Direct-Transfer Pre-Swirl System: Performance Modelling, Validation and Optimisation

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Paper Objectives

- Construct a model of a gas turbine direct-transfer pre-swirl air system using models of its individual components

- Validate the modelling against experimental results from 3 different publicly available test cases

- Optimise the design of such a system on its own and as part of a complete engine performance model

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- ☐ MODELLING PHILOSOPHY
- ☐ MODEL VALIDATION
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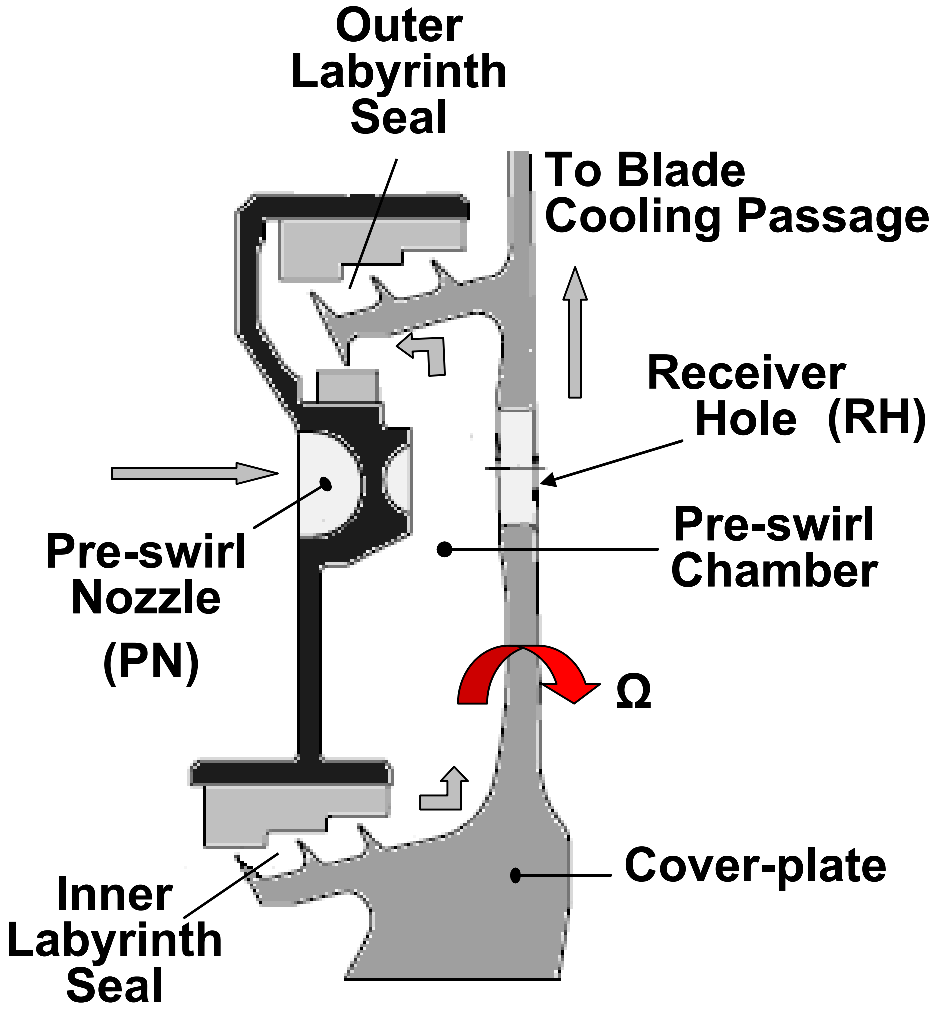
    - o Test Case 3
- ☐ DESIGN OPTIMISATION
    - o System Level
    - o Engine Level
- ☐ CONCLUSION

Direct Transfer Pre-Swirl Air System



Important Parameters

Relative Total Temperature

$T_{t,rel,RH}$

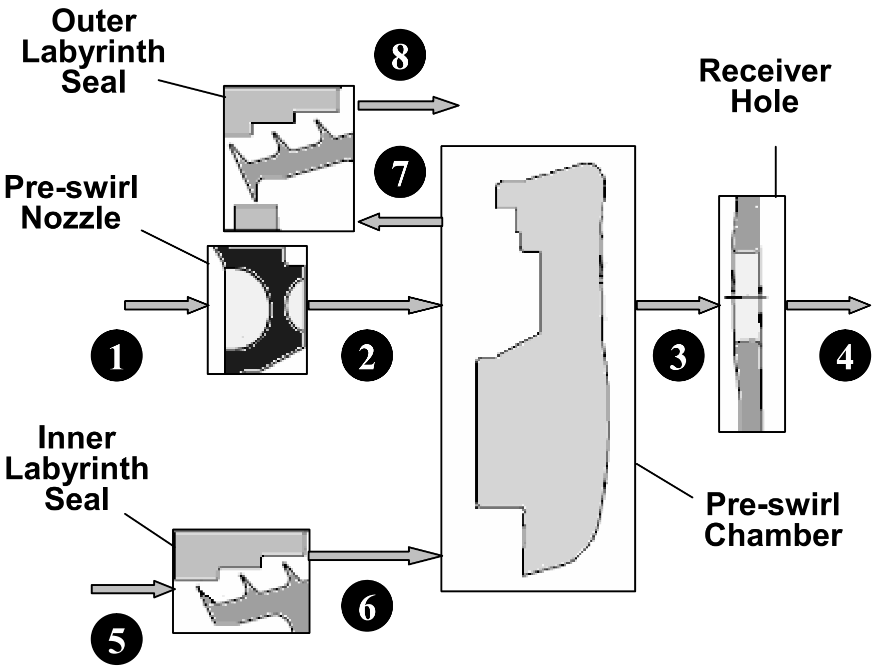
Discharge Coefficient

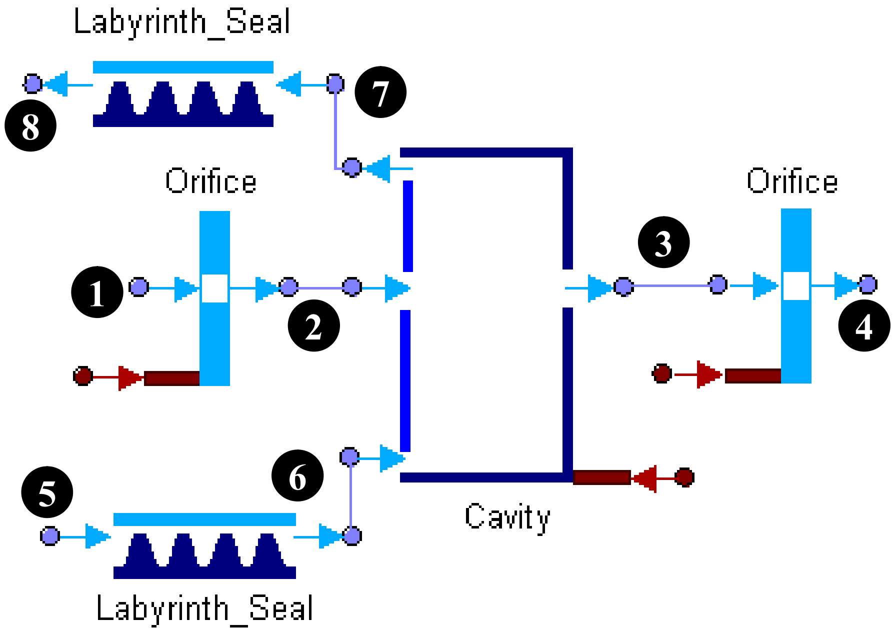
$C_{D,RH}$

Swirl Ratio

$\beta = V_\varphi / \Omega r$

Modelling Philosophy

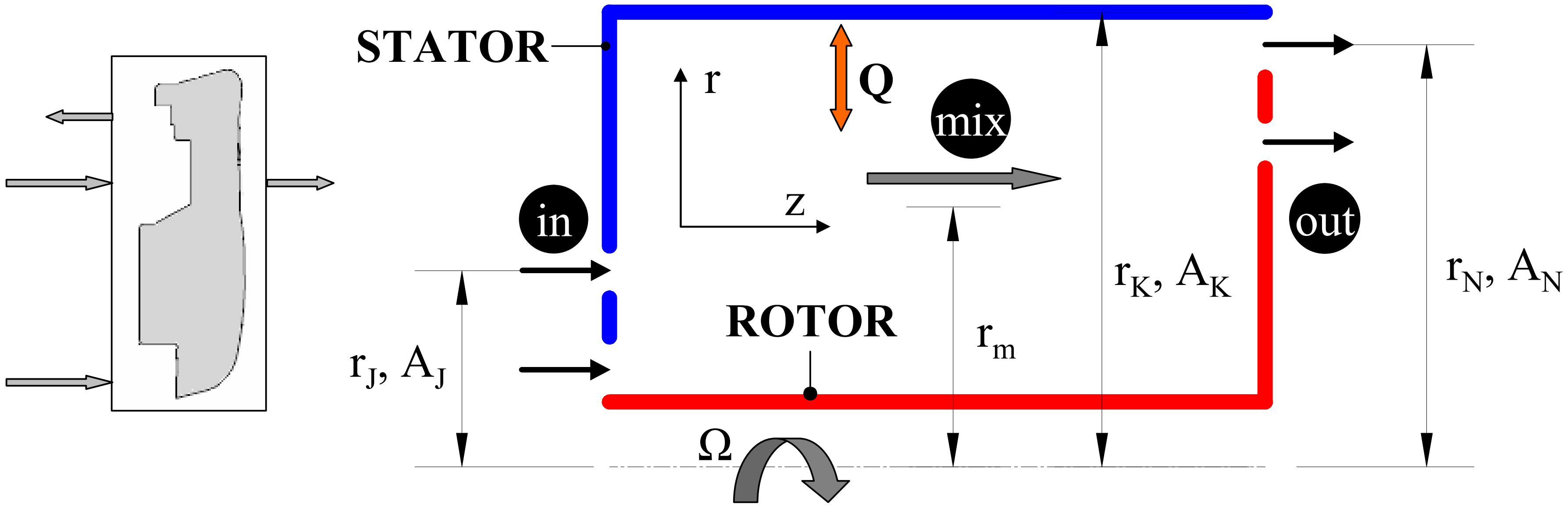




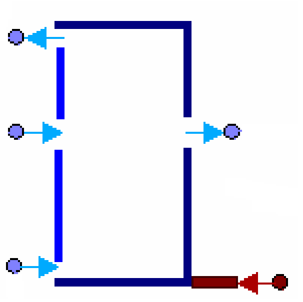
Connected components communicate through their external interfaces by exchanging a pre-defined set of variables. For describing flow conditions, these variables are mass flow, total temperature, total pressure and swirl angle.

The exit flow conditions of a component are linked to the corresponding inlet ones through the conservation equations for mass, energy, axial and angular momentum, the component characteristics and appropriate empirical correlations.

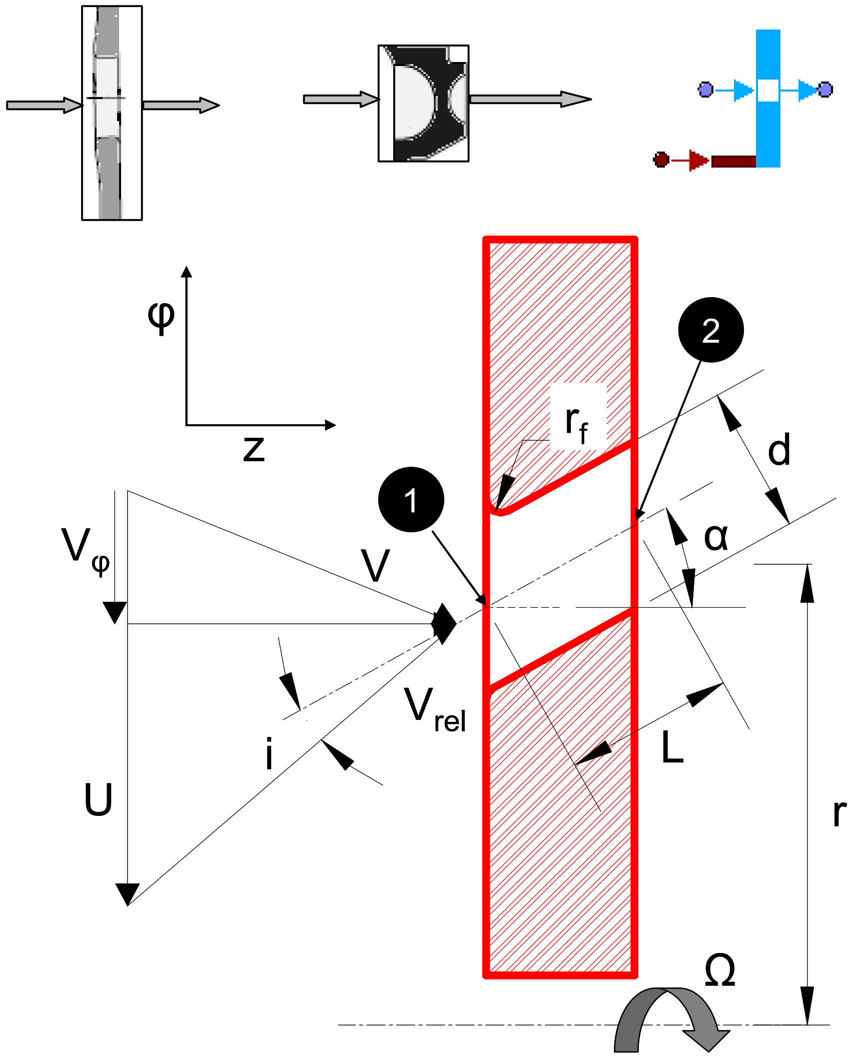
Cavity Component Model



- Arbitrary geometry (discs, cones, cylinders)
- **J** Input flows and **N** output flows
- Fully mixed flow
- Work and heat transfer from surrounding **K** surfaces
- Mixing pressure losses



Orifice Component Model



- ➢ Axial & radial holes
- ➢ Rotating & stationary

Discharge Coefficient C_D corrected through correlations for:

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

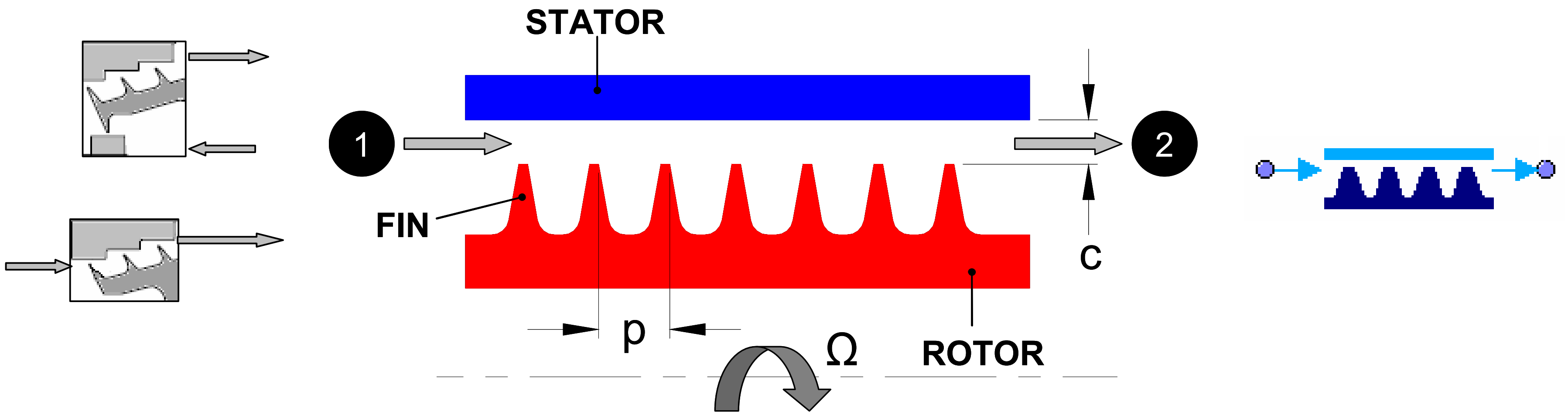
$$C_D = 1 - f_1 \cdot f_{2,r_f/d} \cdot f_{2,L/d'} \cdot f_3 \cdot \left(1 - C_{D:Re}\right) + \Delta C_{D:i}$$

Incidence Angle Definition

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

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 $1.3 < c/t < 2.3$

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

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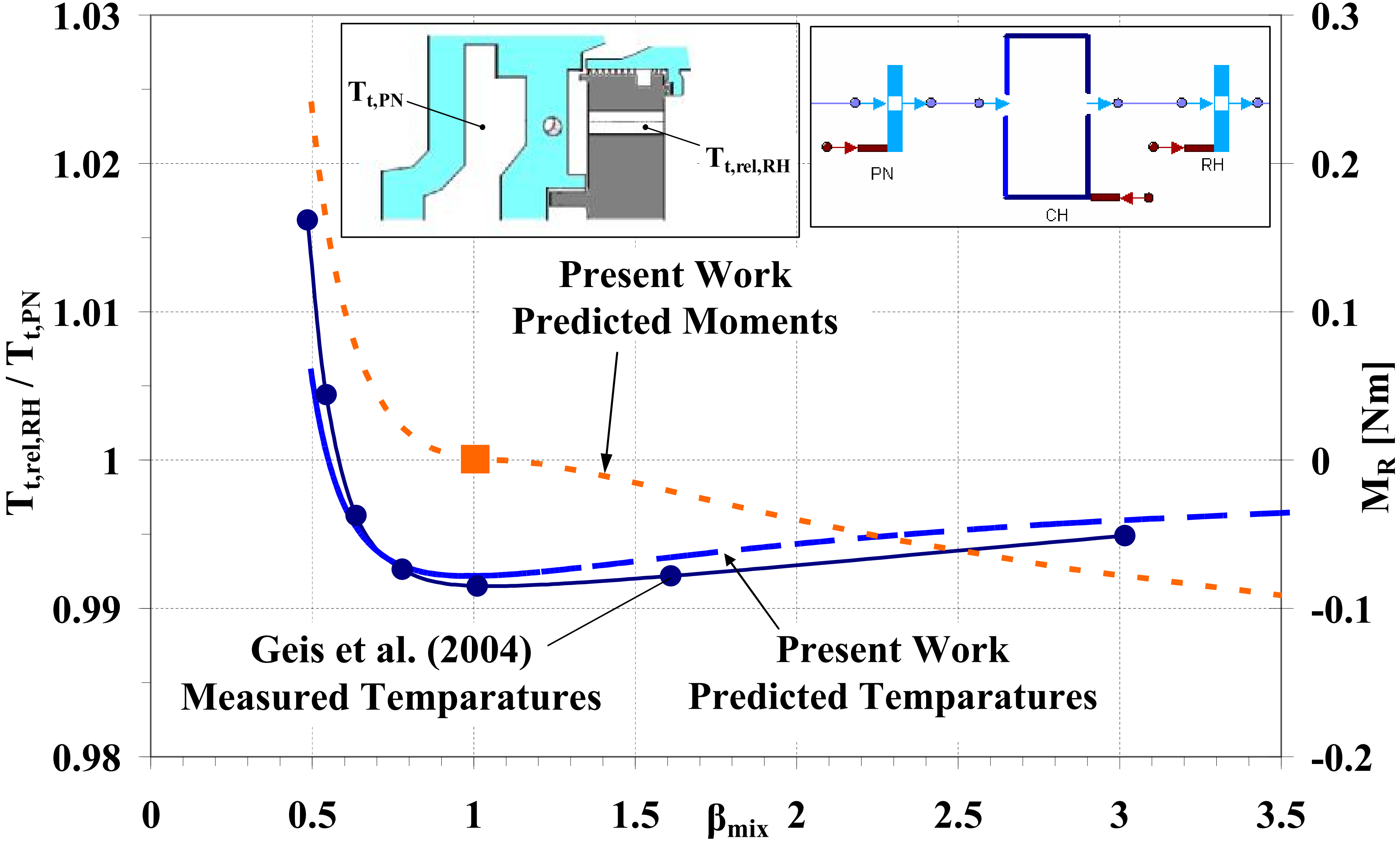
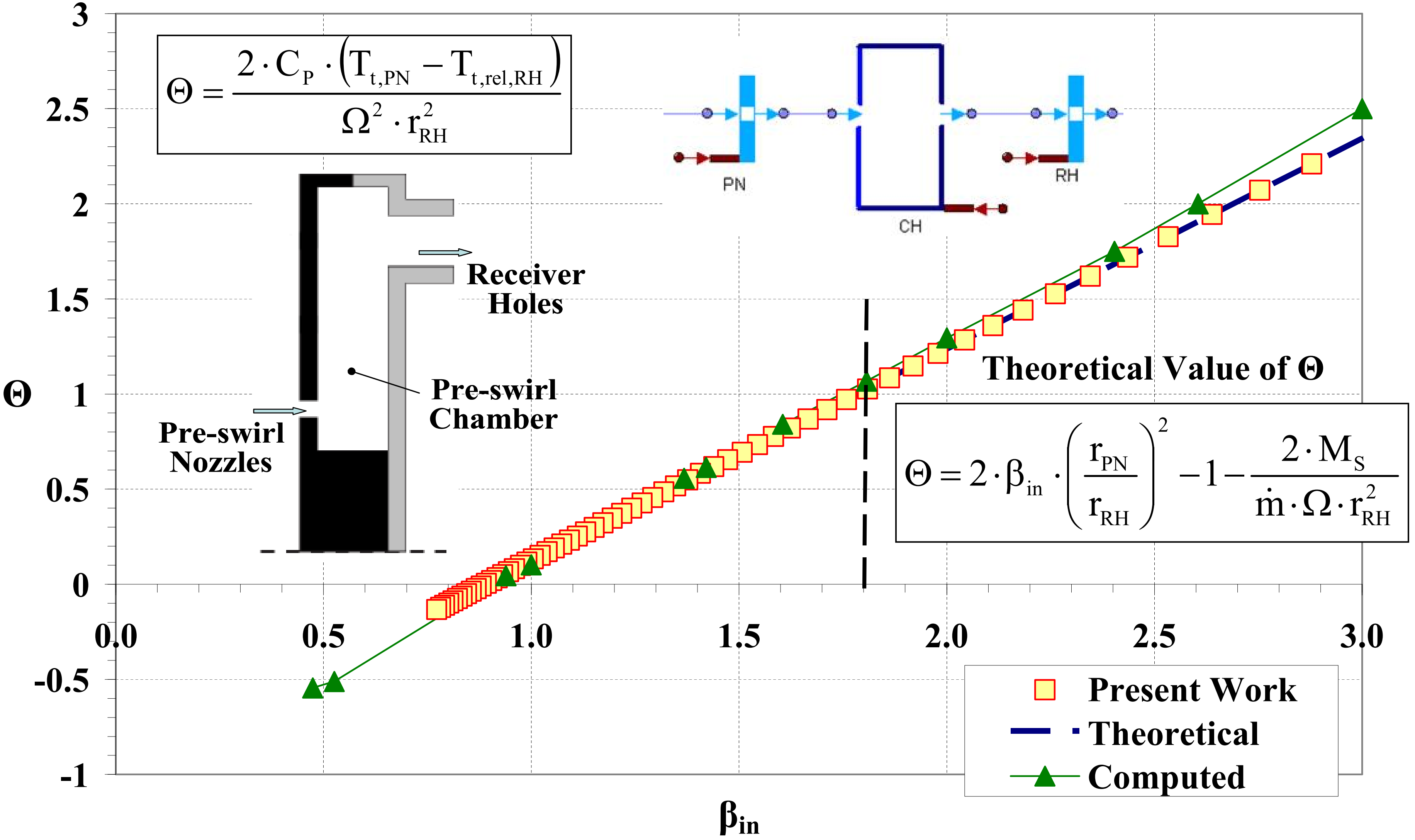
Validation Test Case 1: Geis et al. (2004)



Validation Test Case 2: Lewis et al. (2006) - I

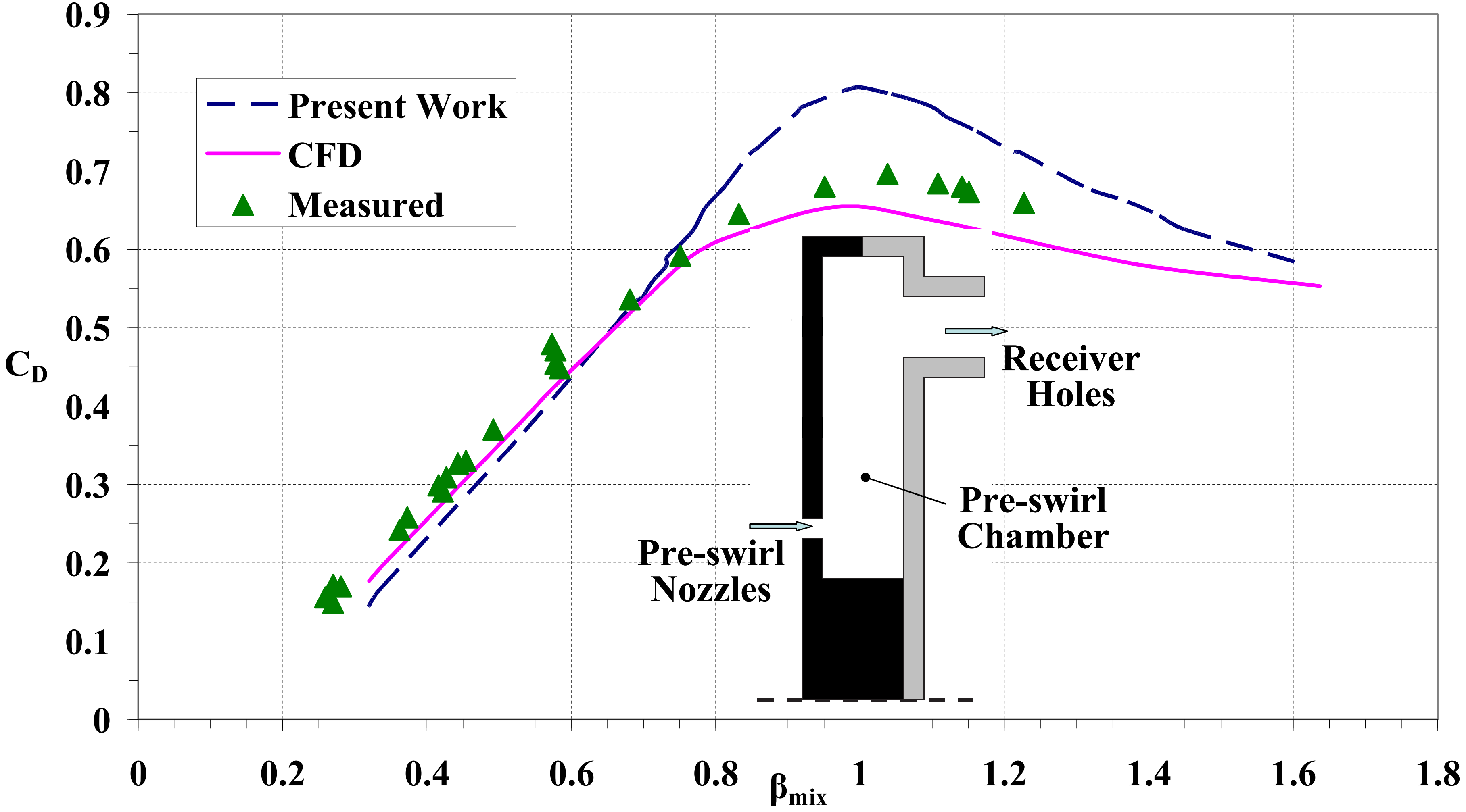


$$\Theta = \frac{2 \cdot C_P \cdot \left(T_{t,PN} - T_{t,rel,RH}\right)}{\Omega^2 \cdot r_{RH}^2}$$

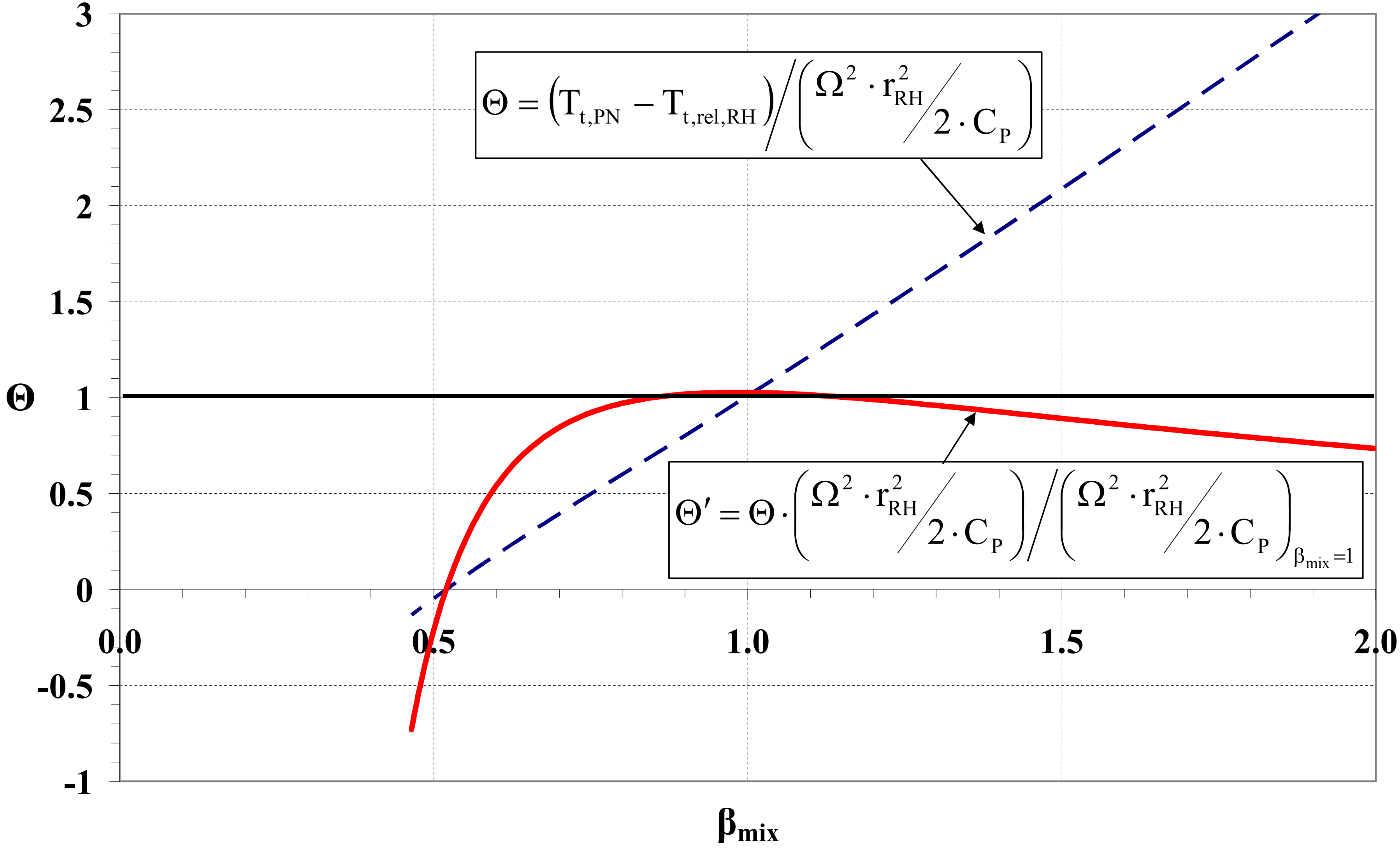
Theoretical Value of Θ

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

Validation Test Case 2: Lewis et al. (2006) - II



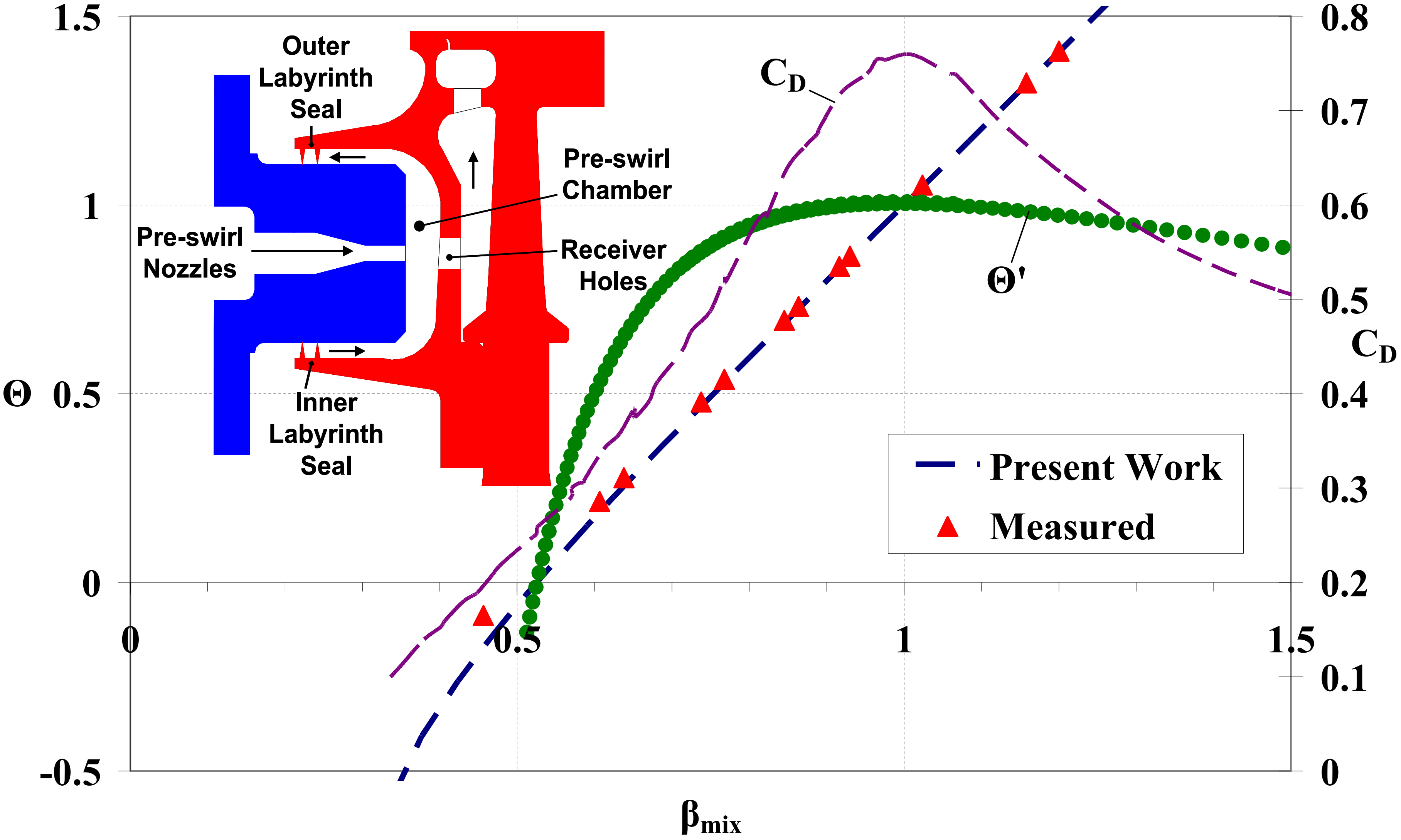
Validation Test Case 2: Lewis et al. (2006) - III



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

$$\Theta' = \Theta \cdot \left(\Omega^2 \cdot r_{RH}^2 \big/ 2 \cdot C_P\right) \Big/ \left(\Omega^2 \cdot r_{RH}^2 \big/ 2 \cdot C_P\right)_{\beta_{mix}=1}$$

Validation Test Case 3: Chew et al. (2003)



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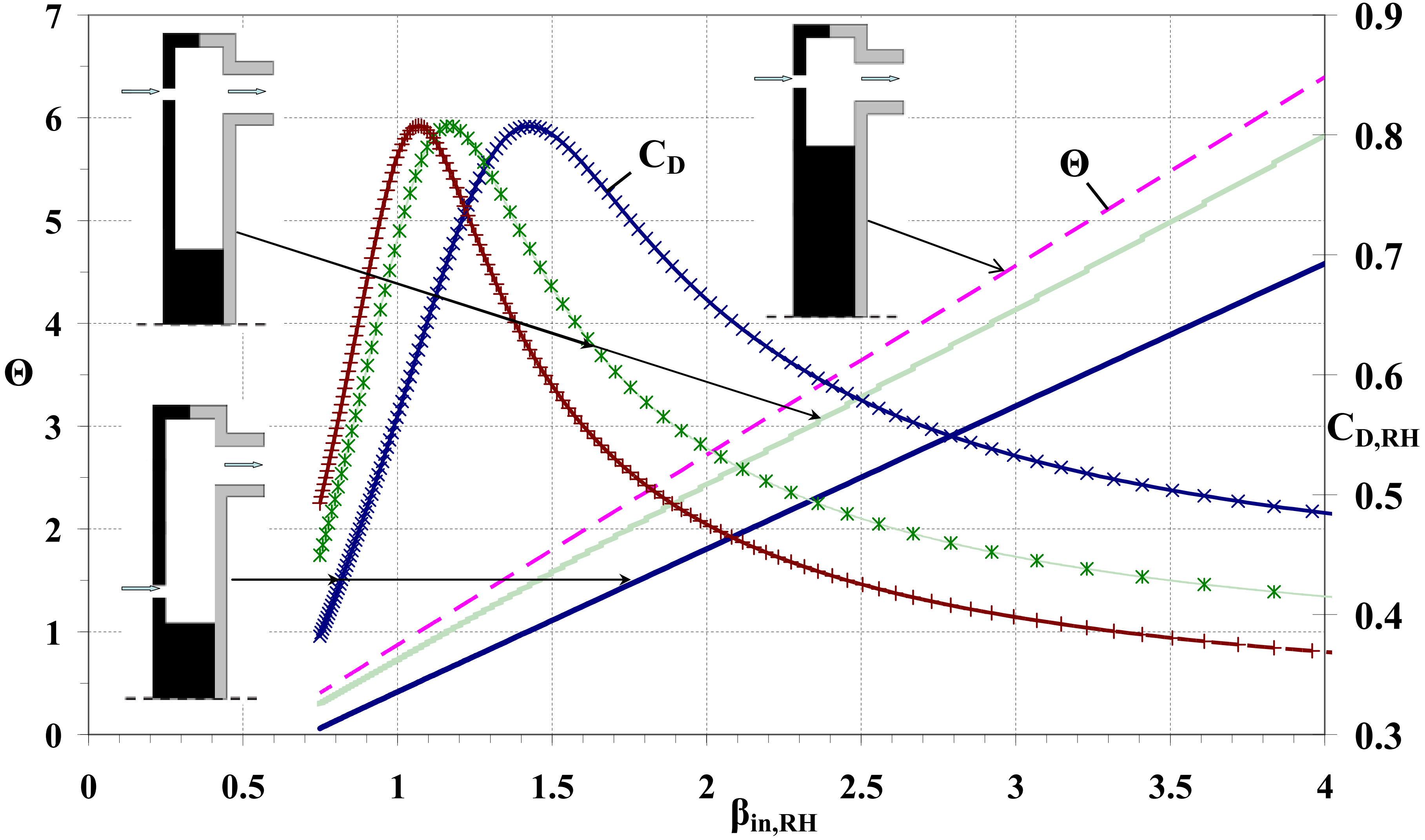
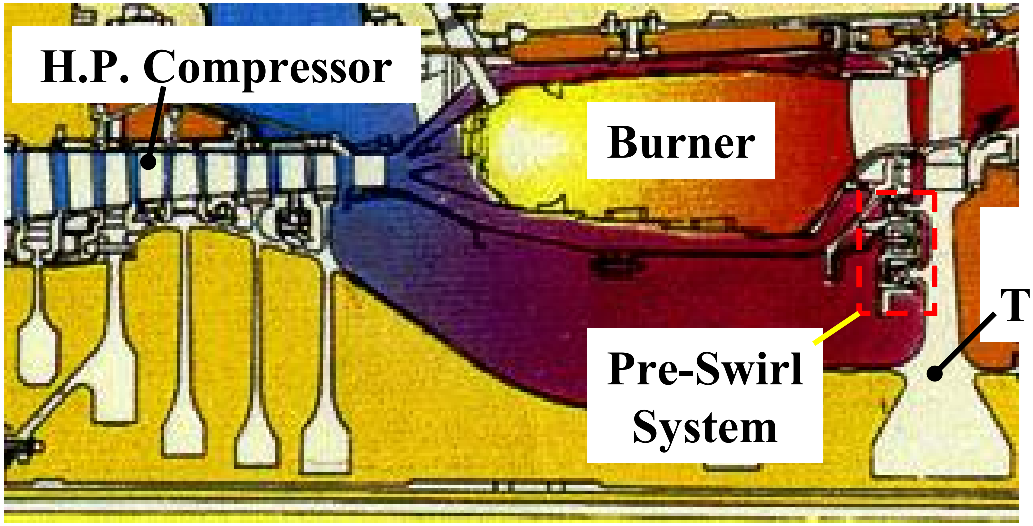
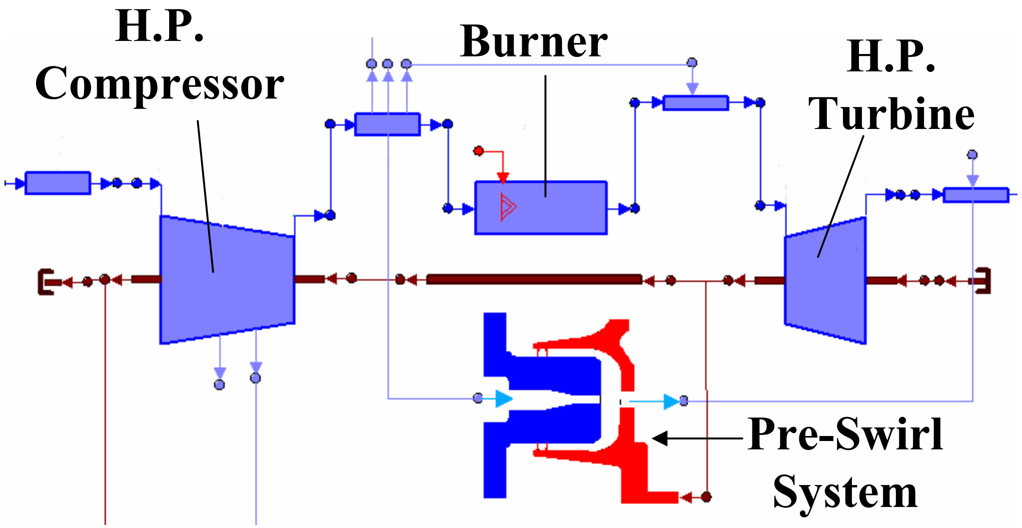
Optimisation: System Level

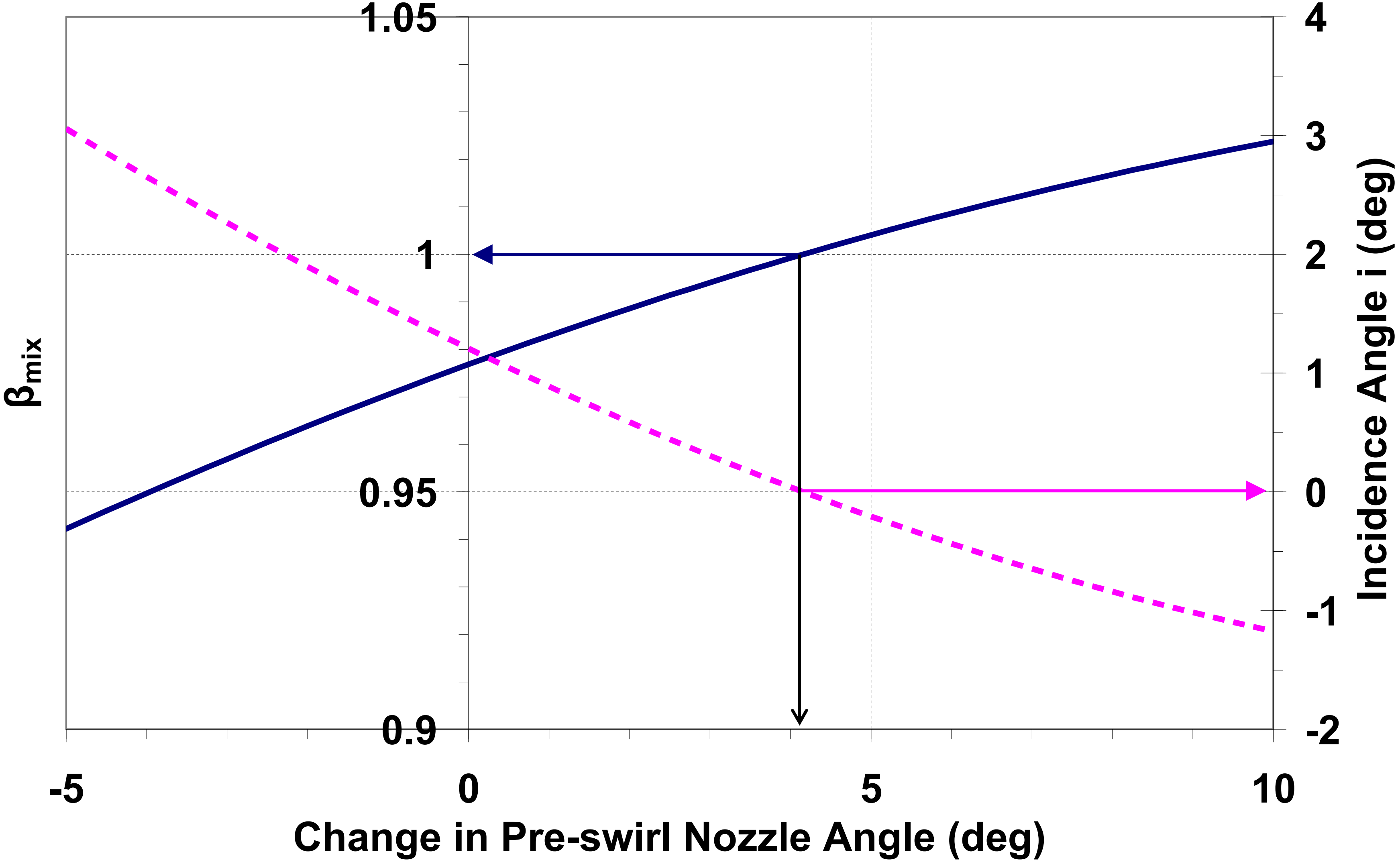


Optimisation: Engine Level - I

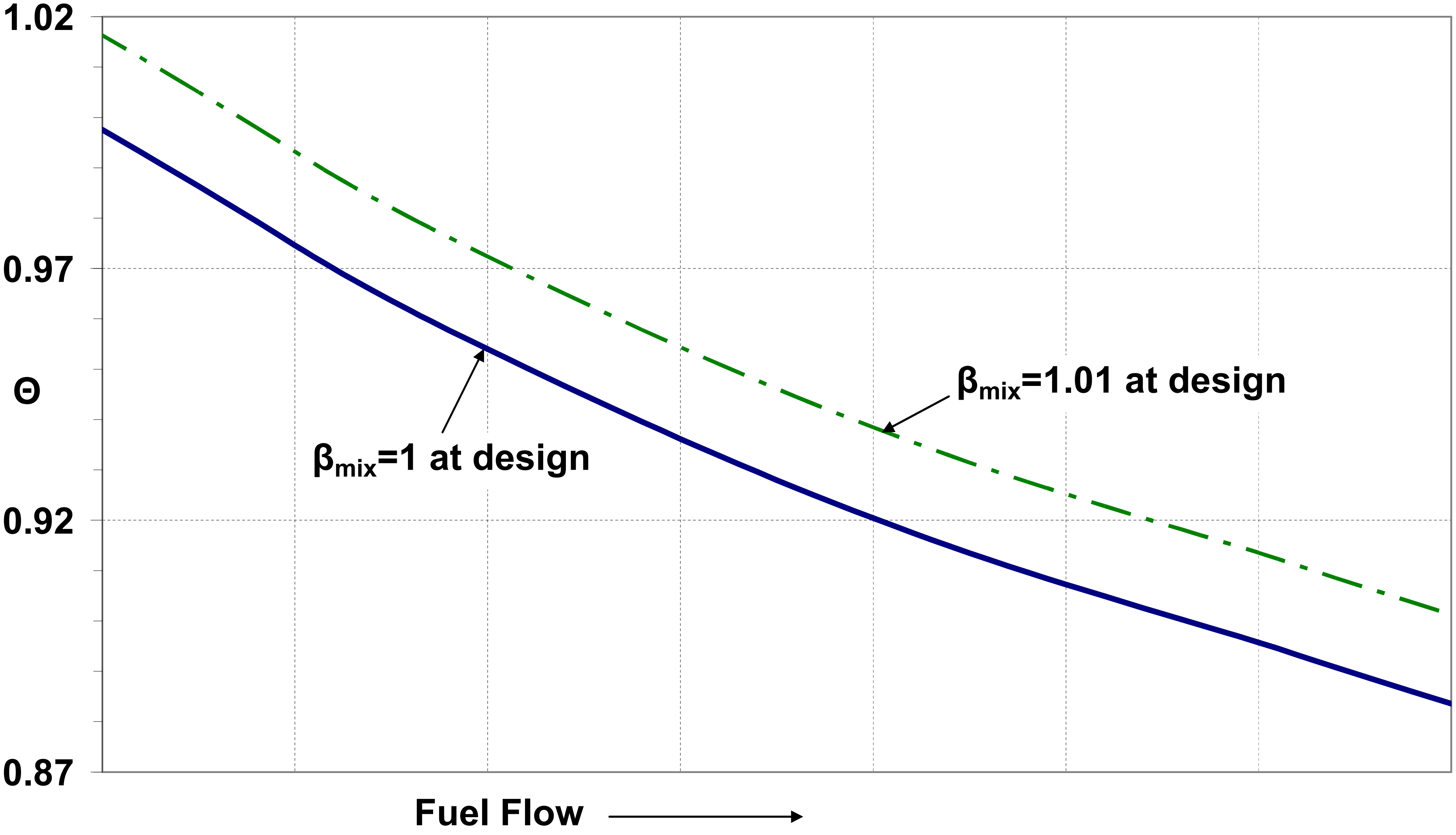




Optimisation: Engine Level - II



Optimisation: Engine Level - III



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Conclusions

- A generic approach for modelling direct-transfer pre-swirl air systems using object-oriented simulation principles is presented.
- Three components (orifice, cavity and labyrinth seal) are combined together to simulate different experimental pre-swirl systems found in the open literature. The predicted results are consistent with the experimental data and computational results reported in the relevant references.
- The ease with which the proposed approach allows different pre-swirl system configurations to be constructed and evaluated, both on their own and as part of a complete engine performance model is demonstrated.
- 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.

Cavity Component Equations (I)

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

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

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 → $T_{t,mix}$

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

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

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

Cavity 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 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:

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