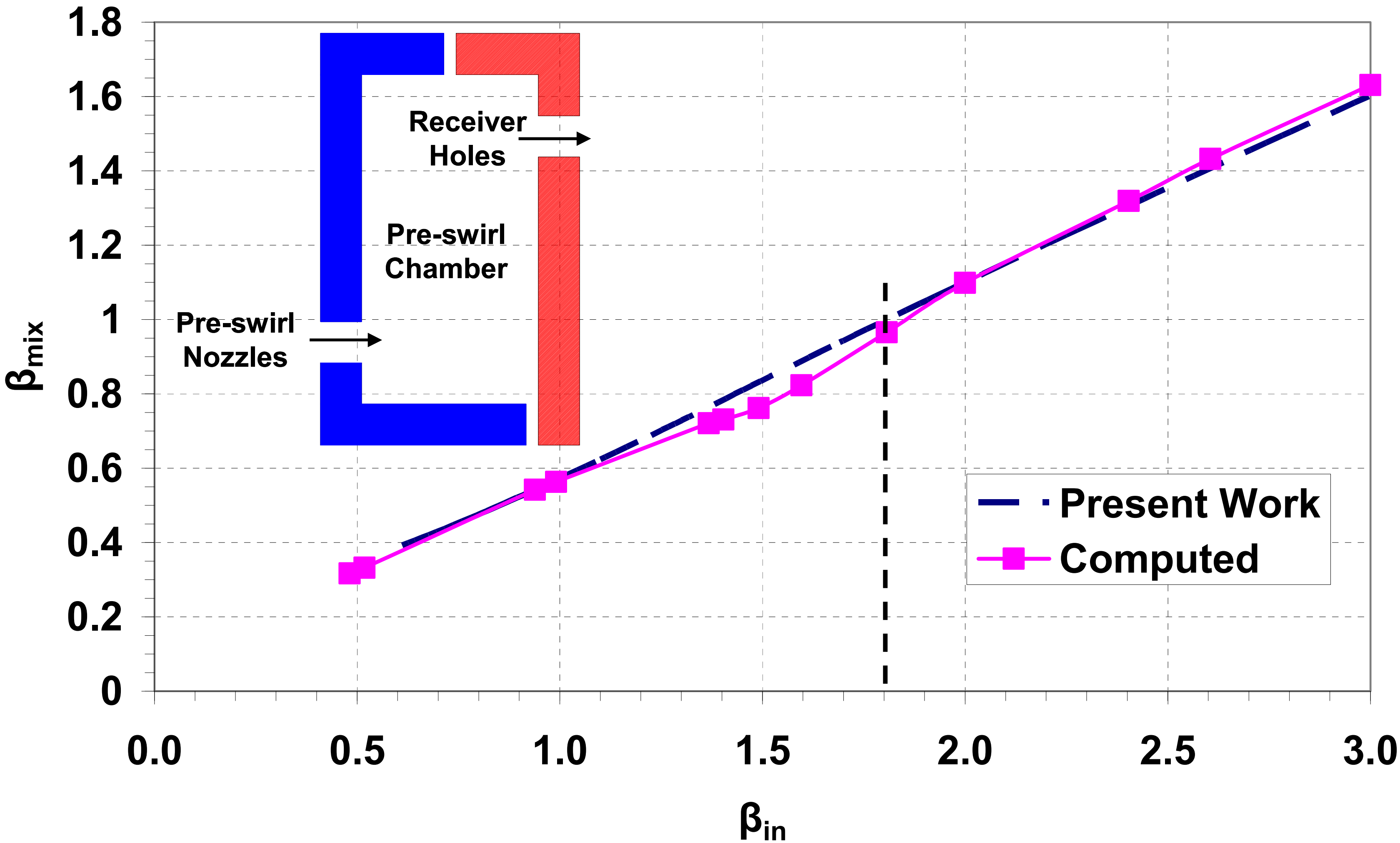
Test Cases: Pre-Swirl Chamber

Lewis et al, ASME GT-2006-90132



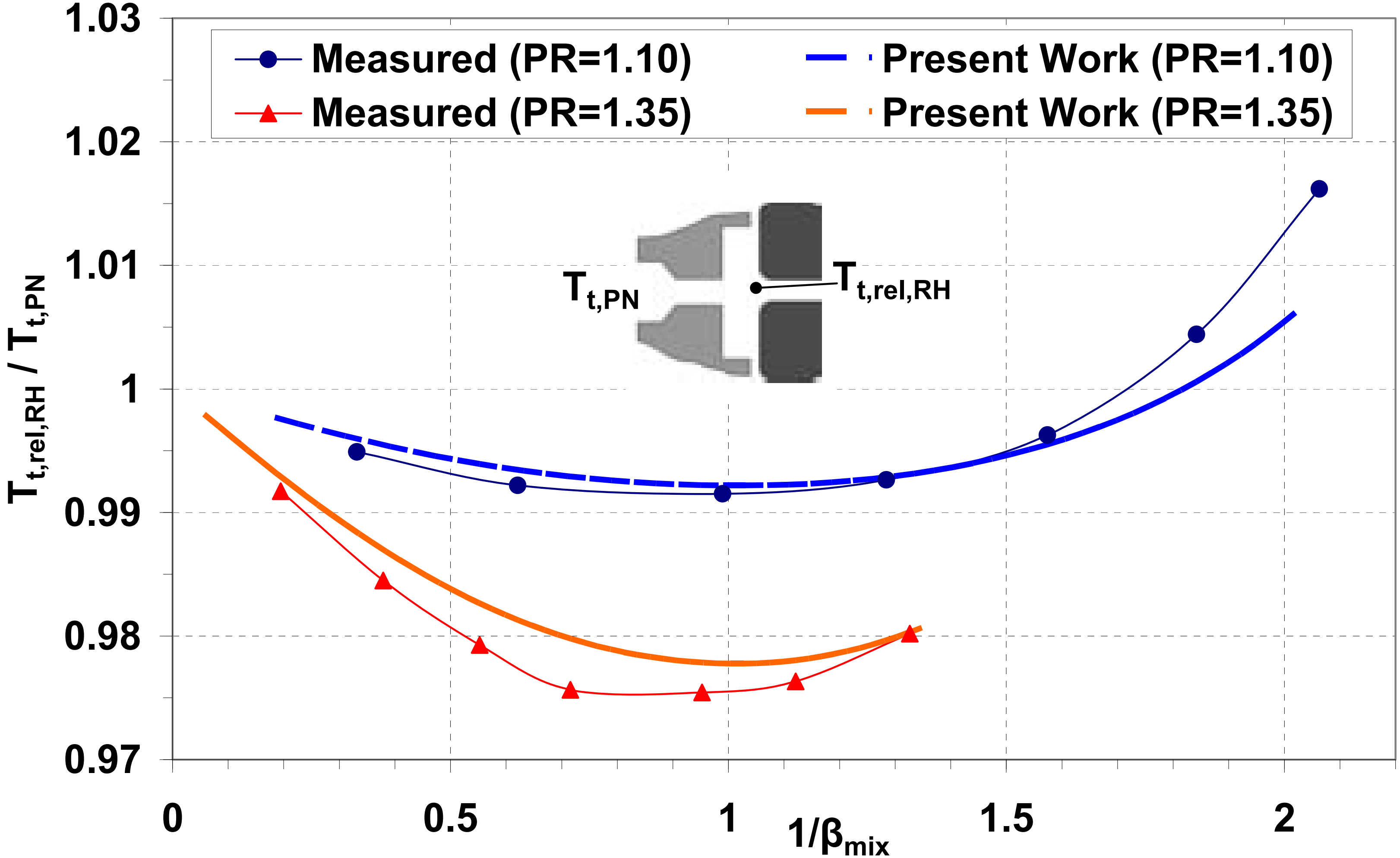
Test Cases: Pre-Swirl Chamber

Lewis et al, ASME GT-2006-90132



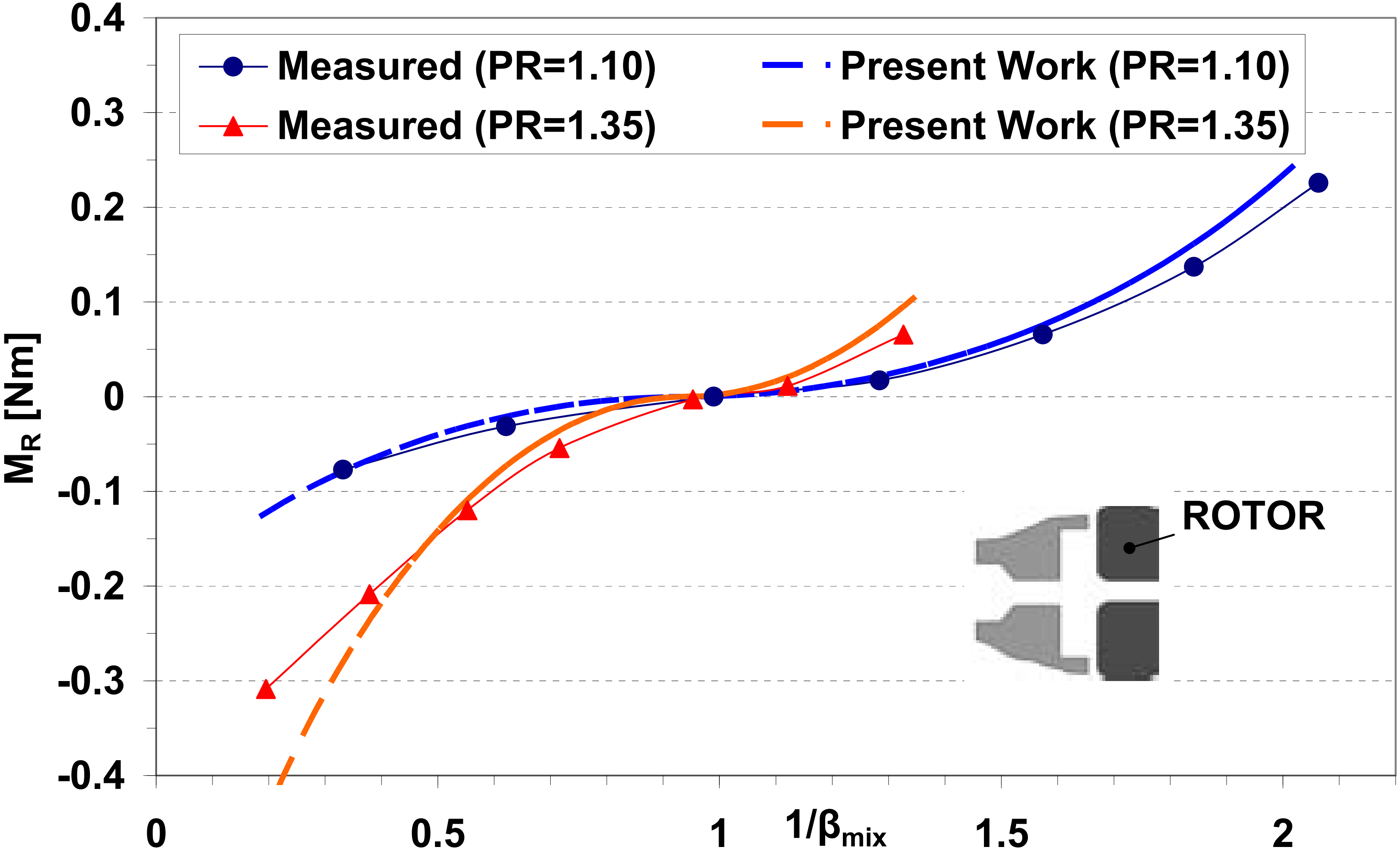
Test Cases: Pre-Swirl Chamber

Geis et al, J. Eng. Gas Turbine and Power, 126 (4), pp. 809-815



Test Cases: Pre-Swirl Chamber

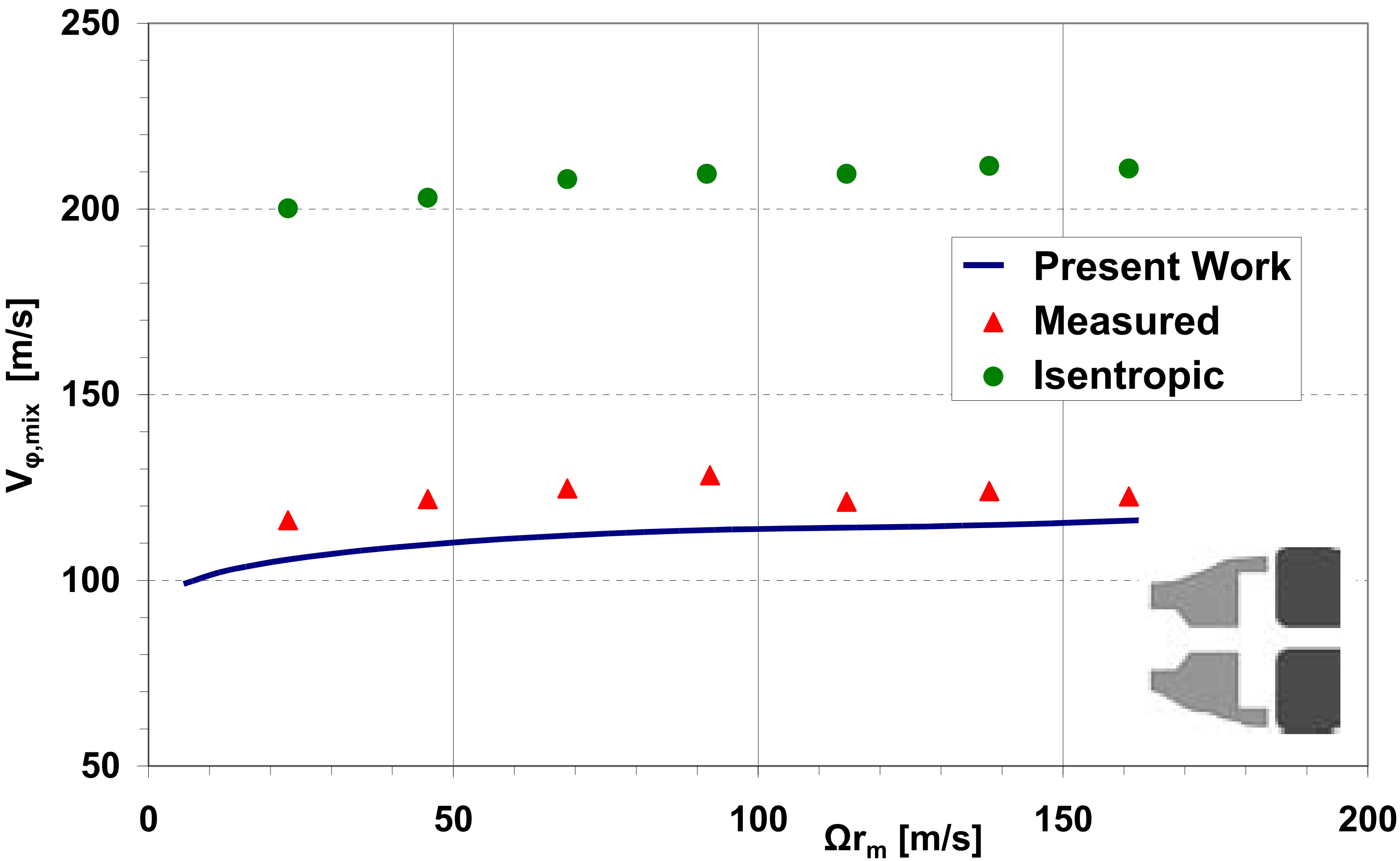
Geis et al, J. Eng. Gas Turbine and Power, 126 (4), pp. 809-815



A. Alexiou & K. Mathioudakis

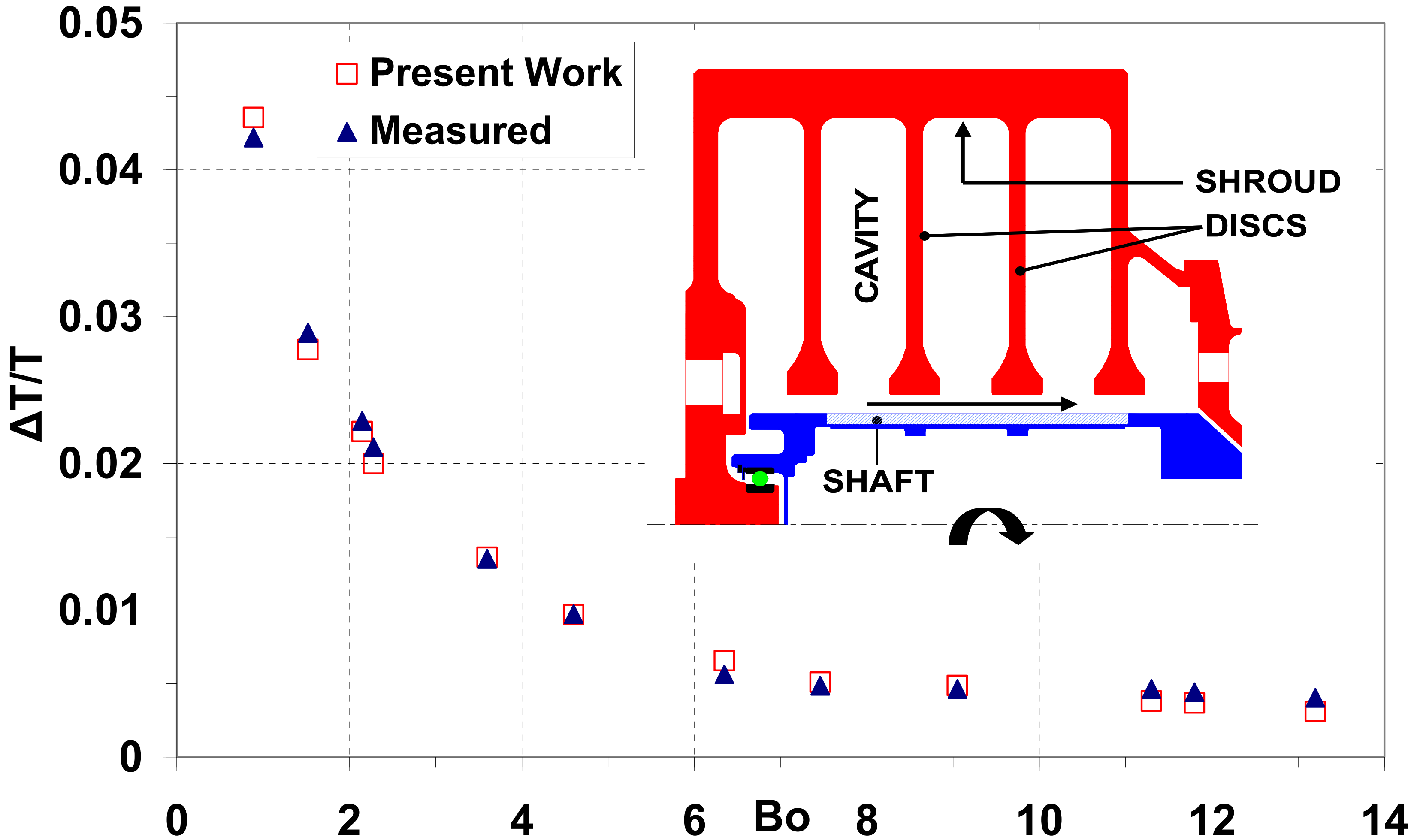
Test Cases: Pre-Swirl Chamber

Geis et al, J. Eng. Gas Turbine and Power, 126 (4), pp. 809-815



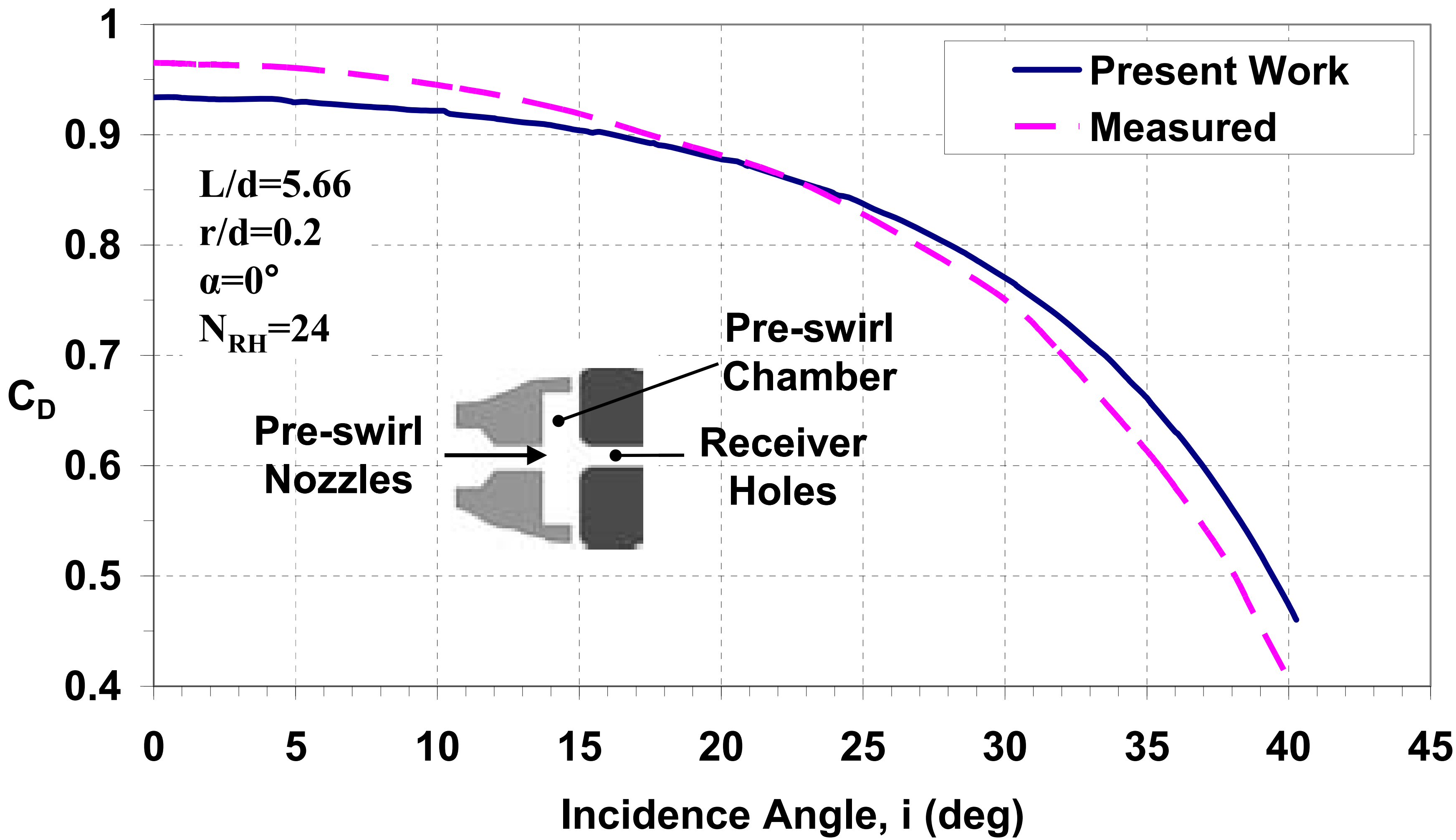
Test Cases: Rotating Cavities

Alexiou et al, Int. J. Experimental Heat Transfer, 13, pp. 299-328



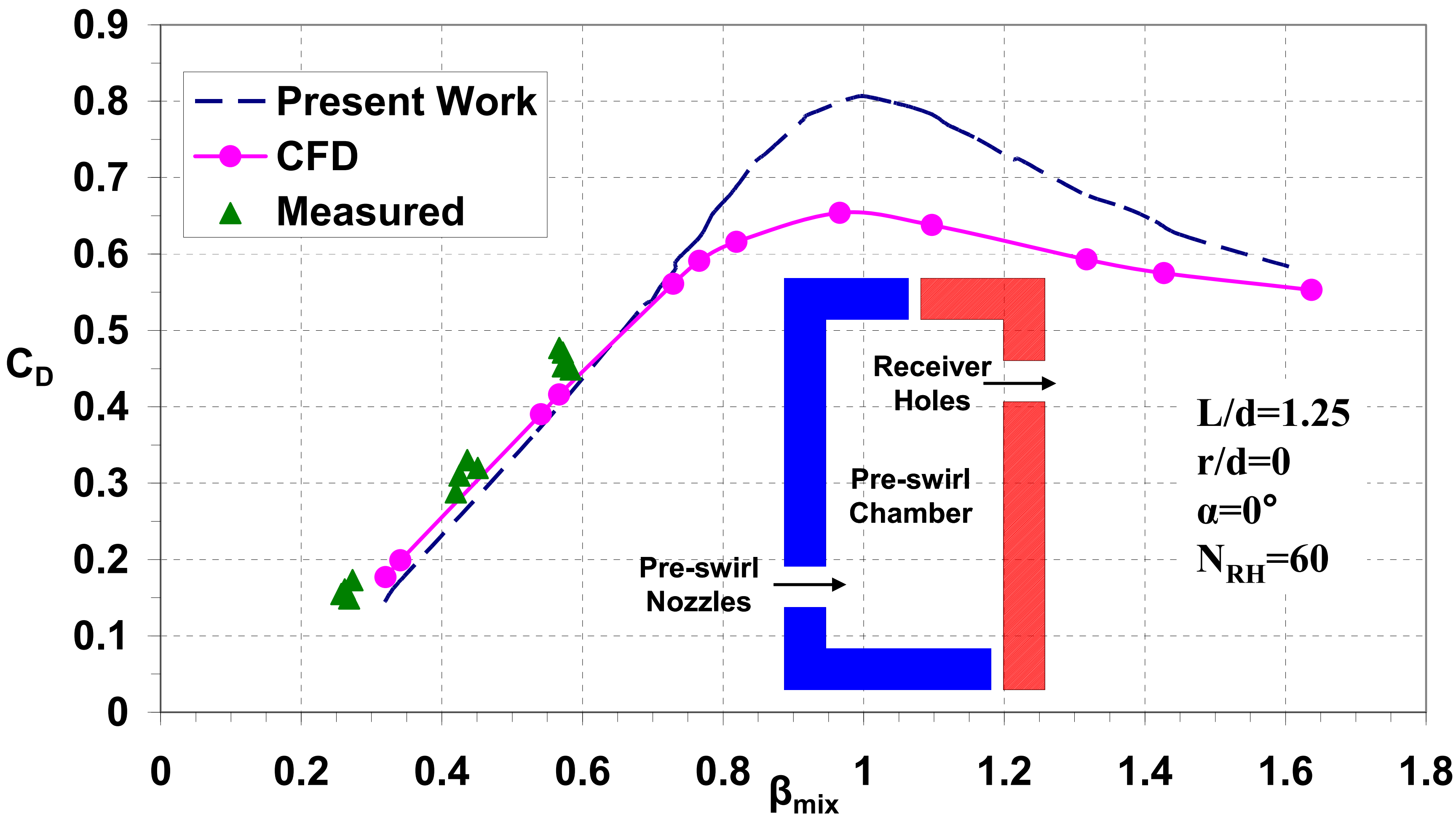
Test Cases: Rotating Holes – Axial

Dittmann et al, J. Eng. Gas Turbine and Power, 127, pp. 383-388



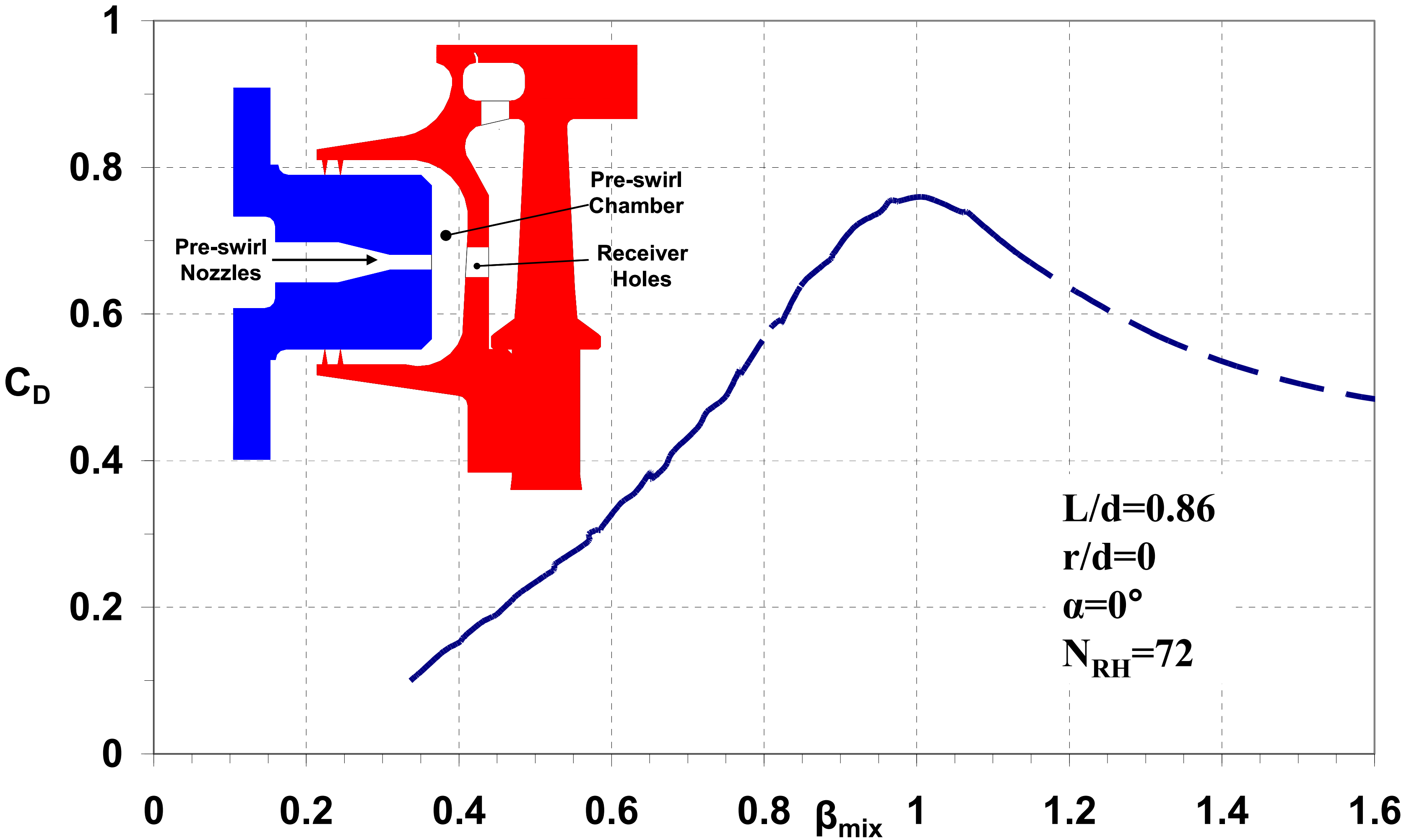
Test Cases: Rotating Holes – Axial

Lewis et al, ASME GT-2006-90132



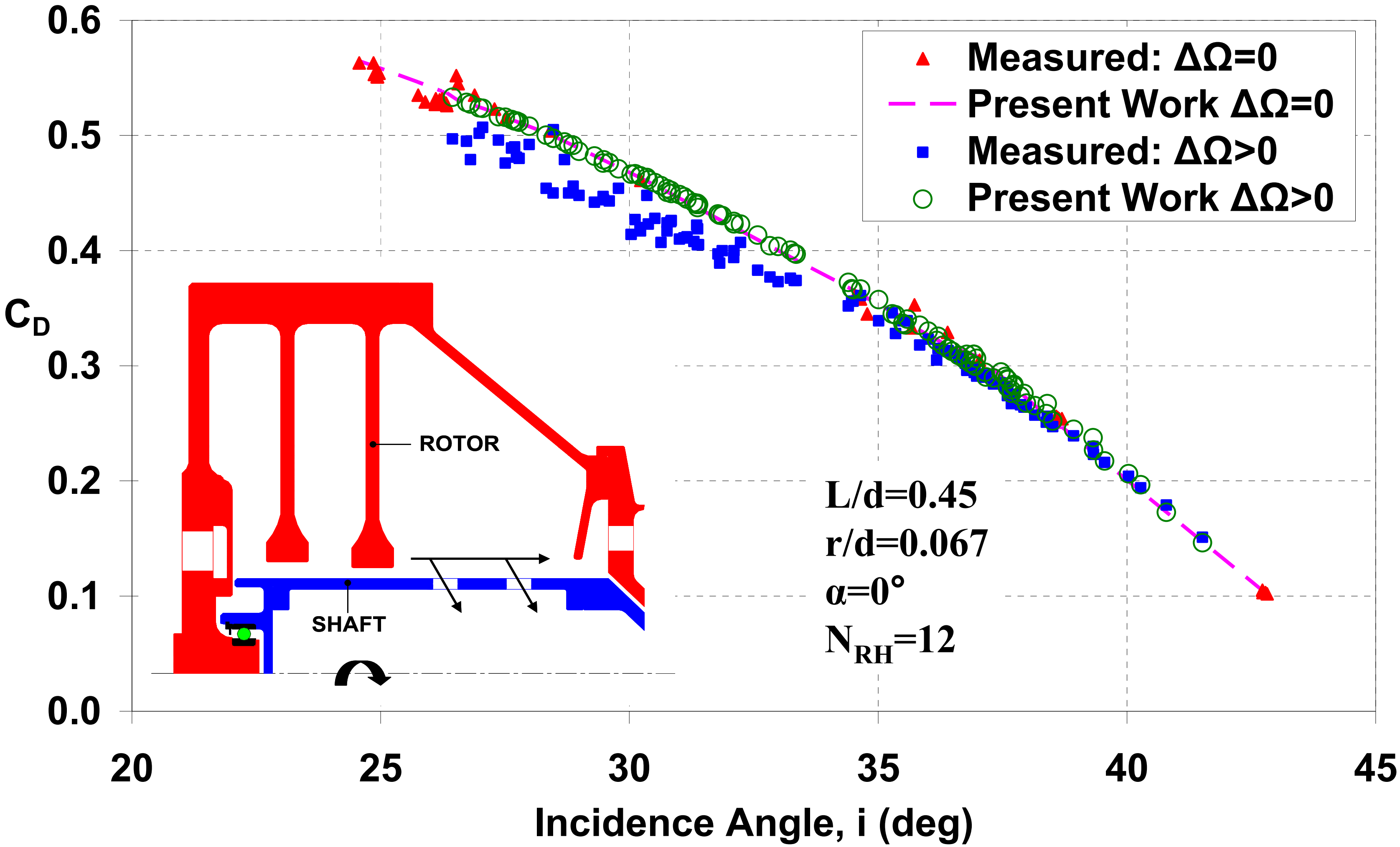
Test Cases: Rotating Holes – Axial

Chew et al, ASME GT-2003-38084



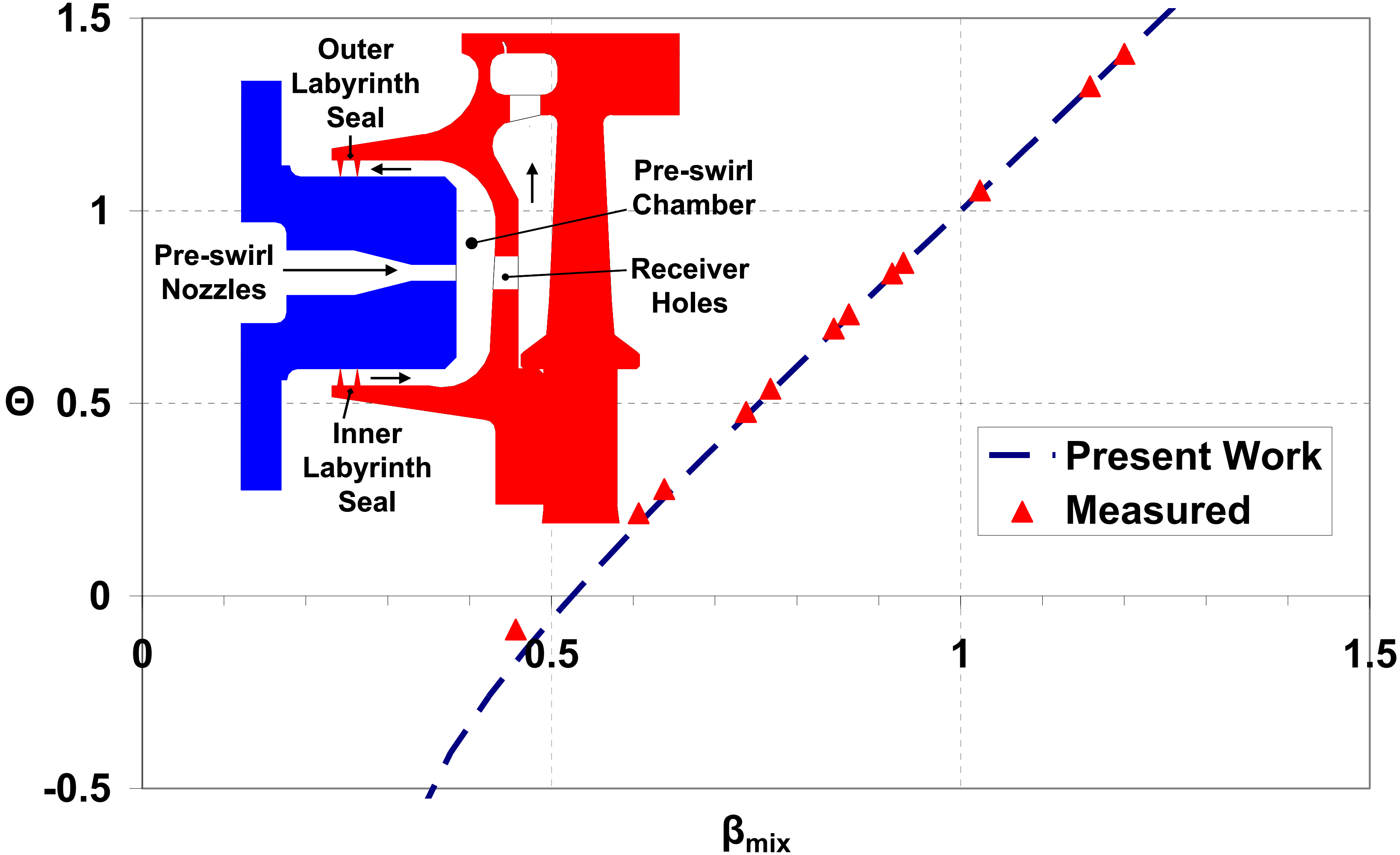
Test Cases: Rotating Holes – Radial

Alexiou et al, Int. J. Heat and Fluid Flow, 21, pp. 701-709

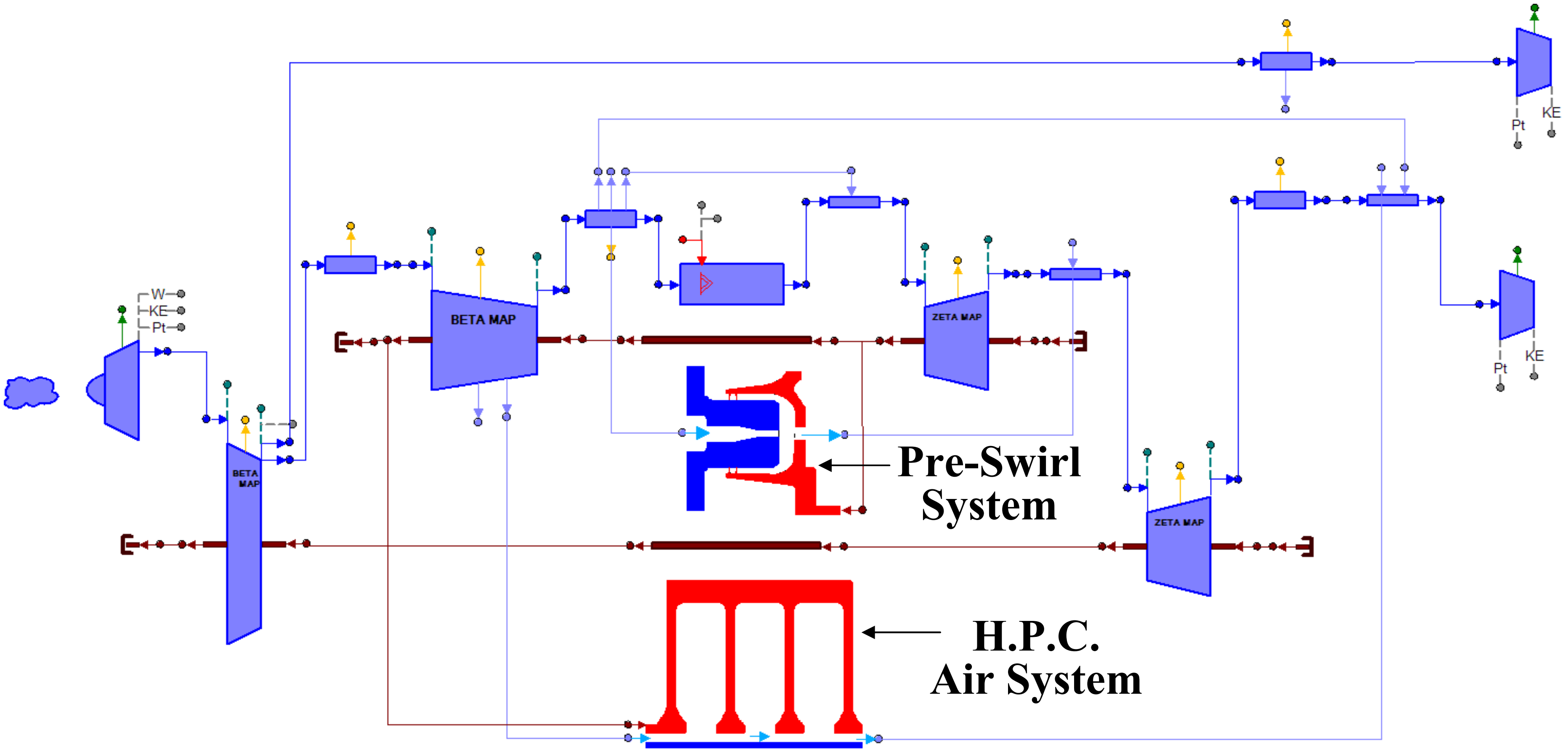


Test Cases: Pre-swirl System with Labyrinth Seals

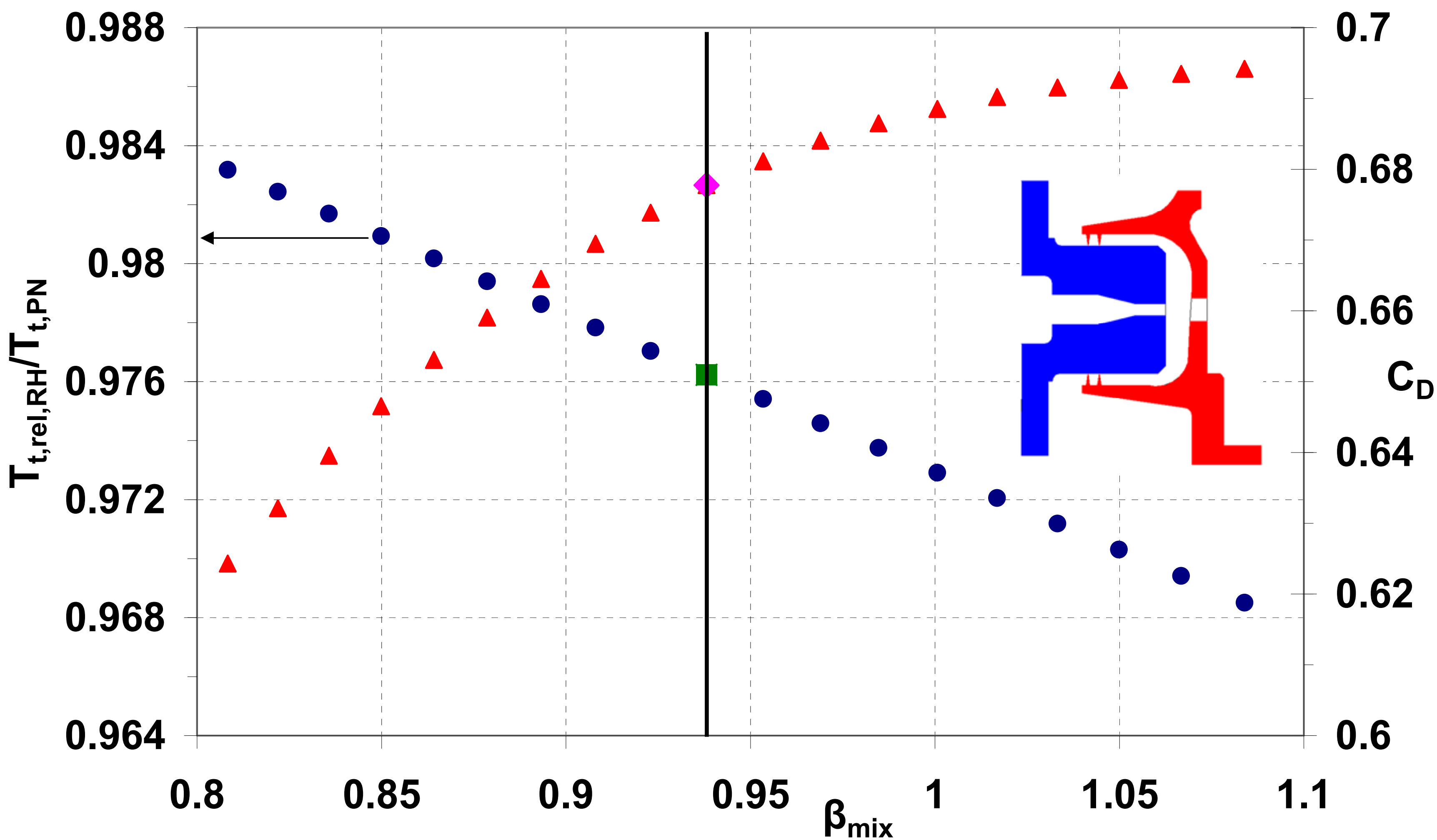
Chew et al, ASME GT-2003-38084



Whole Engine Model (I)



Whole Engine Model (II)



A. Alexiou & K. Mathioudakis

Contents

Summary & Conclusions

➢ **An approach for modelling secondary air systems within an object-oriented environment for gas turbine engine performance simulations was presented.**

➢ **The modelling of selected components was presented in detail. The components were used to simulate various air system configurations and the predicted results are consistent with available experimental data and computational results.**

➢ **An example of adding parts of an air system to a whole engine performance model was given to demonstrate the benefits of this approach.**

❖ **The flexibility of the simulation environment and the generality of the component modelling approach allow easily different air system configurations to be constructed and evaluated, both on their own and as part of a complete engine performance model.**

❖ **Since the approach presented allows components to be represented in varied levels of detail, it is possible to create more realistic models early in the engine design process.**

Friction Coefficients

For free disks or cones with non-zero inner radius and half angle θ:

$$C_m = 0.07288 \cdot (\sin\theta)^{-0.8} \cdot \left[1 - \left(\frac{r_i}{r_o}\right)^5\right] \cdot Re_\varphi^{-0.2}$$

For a smooth cylinder of length L:

$$C_m = \frac{2 \cdot \pi \cdot L}{r} \cdot C_f$$

where

$$C_f = \left[4.07 \cdot \log_{10}\left(Re_\varphi \cdot \sqrt{C_f}\right) - 0.6\right]^{-2}$$

Heat transfer Coefficient Correlations

Natural Convection from a Vertical Plate:

for Ra < 10^9

$$h_{av} = 0.68 + \frac{0.67 \cdot Ra^{0.25}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}} \cdot \frac{k}{L}$$

for Gr > 10^9

$$h_{av} = 0.1 \cdot Ra^{1/3} \cdot \frac{k}{L}$$

Natural Convection from Upper Surface of heated Plate:

for $10^4 \leq$ Ra < 10^7

$$h_{av} = 0.54 \cdot Ra^{0.25} \cdot \frac{k}{L}$$

$10^7 \leq$ Ra < 10^{11}

$$h_{av} = 0.15 \cdot Ra^{1/3} \cdot \frac{k}{L}$$

Forced Convection from a Flat Plate:

for $Re_z < 5\times10^5$

$$h_{av} = 0.662 \cdot Pr^{1/3} \cdot Re_z^{0.5} \cdot \frac{k}{L}$$

for $Re_z \geq 5\times10^5$

$$h_{av} = 0.036 \cdot Pr^{1/3} \cdot Re_z^{0.8} \cdot \frac{k}{L}$$