Optimisation Techniques for Combustor Design

By

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Overview

- Introduction and Objectives
- Design Methodology
  - CFD Modelling
    - Background
    - Validation
  - Mathematical Optimisation
    - Background
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  - Formulation of Optimisation Problem
    - Design variables
    - Objective function and constraints
- Case Studies
- Conclusions and Future Work

Introduction

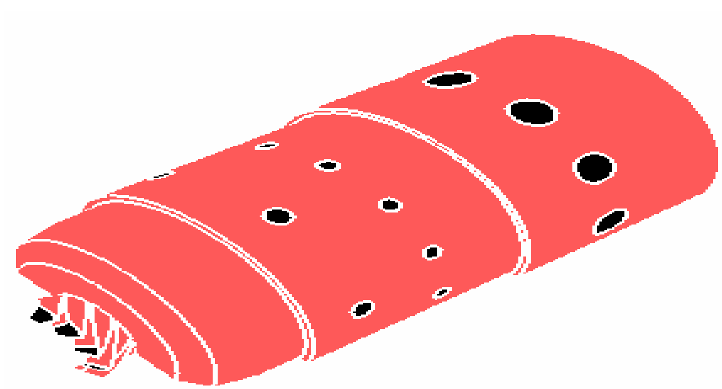
Motivation & Problem Statement

There is a desire to continuously improve gas turbine performance, by increasing thrust: this can be achieved by increasing gas working temperature. But:-

- **high non-uniform temperatures put pressure on materials & blade cooling technologies**
- **high non-uniform temperatures cause varying thermal stresses on turbine blades**
- **current design methods do not fully address the problem of non-uniform temperatures:**

Introduction

- The research was based on an Experimental Combustor
- Role of Combustor
  - Dilution holes
  - Secondary holes
  - Primary holes
  - Swirler



Section of a can type combustor considered

Introduction

- Combustor exit temperature profile
  - Current design methods
    - Empirical: Lefebvre & Norster (1969), Lefebvre (1998)
      Holdeman et al (1997)
    - Parametric (CFD based): Gulati et al (1994)
      & Tangarila et al (2000)
  - Mathematical optimisation: Rogero (2002)
    & Catalano et al (2002)

Current design methods do not fully address the problem of non-uniform temperatures: Therefore, there is need for better design methods

Objectives

As current design methods do not fully address the problem of non-uniform temperatures: Therefore, there is need for better design methods:

- Design a methodology for design optimisation of combustor exit temperature profile
- Apply the methodology to optimise a the temperature profile of a research combustor.

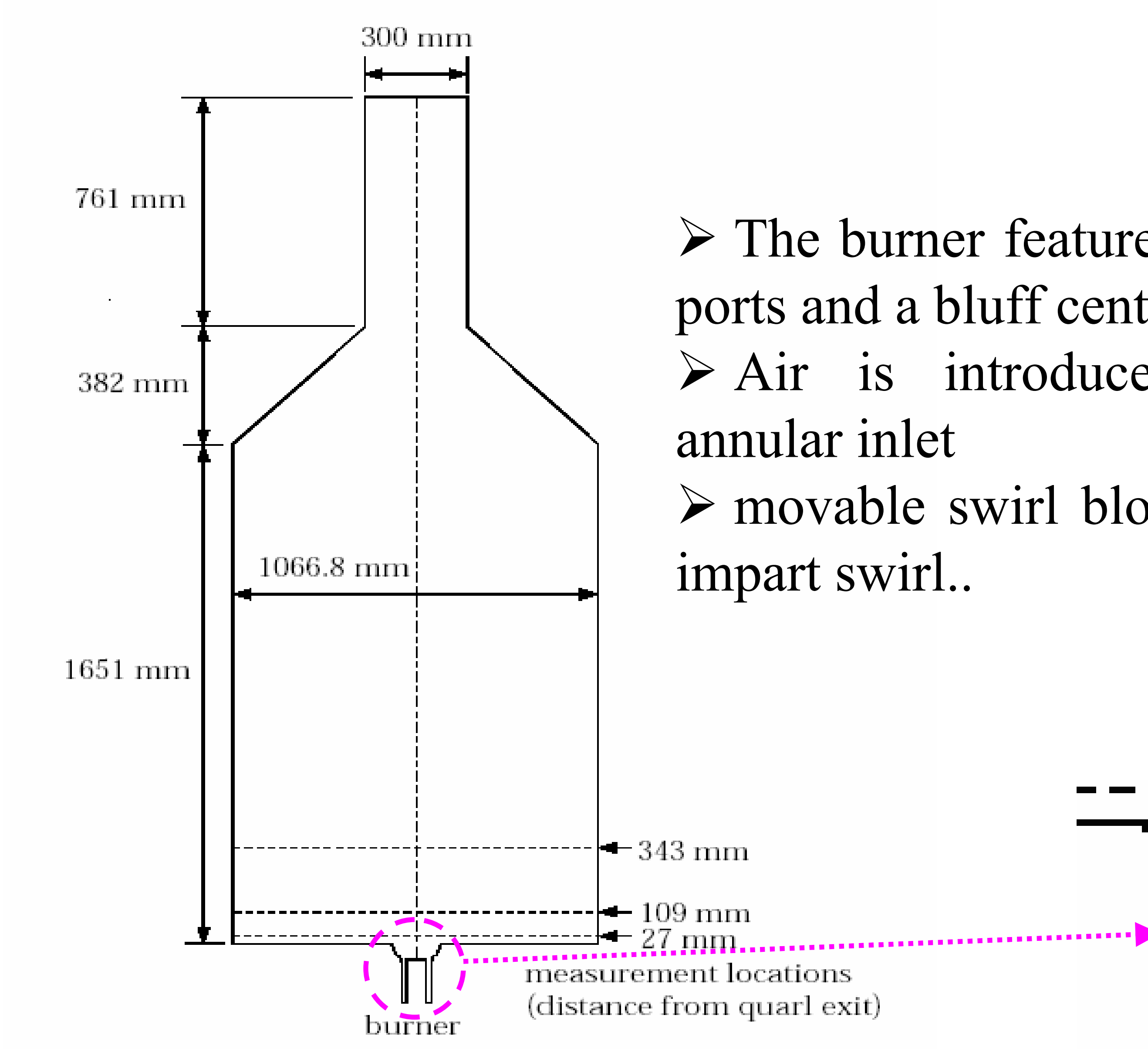
Computational Fluid Dynamics Modelling

- Numerical technique to solve the fluid behaviour in and around engineering equipment
- Commercial CFD package – Fluent was used
  - Use the Finite Volume Method to solve the partial differential equations of mass, momentum and energy conservation
  - Turbulence models account for small fluctuations in flow filed
  - Boussinesq approximation account for buoyancy forces
  - DPM (Lagrangian) model used to model injections
  - Non-premixed (PDF model) with equilibrium chemistry

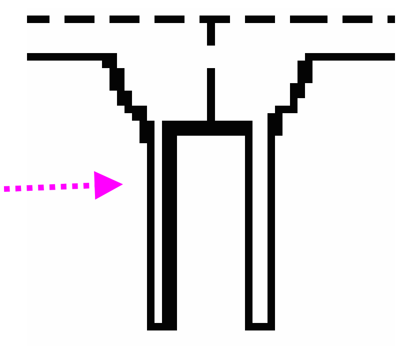
Validation of CFD Models

- Comparing CFD model predictions with measurements for suitable test case (Berl combustor)
- Commercial CFD package – Fluent was used
  - Different turbulence models were assessed for their accuracy in calculating turbulent reacting flows in a combustor
- Two-dimension of the burner
- Results
  - Axial Velocity (at radial position 27mm, 109mm and 343mm)
  - Temperature (at radial position 27mm, 109mm and 343mm)
- Conclusions
- Results discrepancies

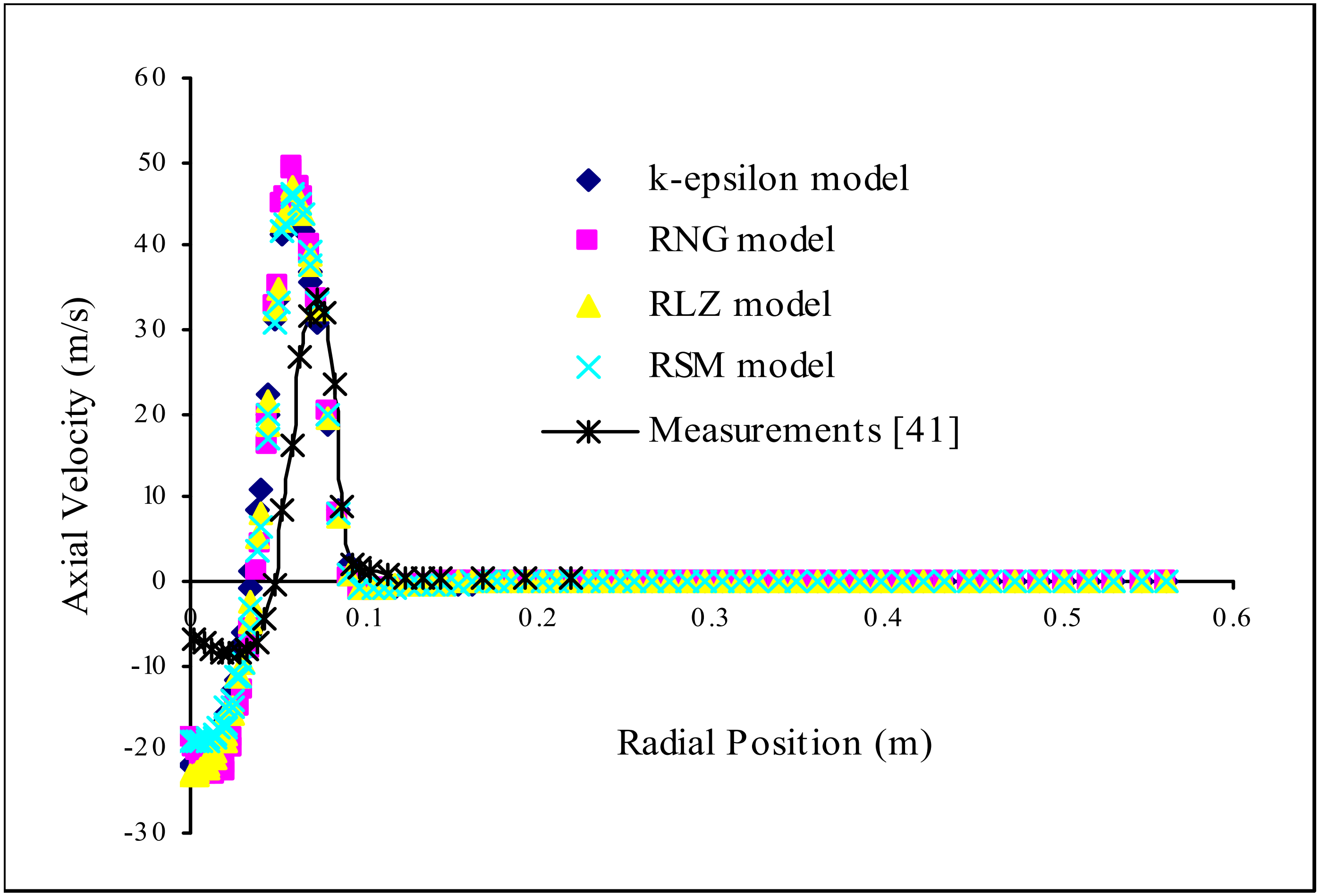
Validation of CFD Models



- The burner features 24 radial fuel ports and a bluff centre-body
- Air is introduced through an annular inlet
- movable swirl blocks are used to impart swirl..

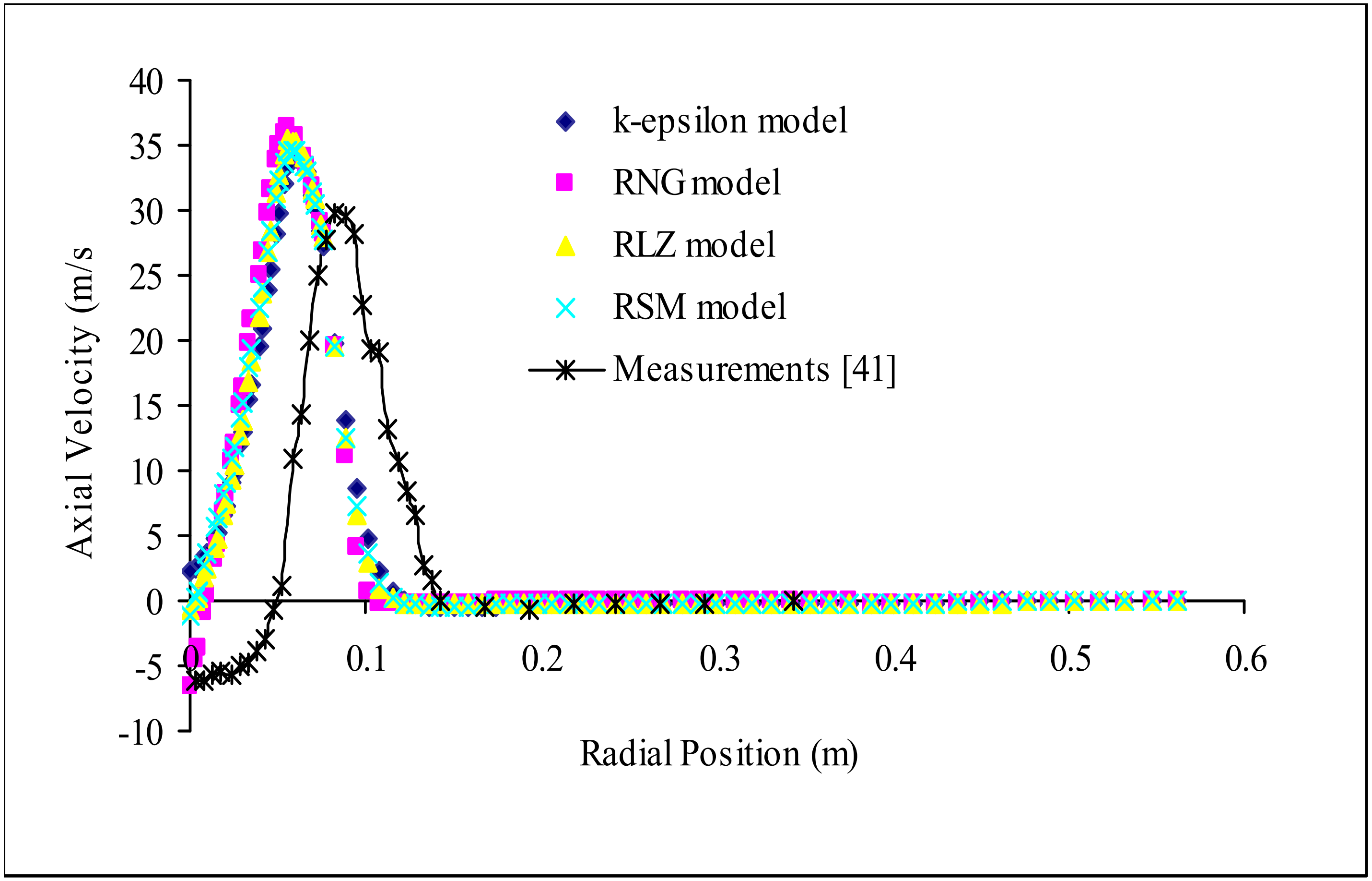


Validation of CFD Models



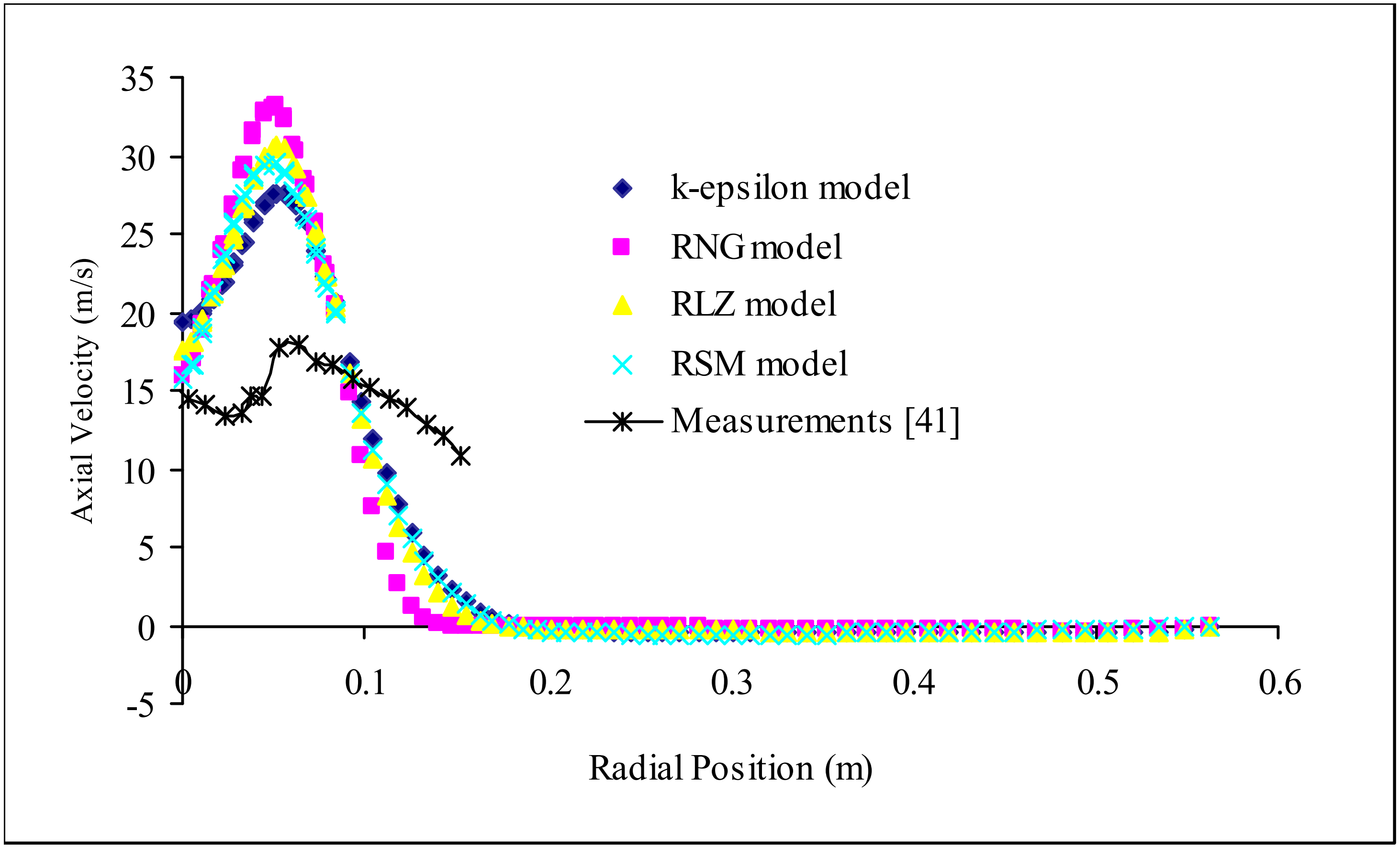
Axial velocity at 27 mm from the quarl exit

Validation of CFD Models



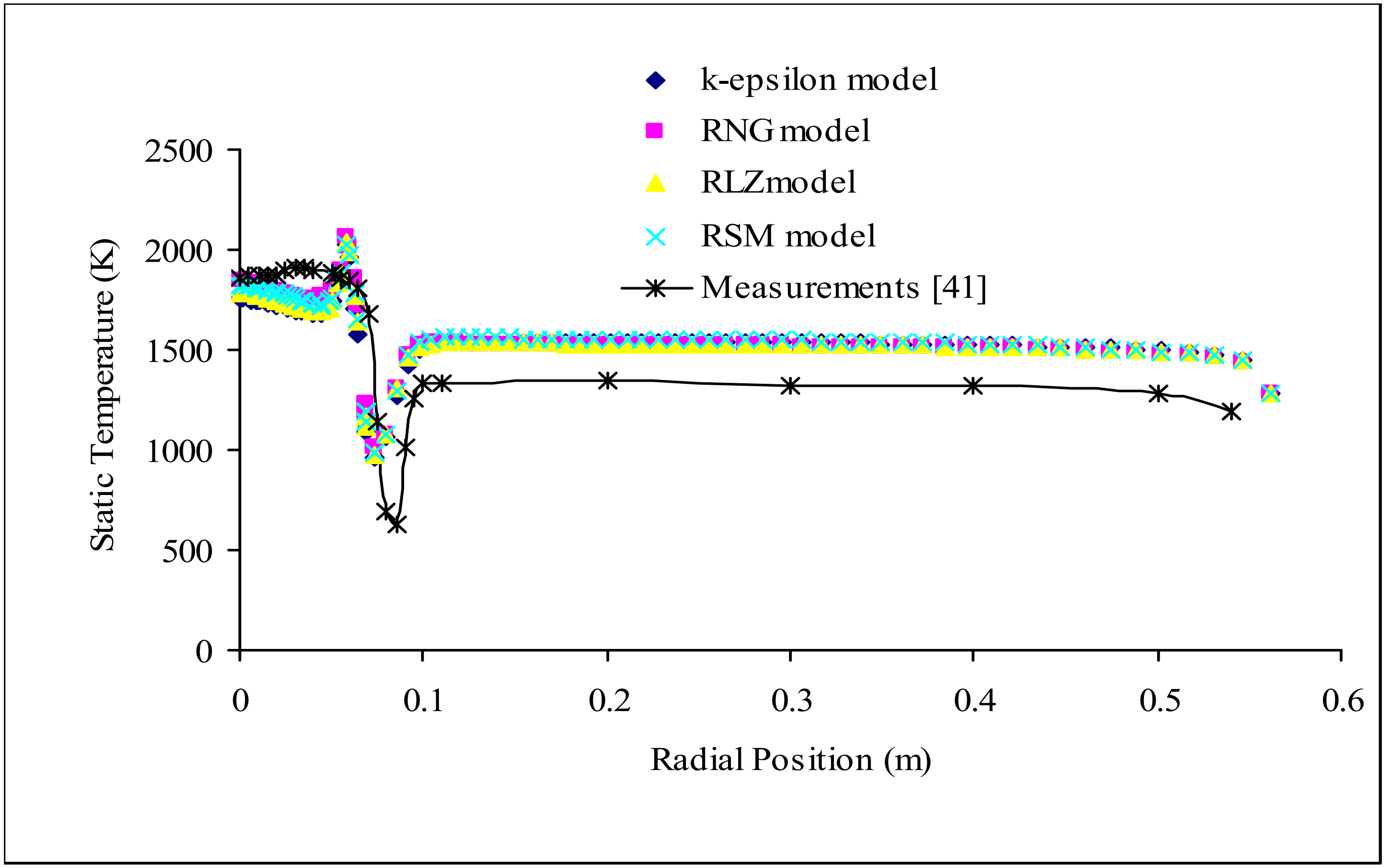
Axial velocity at 109 mm from the quarl exit

Validation of CFD Models



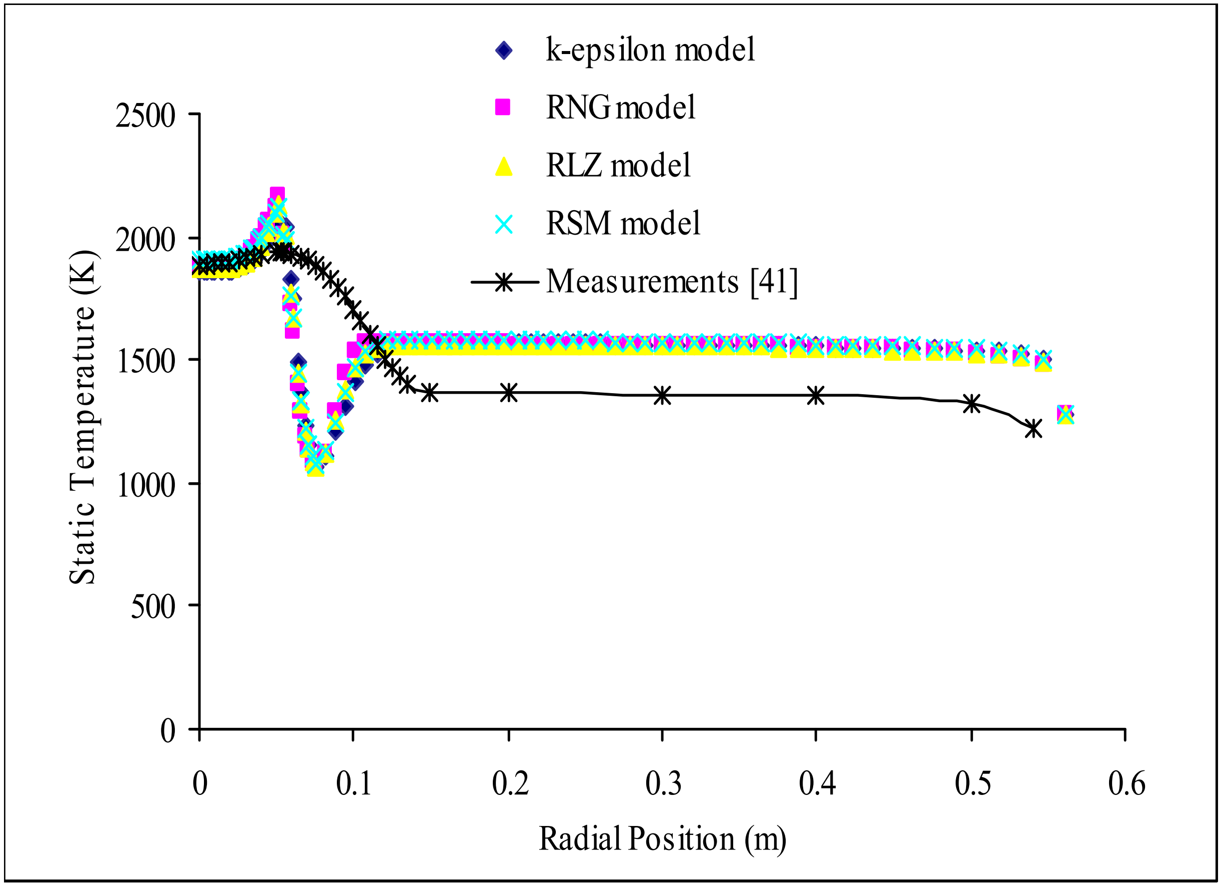
Axial velocity at 343 mm from the quarl exit

Validation of CFD Models



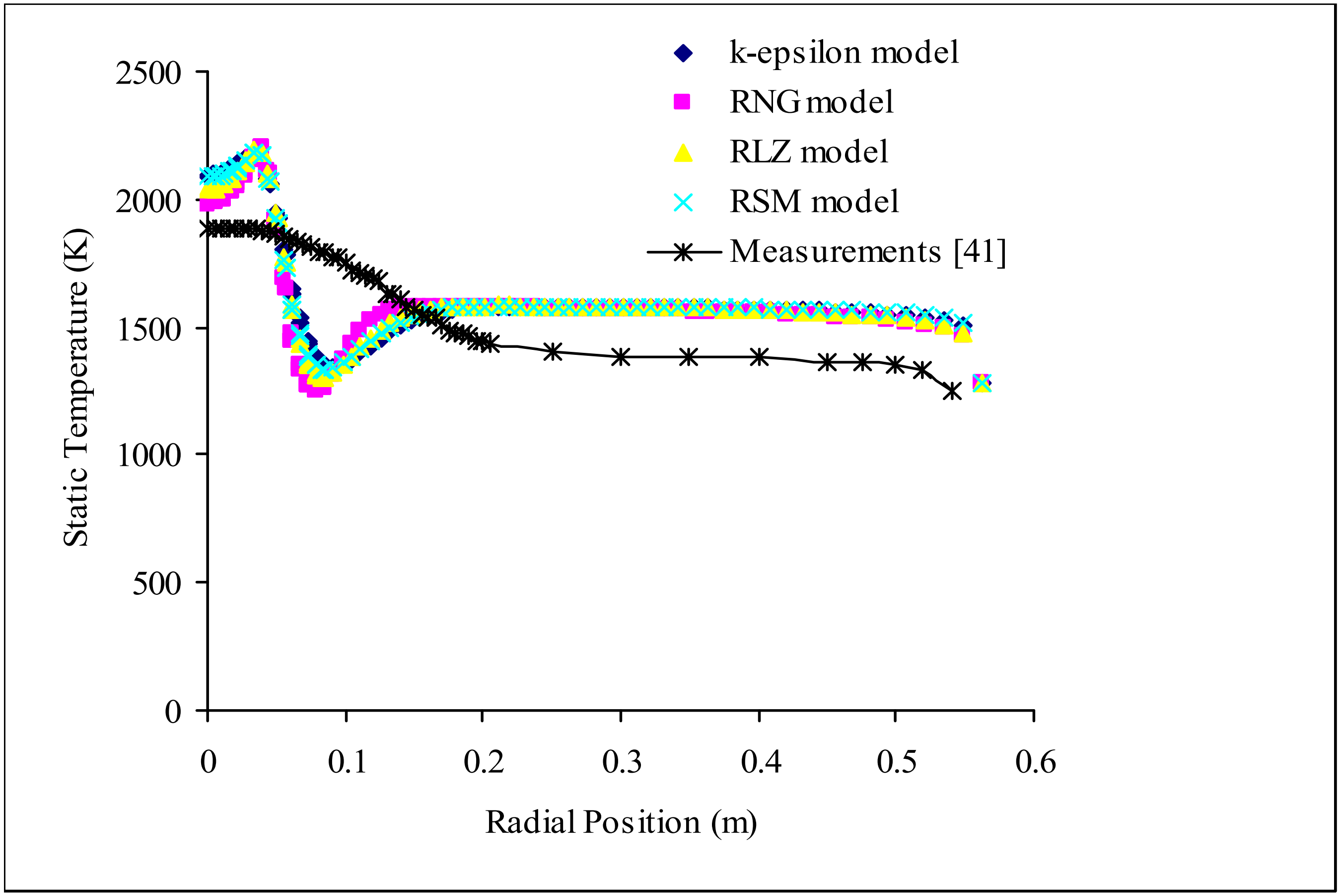
Axial velocity at 27 mm from the quarl exit

Validation of CFD Models



Axial velocity at 109 mm from the quarl exit

Validation of CFD Models



Axial velocity at 343 mm from the quarl exit

Validation of CFD Models

- Conclusions
  - The agreements between CFD predictions and measurements are satisfactory (when considering model limitations)
  - Similar differences have been reported by other researchers [34,40,47]
  - The turbulence models investigated have varying strengths
  - Globally, it is possible to conclude that the models are of adequate accuracy and robust enough in the simulation of diffusion flames to be used for design optimisation study.

Mathematical Optimisation

- Standard Non-Linear Optimisation Problem:

$$\min_{x} f(\boldsymbol{x});\ \boldsymbol{x} = [x_1, x_2, \ldots, x_i, \ldots, x_n]^{\mathrm{T}}, x_i \in R$$

$$s.t.\quad g_j(\boldsymbol{x}) \leq 0;\quad j - 1, \ldots, m$$

$$h_k(\boldsymbol{x}) = 0;\quad k = 1, \ldots, p < n$$

$$\mathbf{x}^* = \left[x_1^*, x_2^*, \ldots, x_n^*\right]^T$$

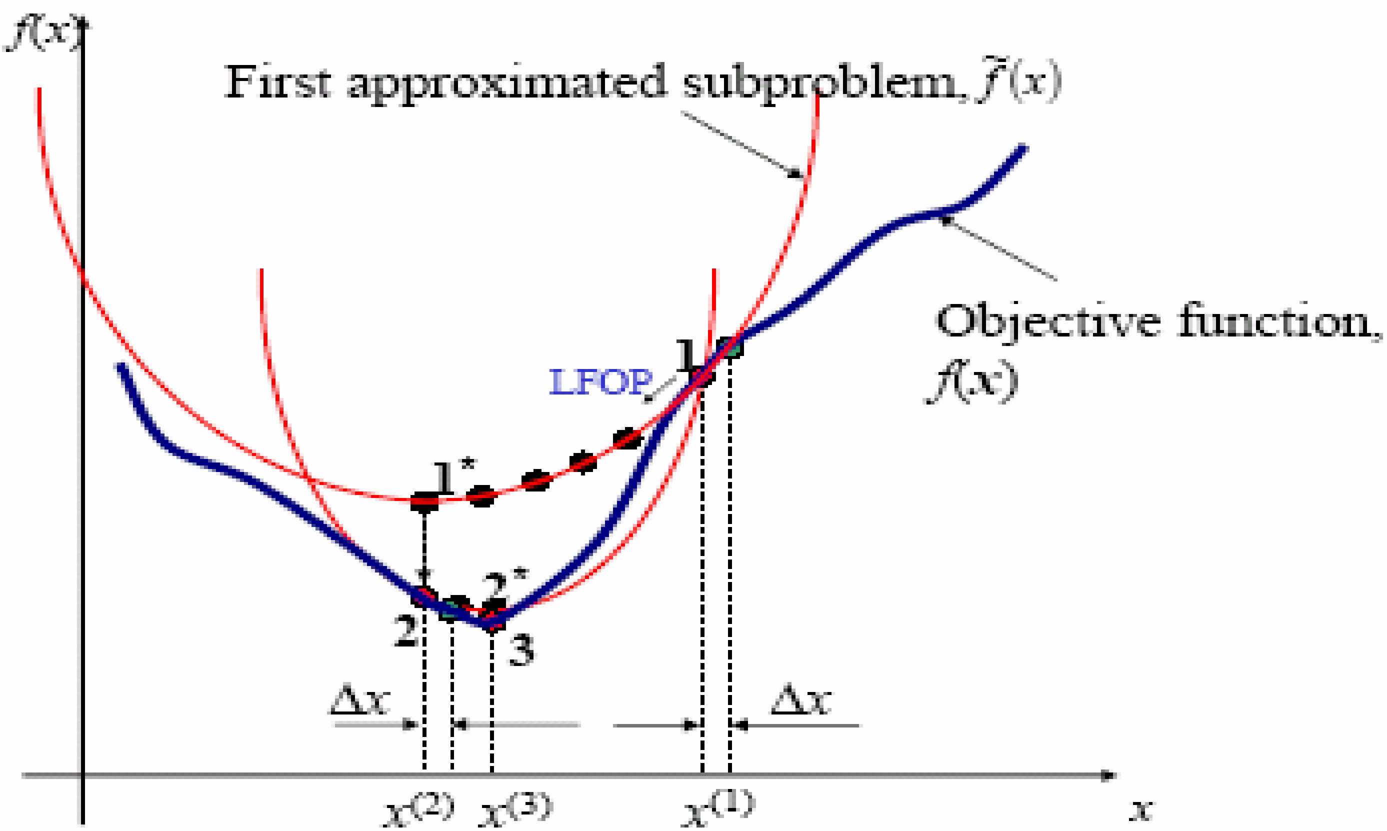
Mathematical Optimisation

- Dynamic-Q Method of Snyman
  - Dynamic Trajectory Method (LFOP)
  - Successive Quadratic Subproblems (see figure)
  - Penalty Function Formulation
  - Requires Only Gradient Information
  - Advantages
    - Robust
    - Economical

Mathematical Optimisation

Dynamic-Q-Quadratic subproblems

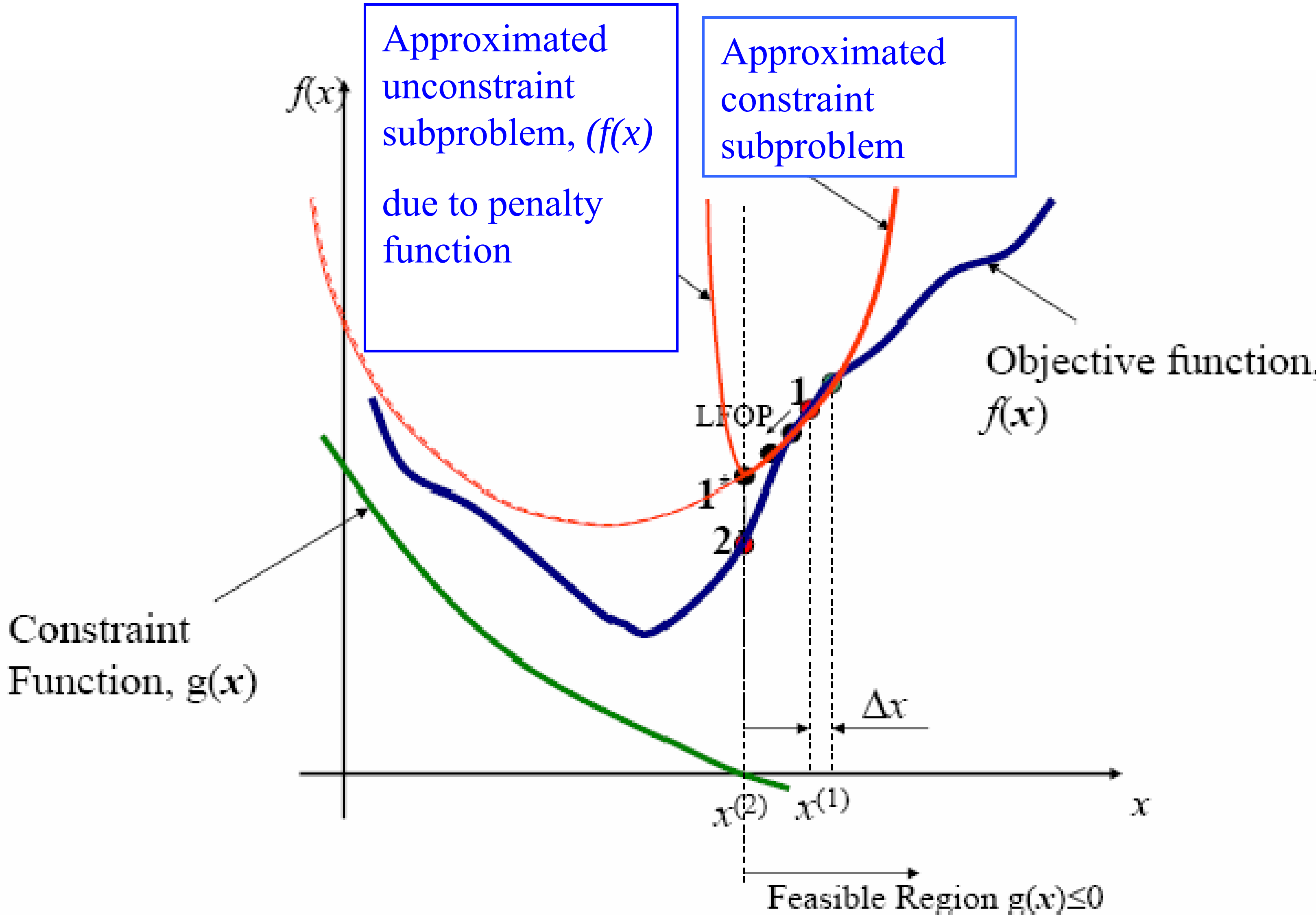
Unconstrained optimisation with approximated objective function



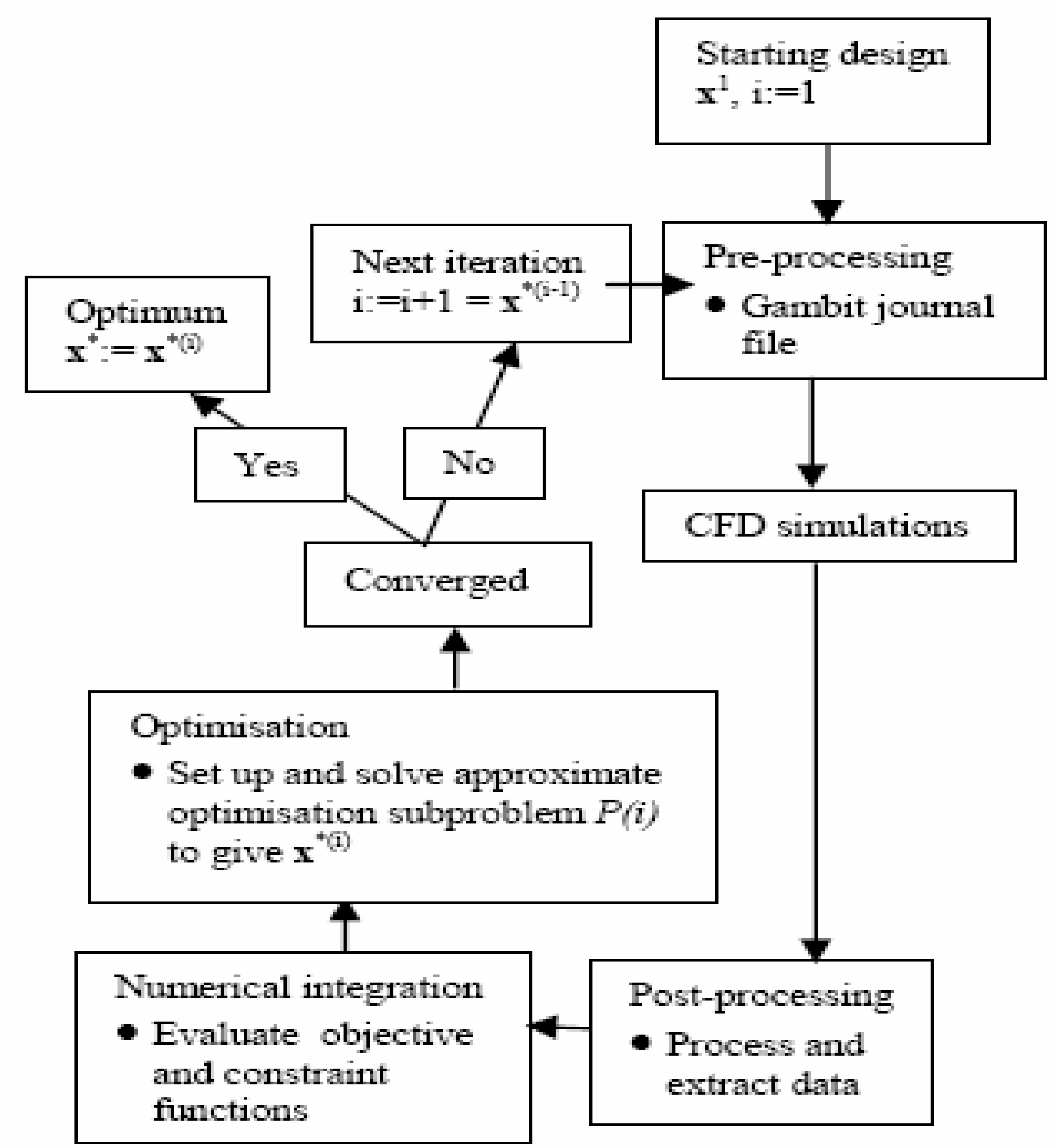
Dynamic-Q-Quadratic subproblems - cont..

Constrained optimisation with approximated objective function

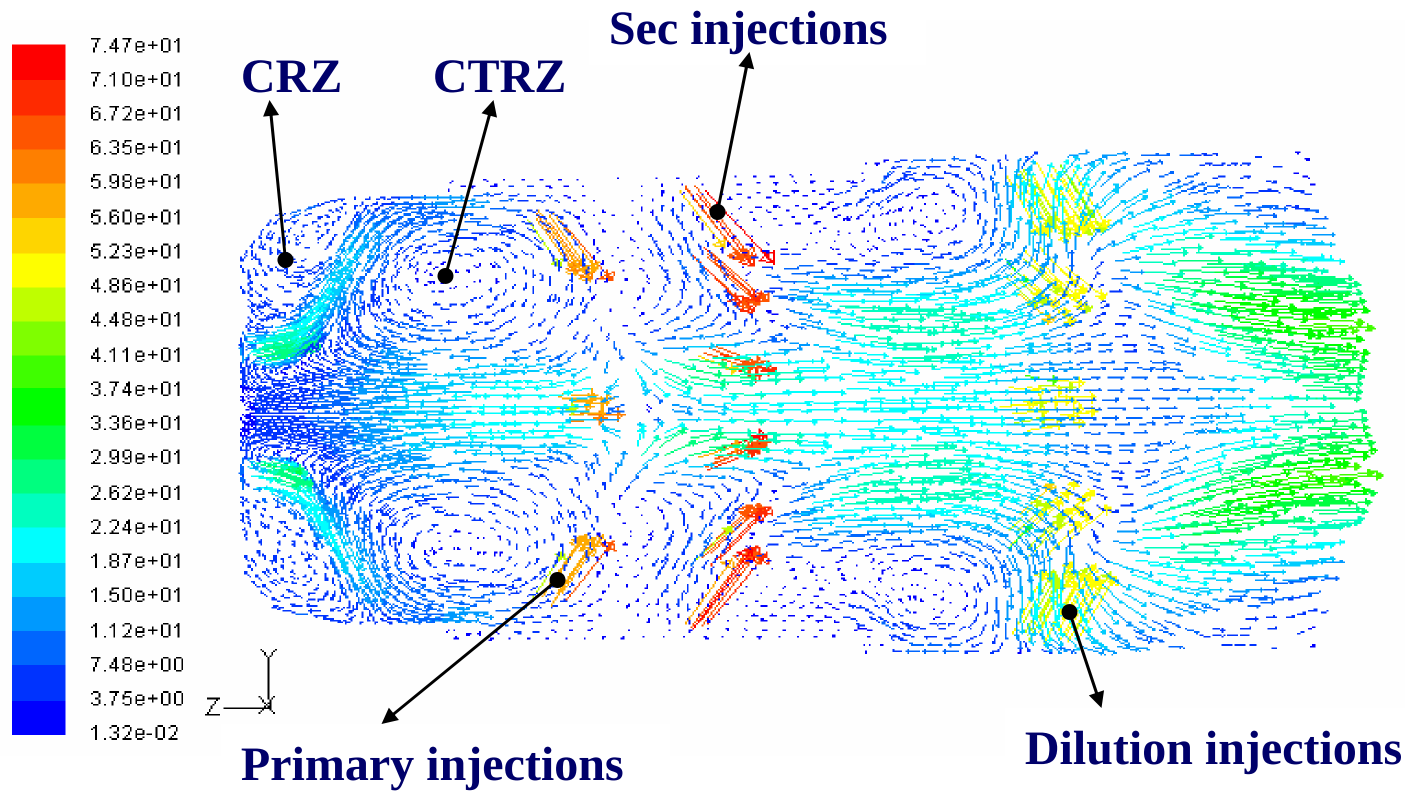
And analytical constraint



Flow chart of Optimisation run

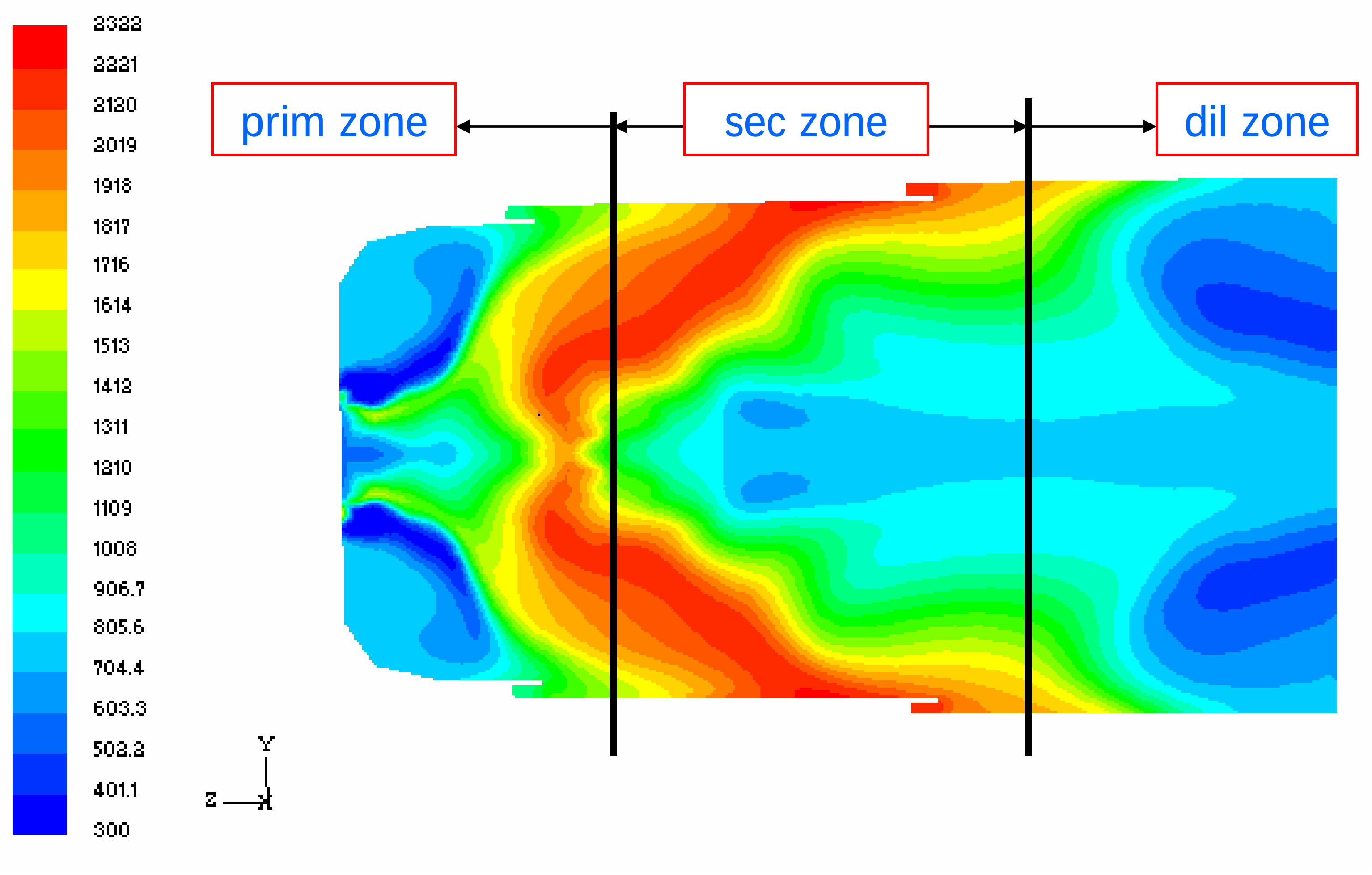


Non-Optimised Combustor Numerical Flow Fields



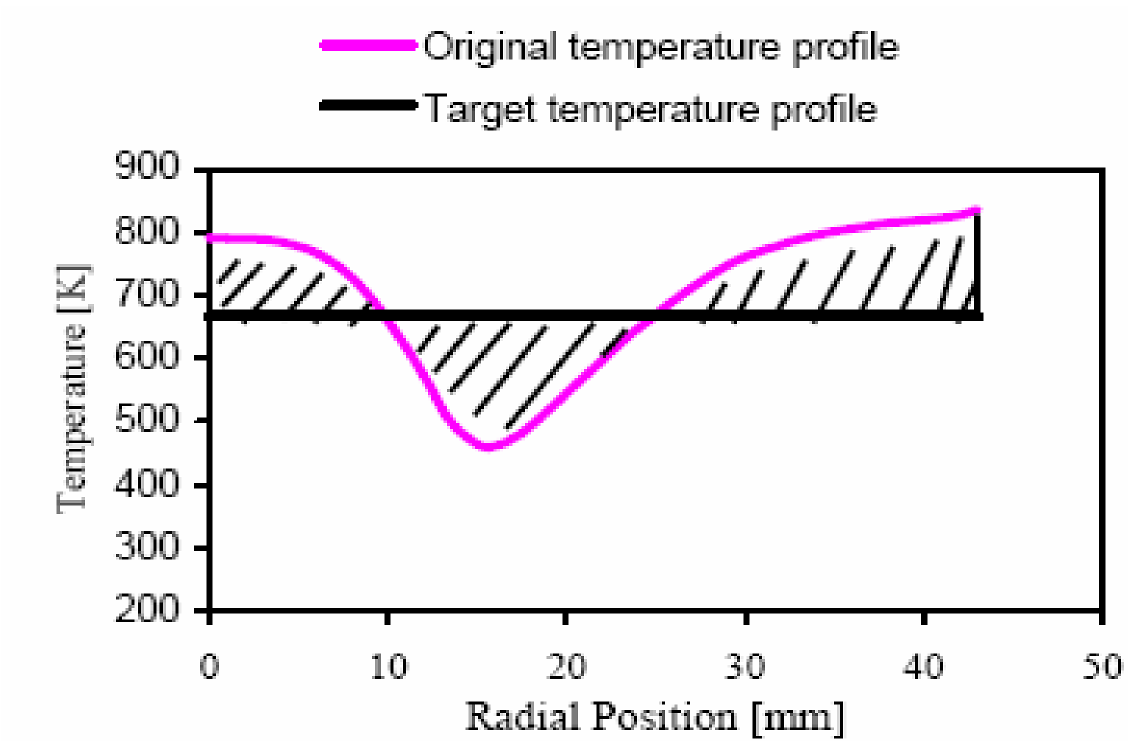
Velocity vectors on the half plane

Non-Optimised Combustor Flow Fields – cont..



Temperature contours on the half plane

Optimisation Problem Definition



Target and non-optimised temperature profile

- The two profiles differ in shape
- The Objective is to achieve a uniform combustor temperature profile
- This was achieved by minimising the shaded area between the two profiles

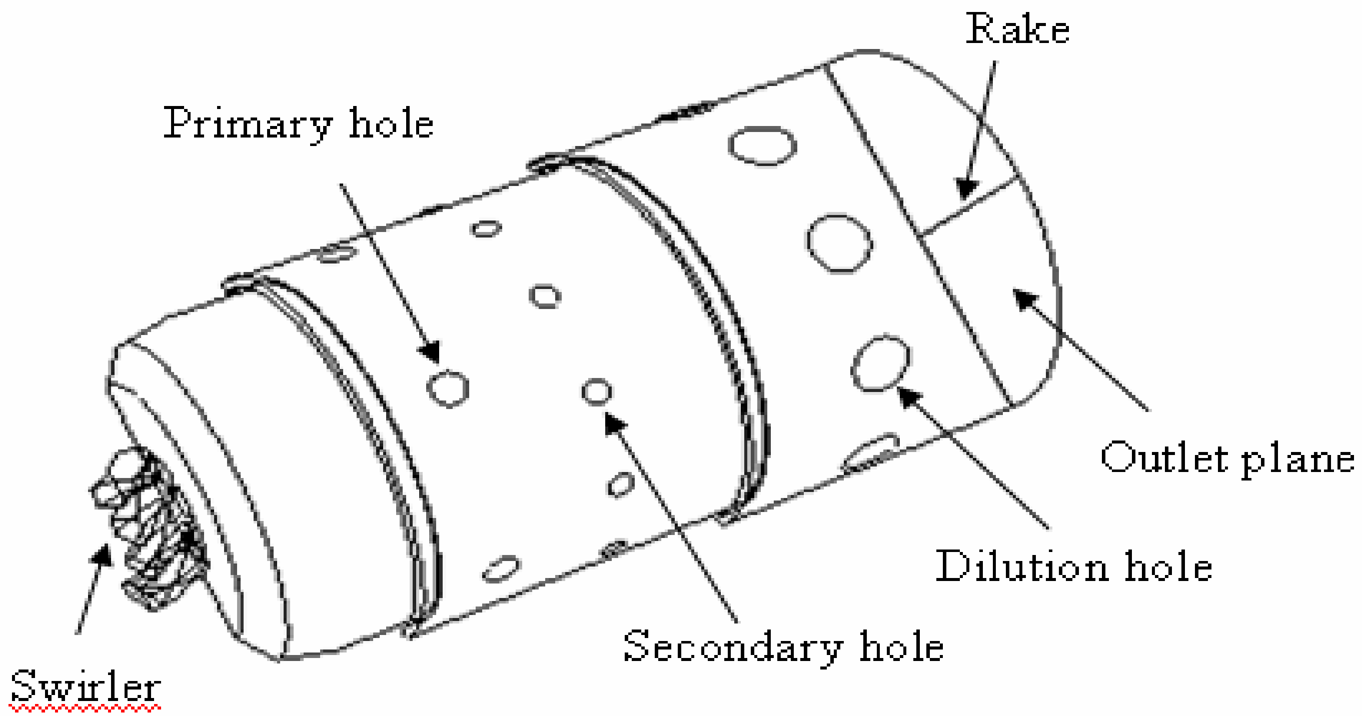
temp: can also be derived from a simple thermodynamic relationship

- The shaded area in the figure was derived by Trapezoidal rule

Formulation of Optimisation problem

- Objective function, *f(x):* obtain a flatter (uniform) combustor exit temperature profile that closely matches the target profile.
  - The objective is not analytical equation but an **approximated value** derived by a numerical integration procedure
- **Design variables**
  - **Process variables (flow rates and temperature)**
  - **Geometric variables (geometric that affect temperature profile) (Dilution holes, secondary holes, primary holes and swirler angle)**
- Design constraints
  - Inequality constraint: pressure drop
  - Equality constraint: constant mass-flow though the all the inlets

Formulation of Optimisation problem – cont…



Combustor design variables

Case Studies

- Case 1 (two design variables)

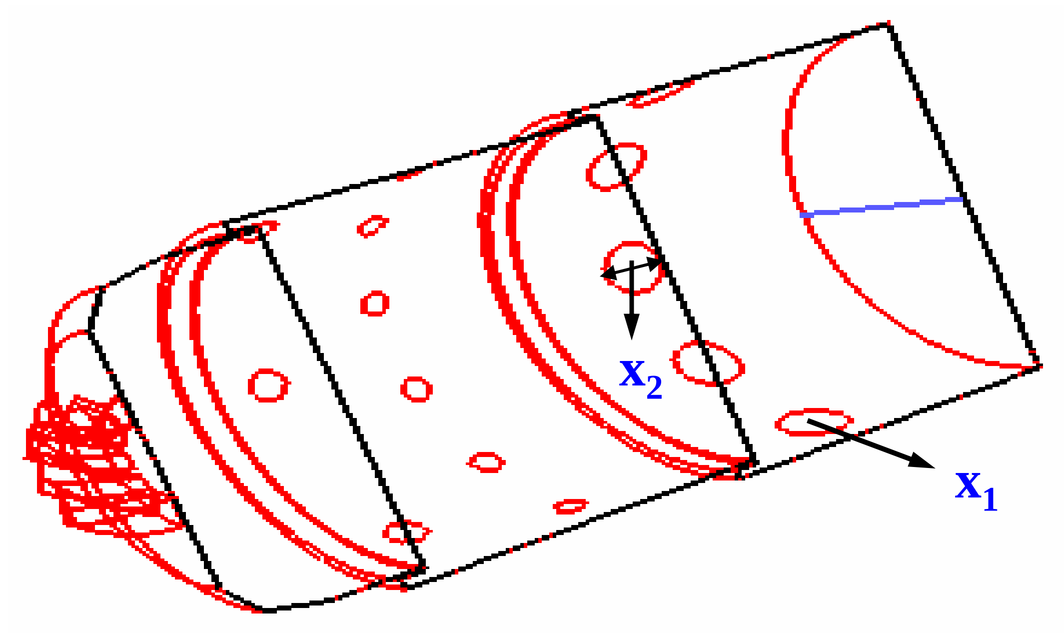
  Minimise $f(\mathbf{x})$ = shaded area

  such that: x_1 an integer, $x_2 \in R$

The limits are $2 \leq x_1 \leq 7$ and $4 \leq x_2 \leq 8$

Where x_1 = number of dilution holes and x_2 = diameter of dilution holes

- Results for Case 1



Results for case 1

- Optimised combustor exit temperature profile (see figure)
- Optimisation history of the objective function (see figure)
- Optimisation history of design variables (see figure)
- Temperature contours on the centre plane of the combustor (see figure)
- In this unconstraint optimisation case, pressure drop increased by 37%, but pattern factor improved from 0.5 to 0.36, indicating good mixing

Therefore, case 2 considered a situation where a constraint was imposed on pressure drop.

Case 2: four design variables

Minimise *f(**x**)* = shaded area

such that:

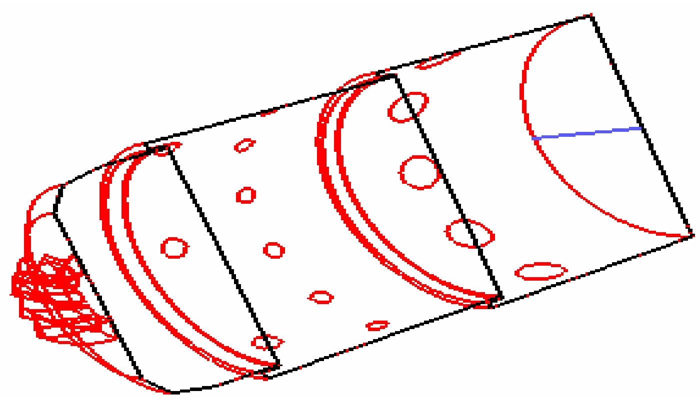
$$g_1 = \Delta p - 160 \leq 0 \quad \text{(inequality constraint)}$$

$$h_1 = x_1 x_2 - 37.5 = 0 \quad \text{(equality constraint)}$$

$$g_j = -x_j + x_j^{\min} \leq 0, \qquad j = 1, 2, \ldots, 4$$

$$g_{j+2} = -x_j - x_j^{\max} \leq 0, \quad j = 1, 2, \ldots, 4$$

where $x_j^{\min}$ and $x_j^{\max}$ denote the upper and lower limits on the variation of variables.



Case 2: four design variables – cont…

In addition move limits (see table) are also imposed
Here x_2, x_3 are integers, and x_1, x_4 $\in R$

	x_1	x_2	x_3	x_4
Initial values	2.5	6	5	6
Move limits	0.4	2	2	1
Perturbations sizes	0.2	1	1	0.4
Lower limit	1.9	3	2	4
Upper limit	3.9	10	7	8

Optimisation parameters for case 2

Results for case 2

- Optimised combustor exit temperature profile (see figure)
- Optimisation history of the objective function (see figure)
- Optimisation history of inequality constraint (see figure)
- Optimisation history of design variables (see figure)
- Temperature contours on the centre plane of the combustor (see figure)
- In this constrained optimisation, pattern factor increased from 0.5 to 0.42

Case 3: four design variables

Minimise *f(**x**)* = shaded area

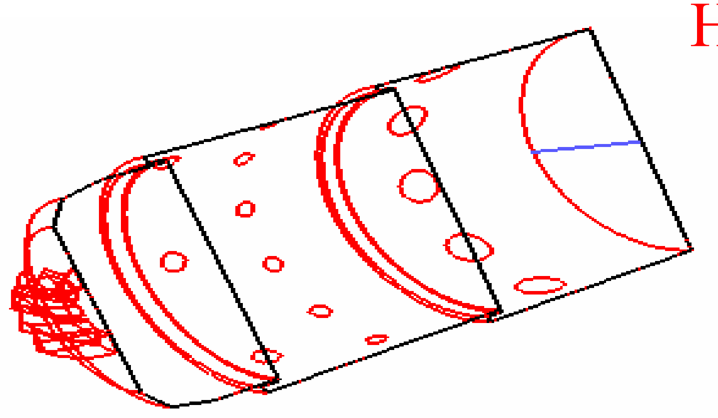
such that:

$$g_1 = \Delta p - 160 \le 0 \quad \text{(inequality constraint)}$$

$$g_j = -x_j + x_j^{\min} \le 0, \qquad j = 1, 2, \ldots, 5$$

$$g_{j+2} = -x_j - x_j^{\max} \le 0, \quad j = 1, 2, \ldots, 5$$

where $x_j^{\min}$ and $x_j^{\max}$ denote the upper and lower limits on the variation of variables.



Here x_2, x_3 are integers, and x_1, x_4, $x_5 \in R$

x_1 is the diameter of primary holes,

x_2 is the number of primary holes

x_3 is the number of dilution holes

x_4 is the diameter of dilution holes

x_5 is the swirler angle.

Optimisation parameters for Case 3

In addition move limits (see table) are also imposed
Here x_2, x_3 are integers, and x_1, x_4, x_5 $\in$ R

	x_1	X_2	x_3	x_4	x_5
Initial values	3.3	3	5	6	45
Move limits	0.4	2	2	1	0.5
Perturbation sizes	0.2	1	1	0.4	1
Lower limit	2.3	2	2	4	45
Upper limit	2.9	6	7	8	65

Results for case 3

- Optimised combustor exit temperature profile (see figure)
- Optimisation history of the objective function (see figure)
- Optimisation history of inequality constraint (see figure)
- Optimisation history of design variables (see figure)
- Temperature contours on the centre plane of the combustor (see figure)
- Swirl velocity at 30mm from the dome face for case 3
- Axial velocity at 30mm from the dome face for case 3
- Temperature contours for optimised case 3 on the symmetrical plane
- In this constrained optimisation, pattern factor increased from 0.5 to 0.55, but pressure drop improved, because of imposed constraint

CONCLUSIONS

- **CFD and mathematical optimisation were successfully combined to optimise combustor exit temperature profile**
- **A more uniform combustor exit temperature profile with improved pattern factor was achieved with two design variables (case 1), but pressure drop increasing**
- **A more uniform combustor exit temperature profile with improved pressure drop and pattern factor was achieved with four design variables**

CONCLUSIONS

- A more uniform combustor exit temperature profile with improved pressure drop was achieved with five design variables, but pattern factor increased a little

Basing on our findings, combing CFD and a mathematical optimiser can be considered a supporting tool for gas turbine design, by which better designs can be achieved.

Future Work

- **Improvements of simulation capabilities**
- **Further development of optimisation capability**
- **Extension of design optimisation process**

Acknowledgement

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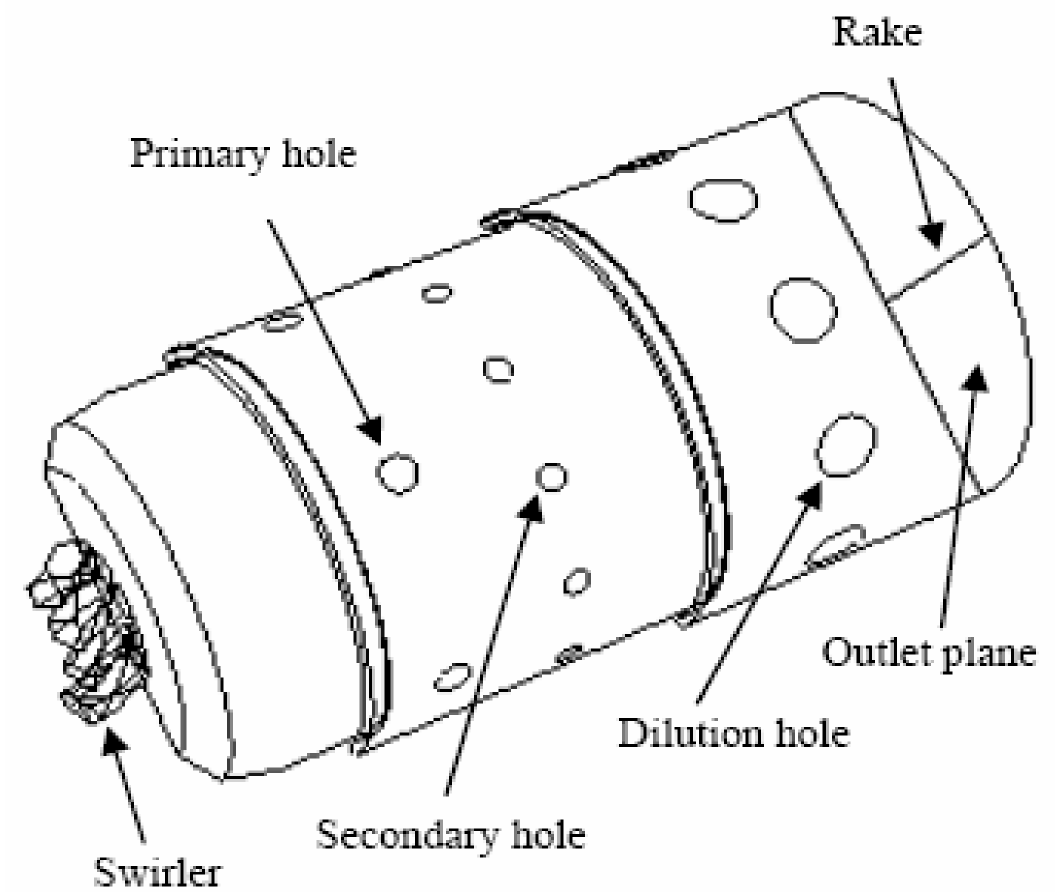
- **Prof J A Visser**
- **Dr J D De Kock, Mr M R Morris**
- **University of Botswana**

END

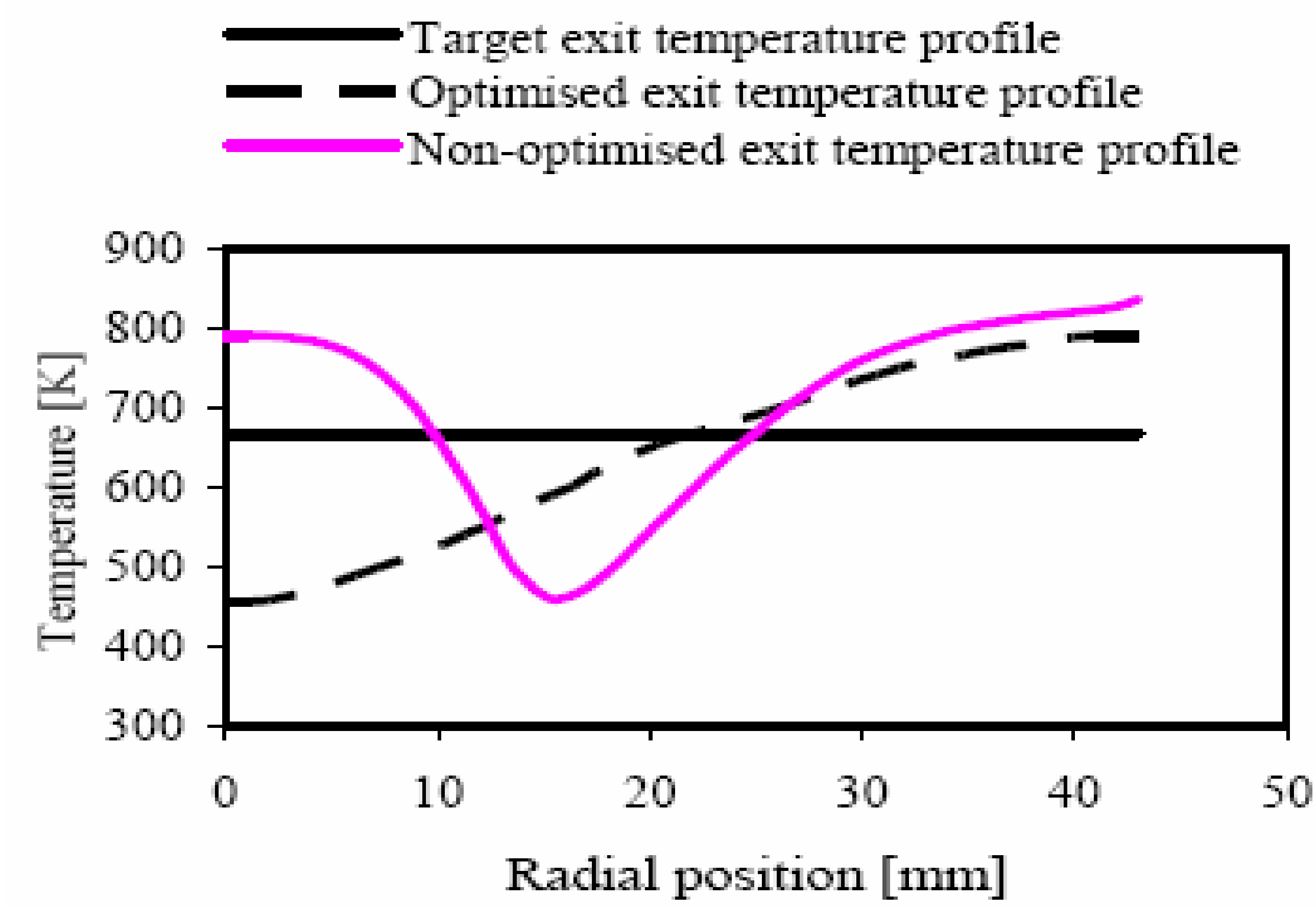
THANK YOU

Boundary conditions

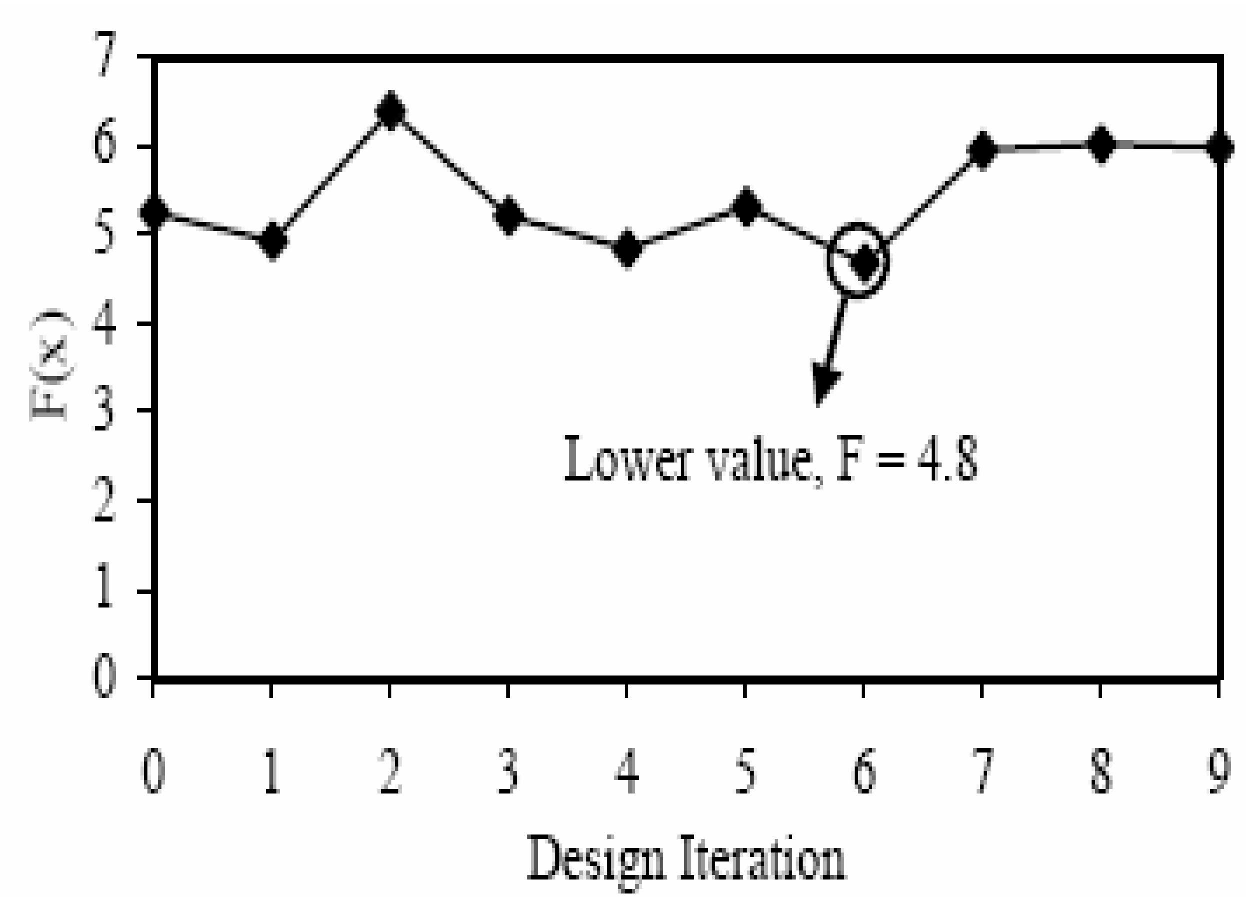


Boundary conditions of the combustor

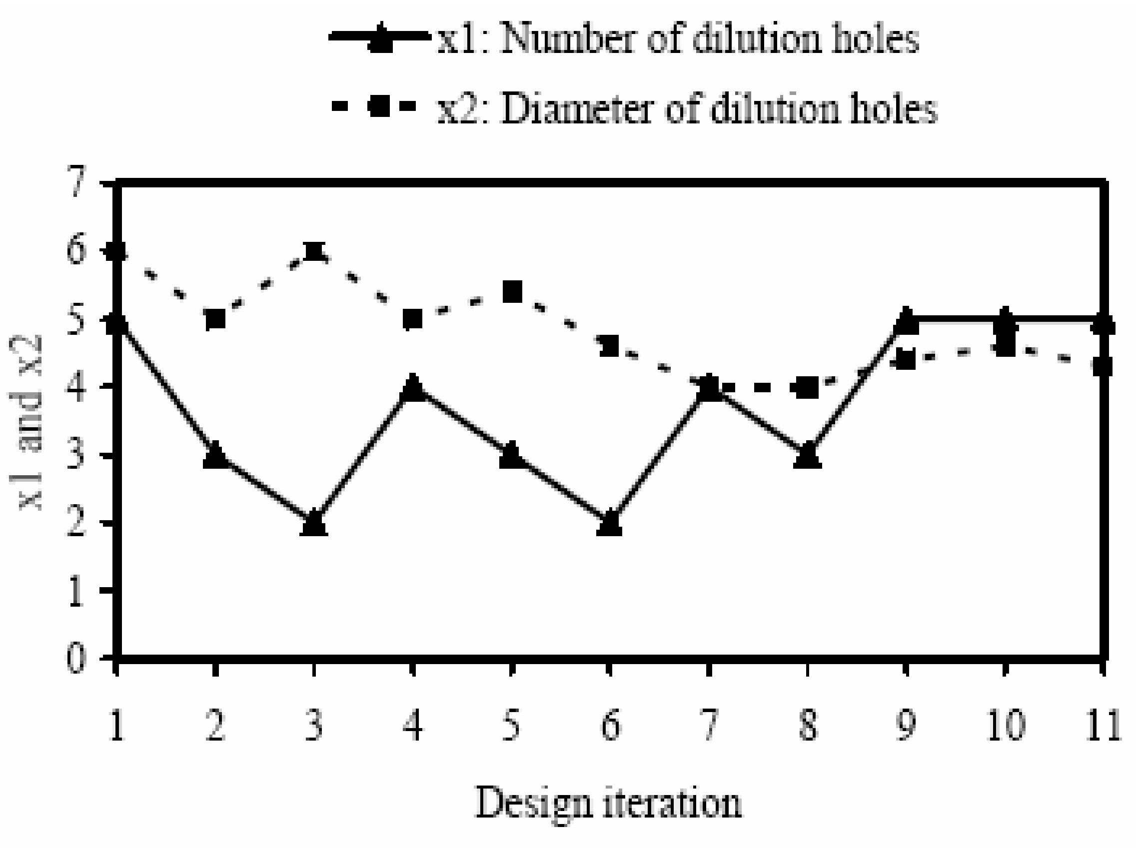
Optimised combustor exit temperature profile for case 1



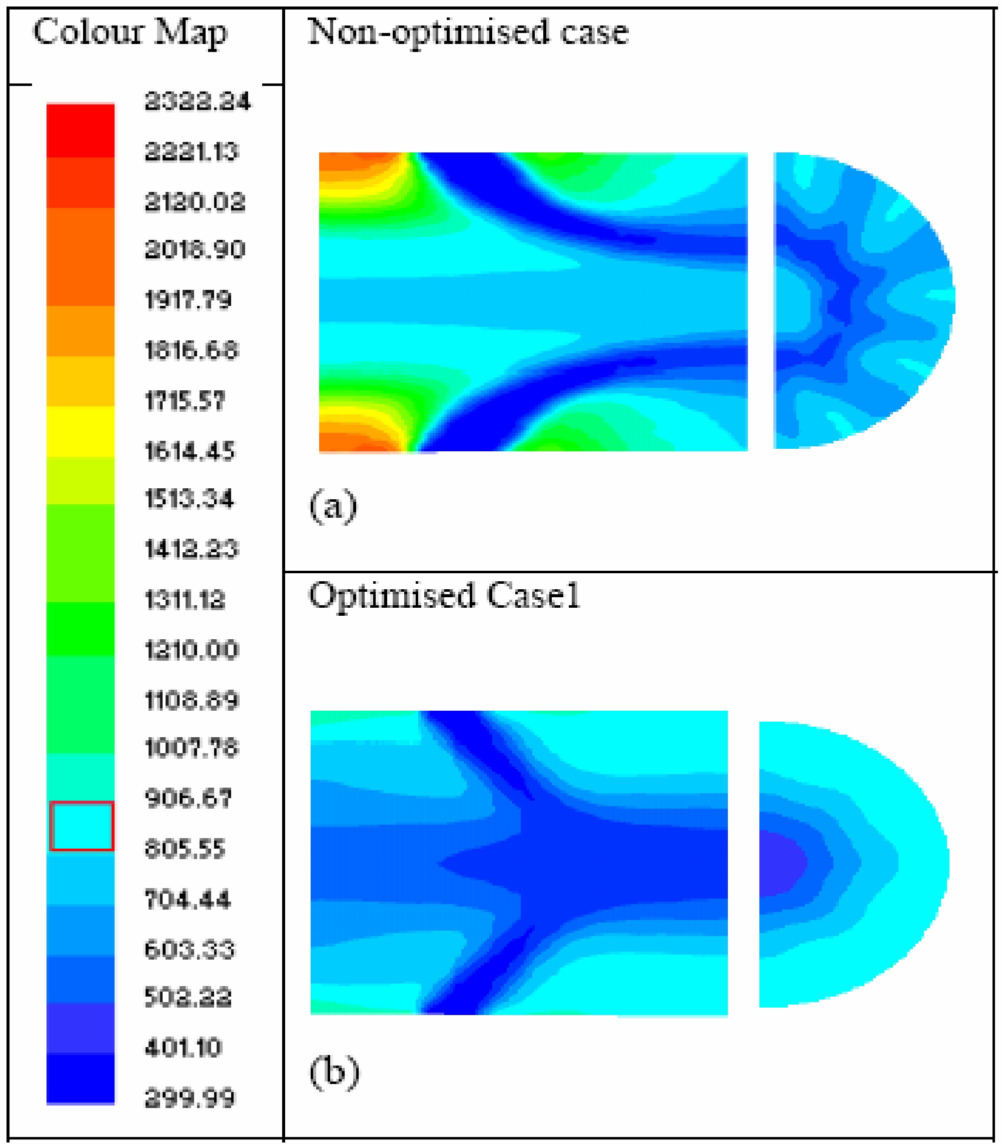
Optimisation history of the objective function for case 1



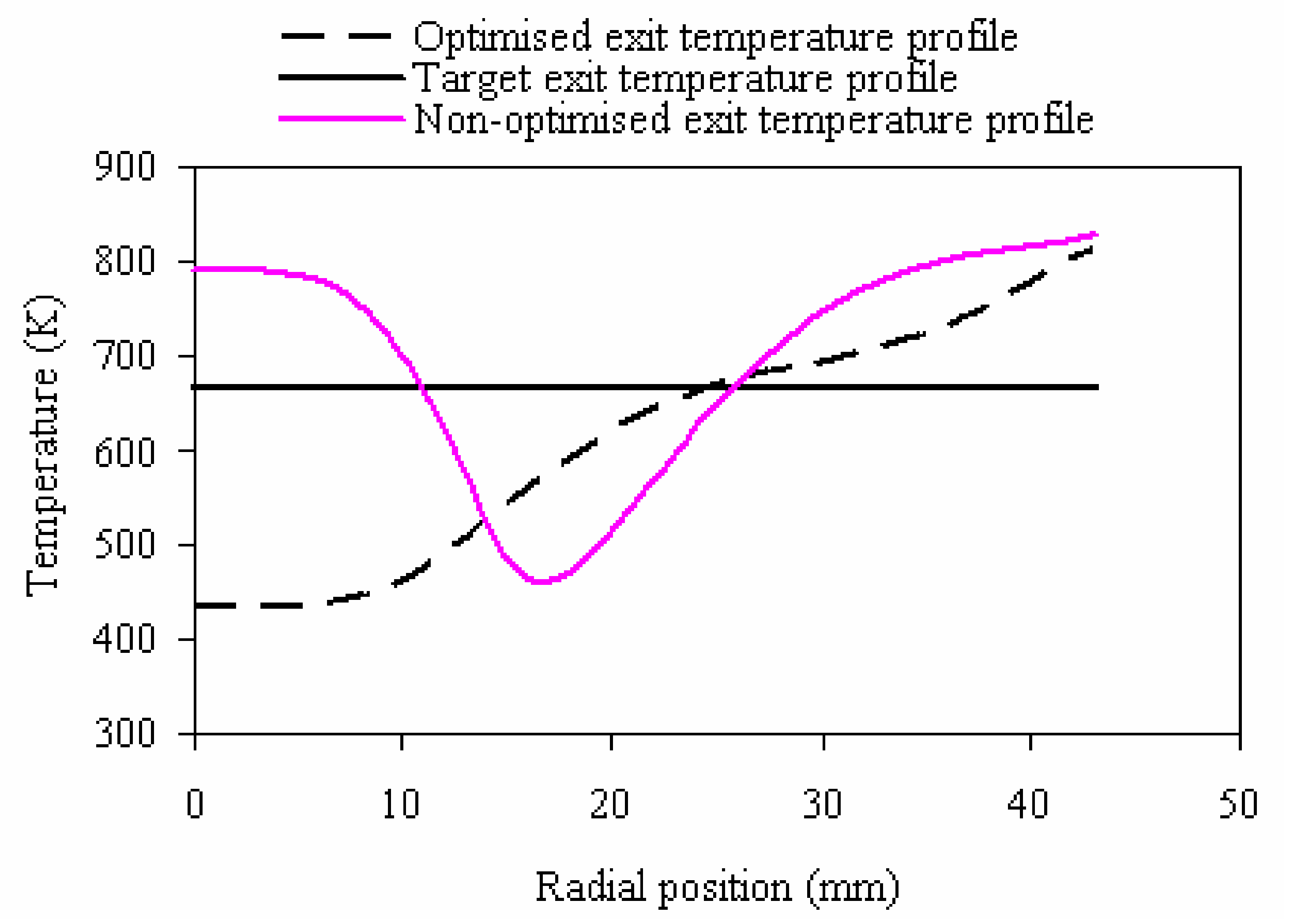
Optimisation history of design variables for case 1



Temperature contours on the centre plane and exit of the combustor for case 1

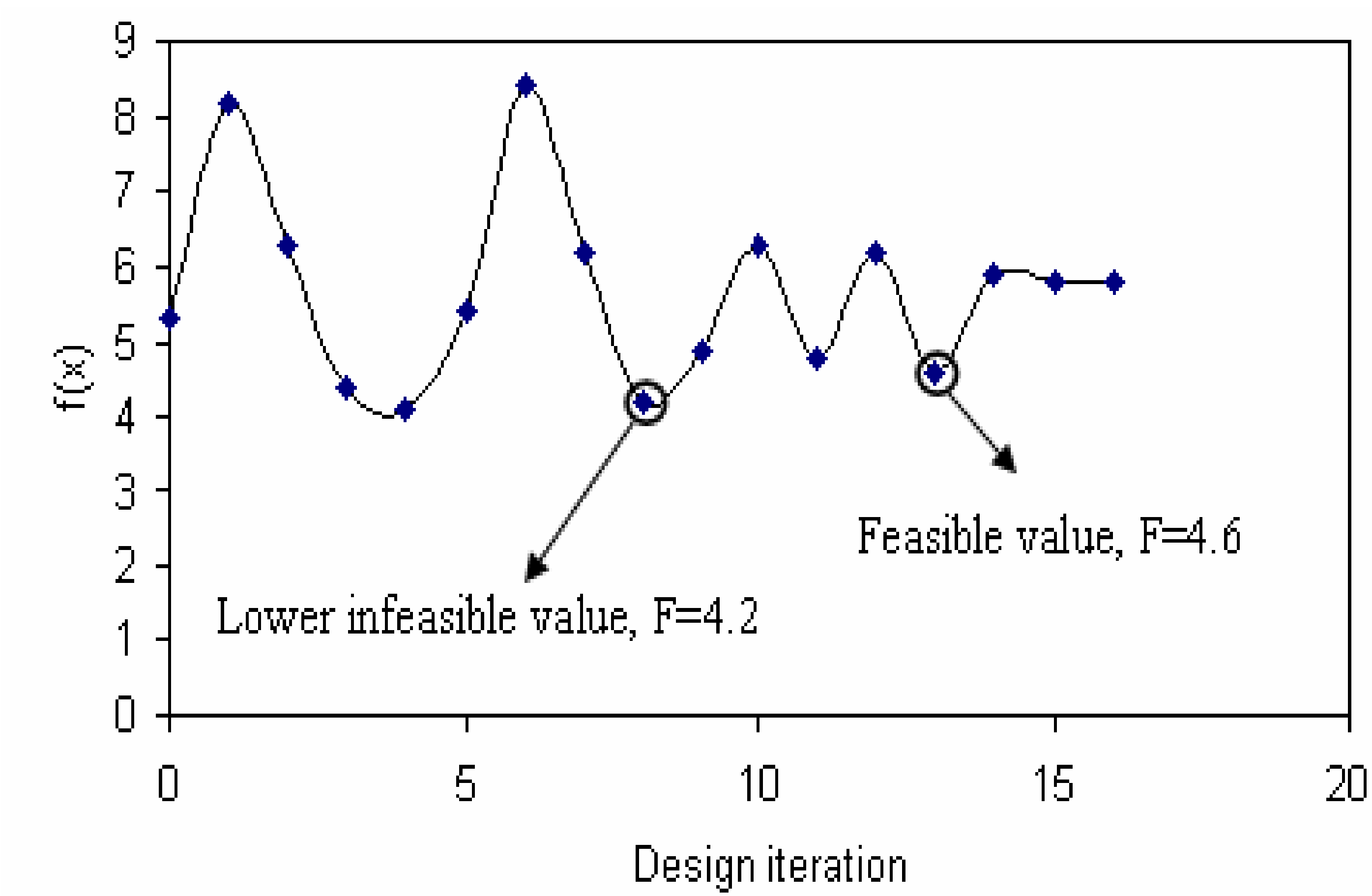


Optimised combustor exit temperature profile for case 2

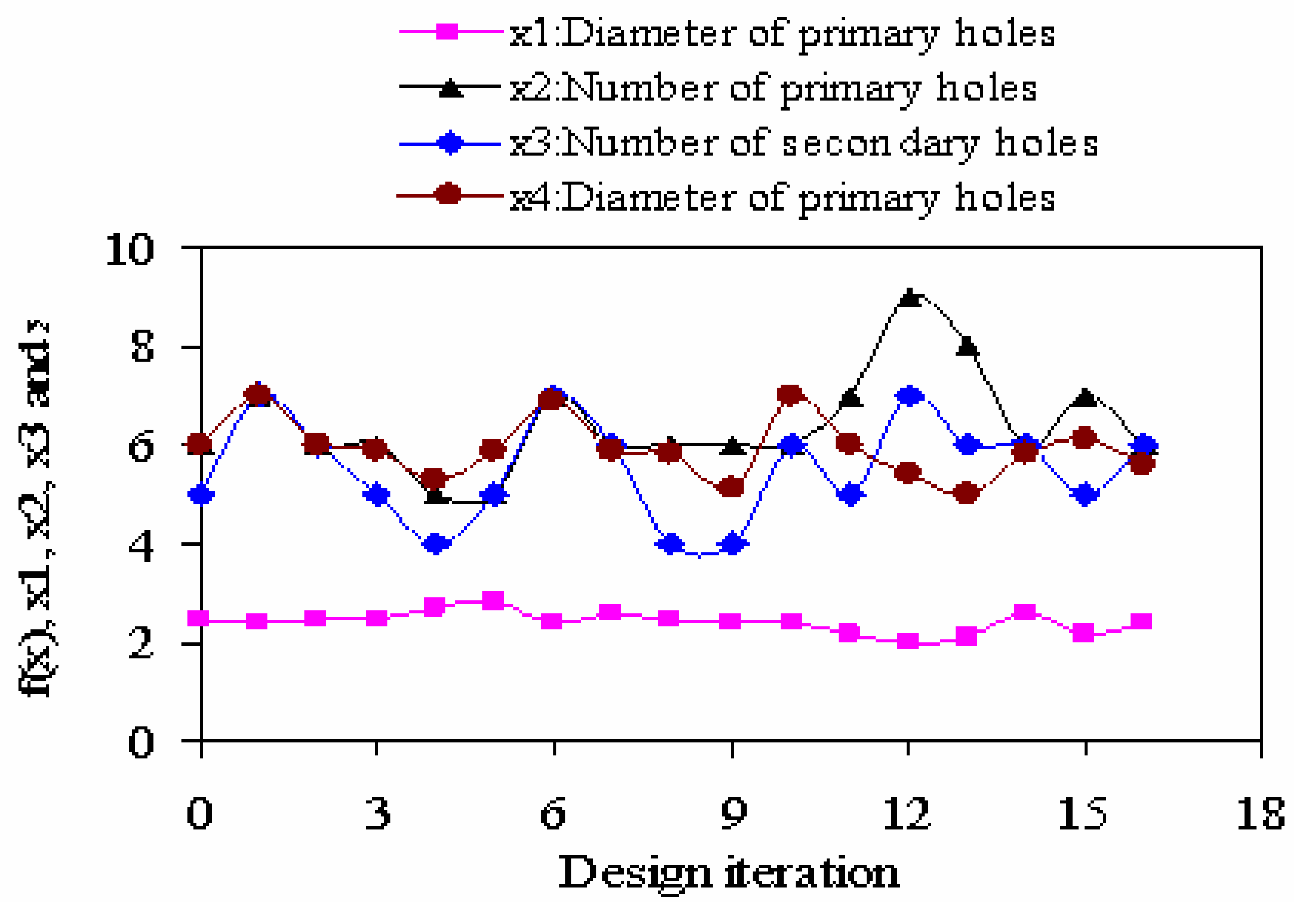


Target, non-optimised and optimised combustor exit temperature profile for Case 2

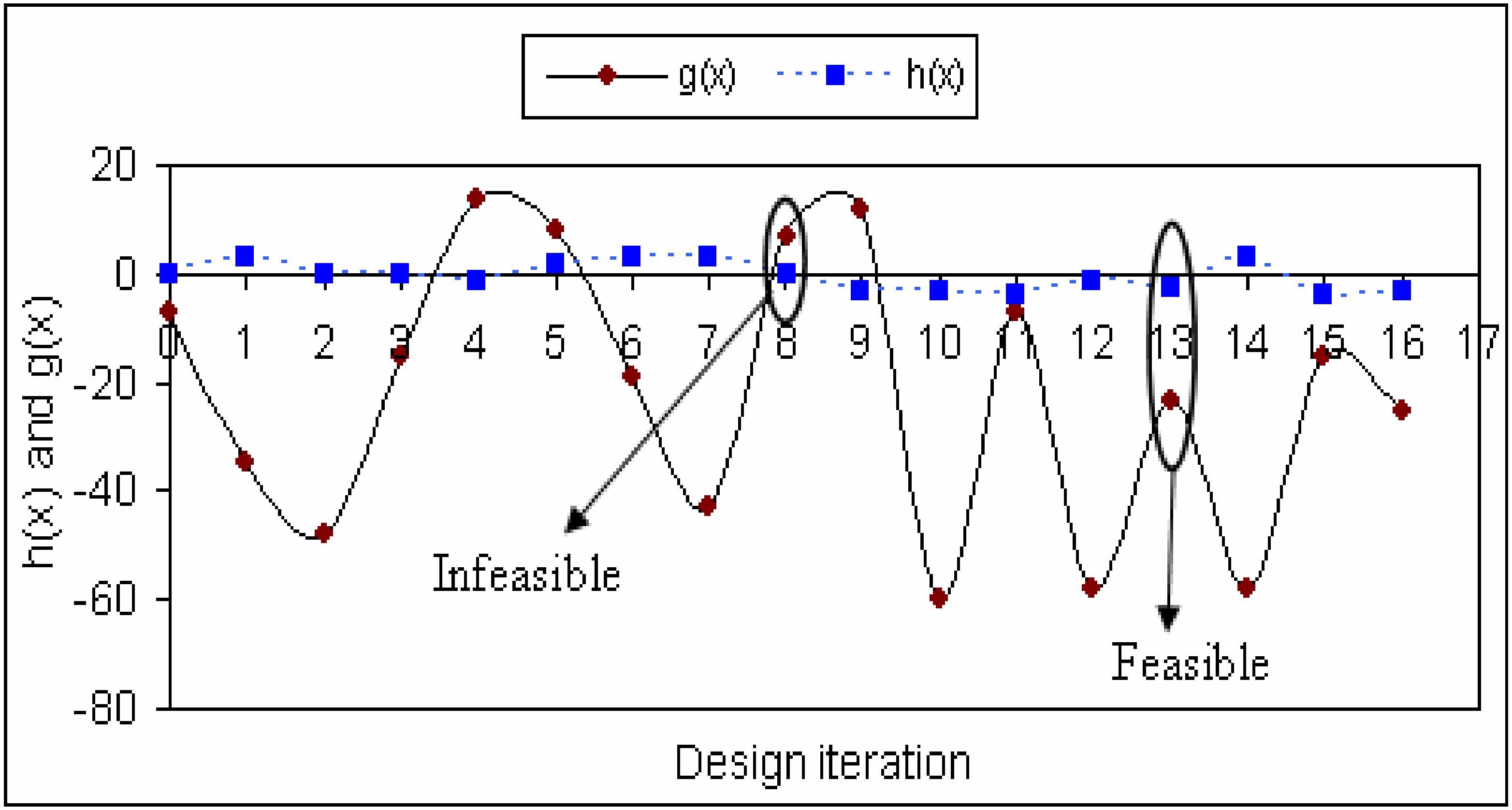
Optimisation history of the objective function for case 2



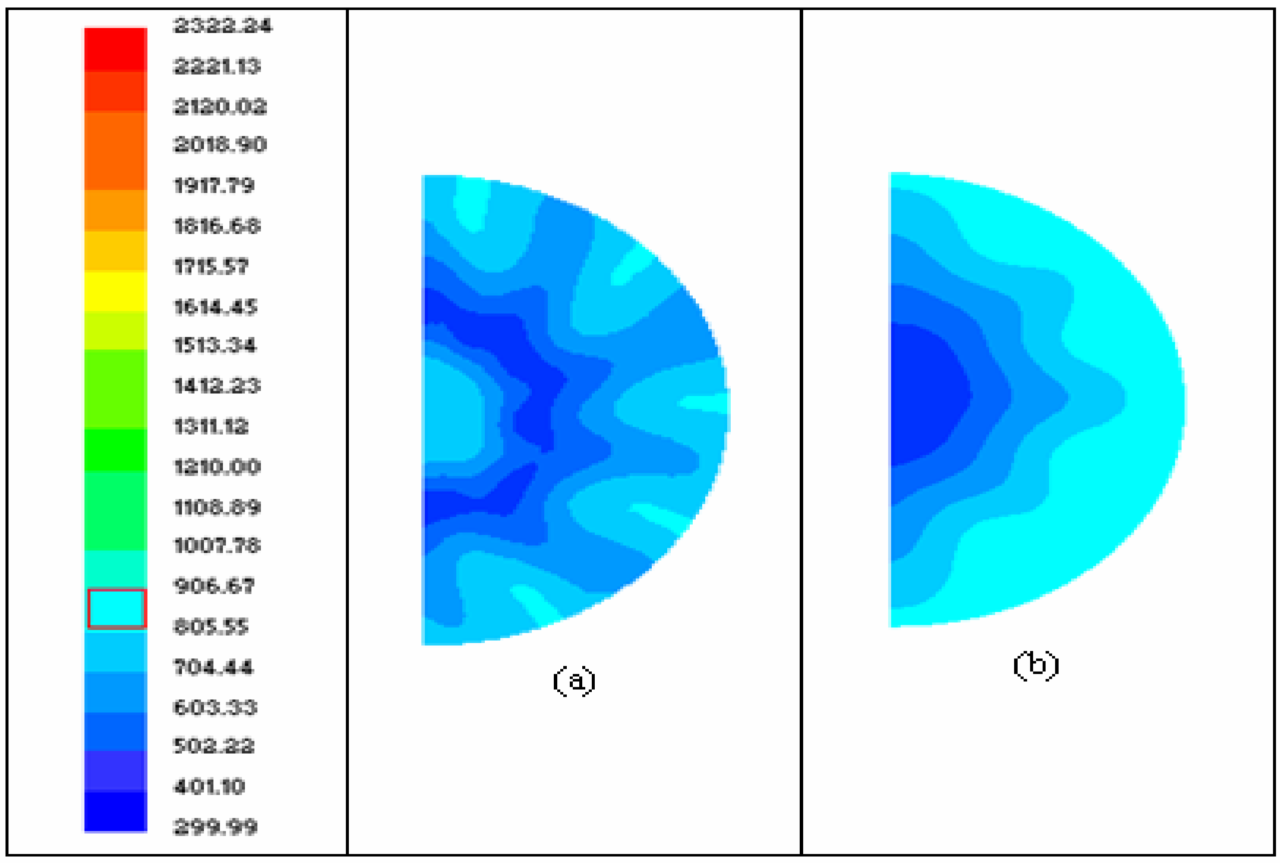
Optimisation history of the design variables for case 2



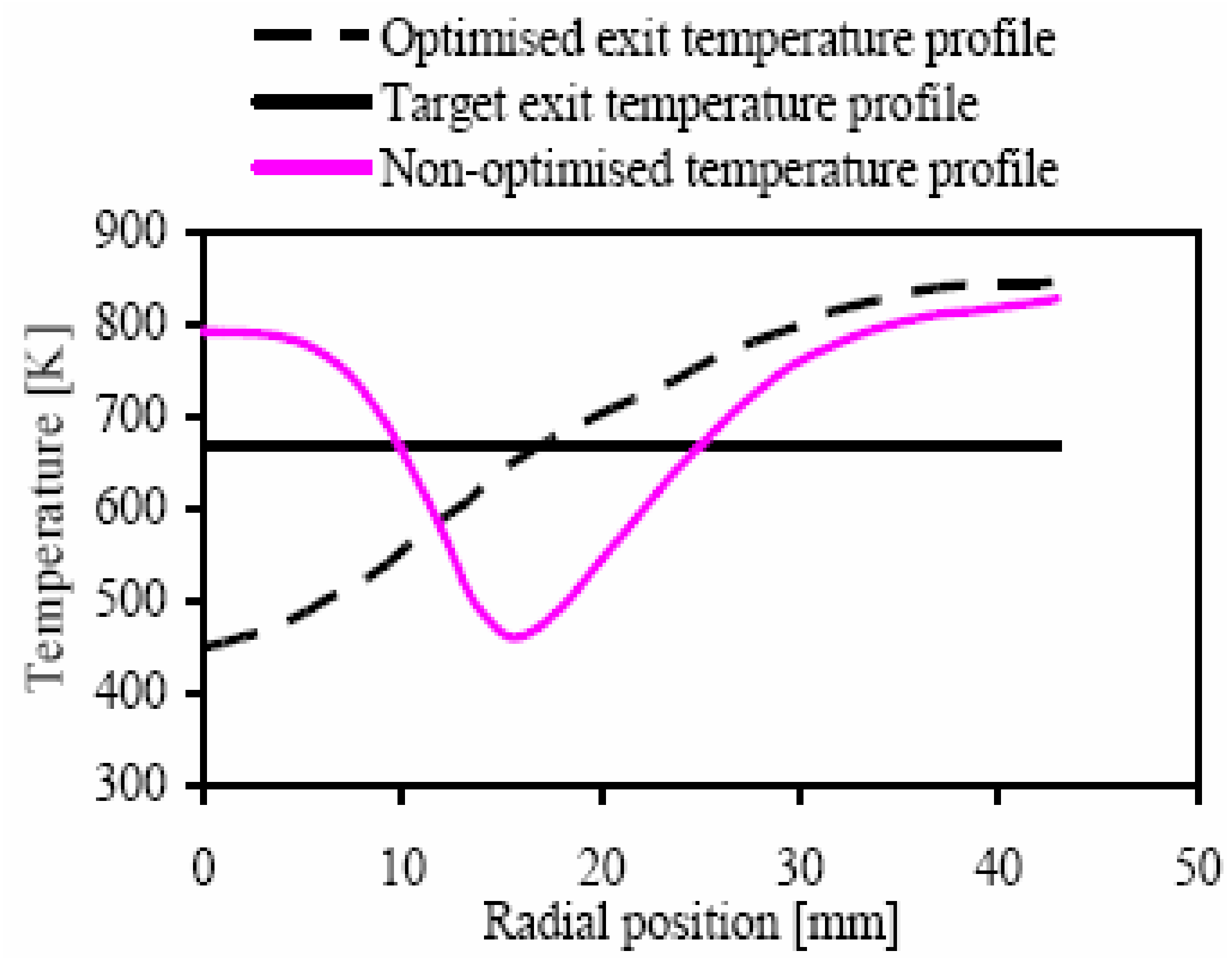
Optimisation history of constraints for case 2



Temperature (K) contours (exit plane) for non-optimised and optimised for case 2



Optimised combustor exit temperature profile for case 3



Optimisation history of the objective function for case 3

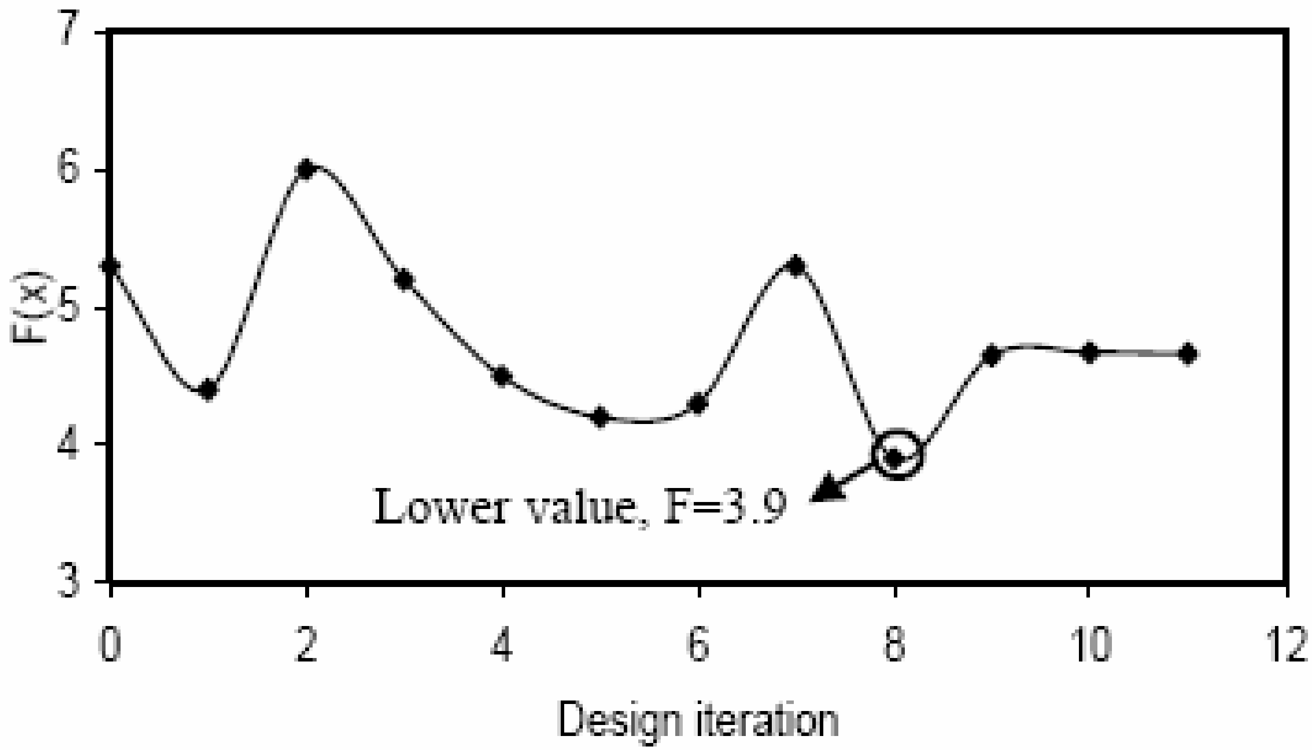


Figure 17. Optimisation history of the objective function for Case 2

Optimisation history of inequality constraint function for case 3

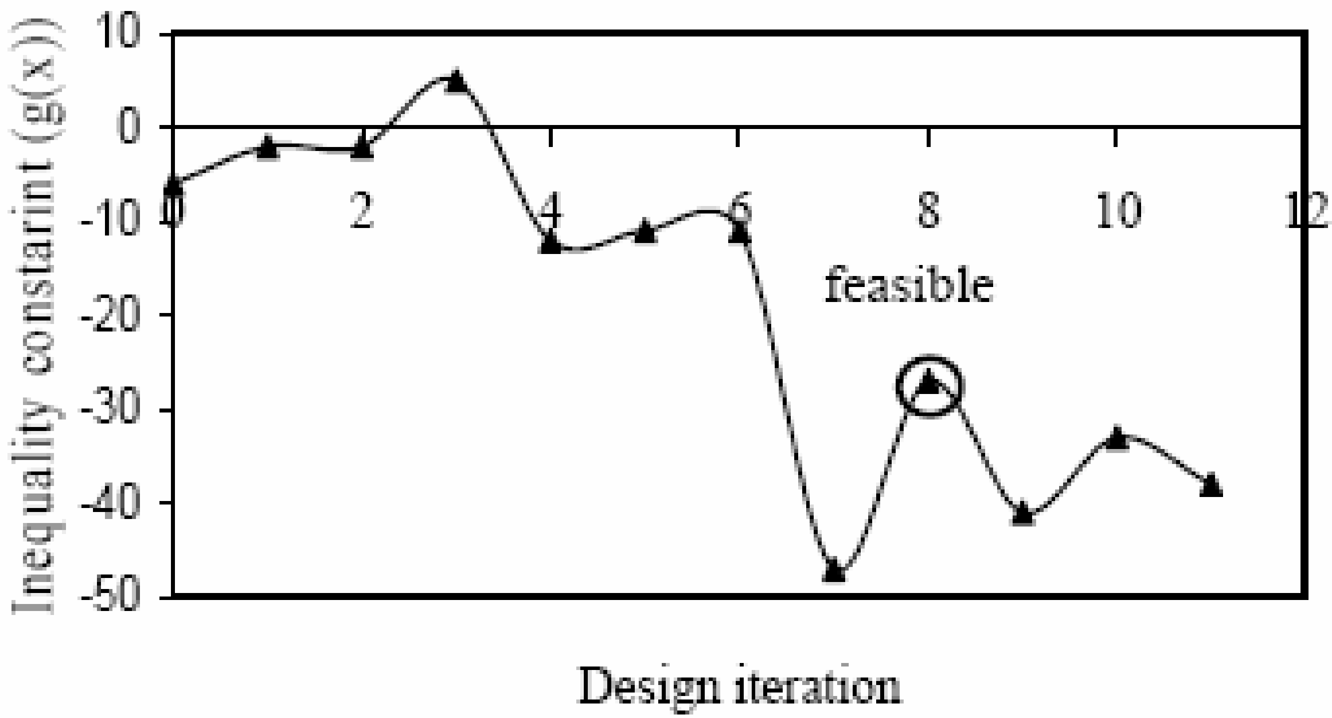
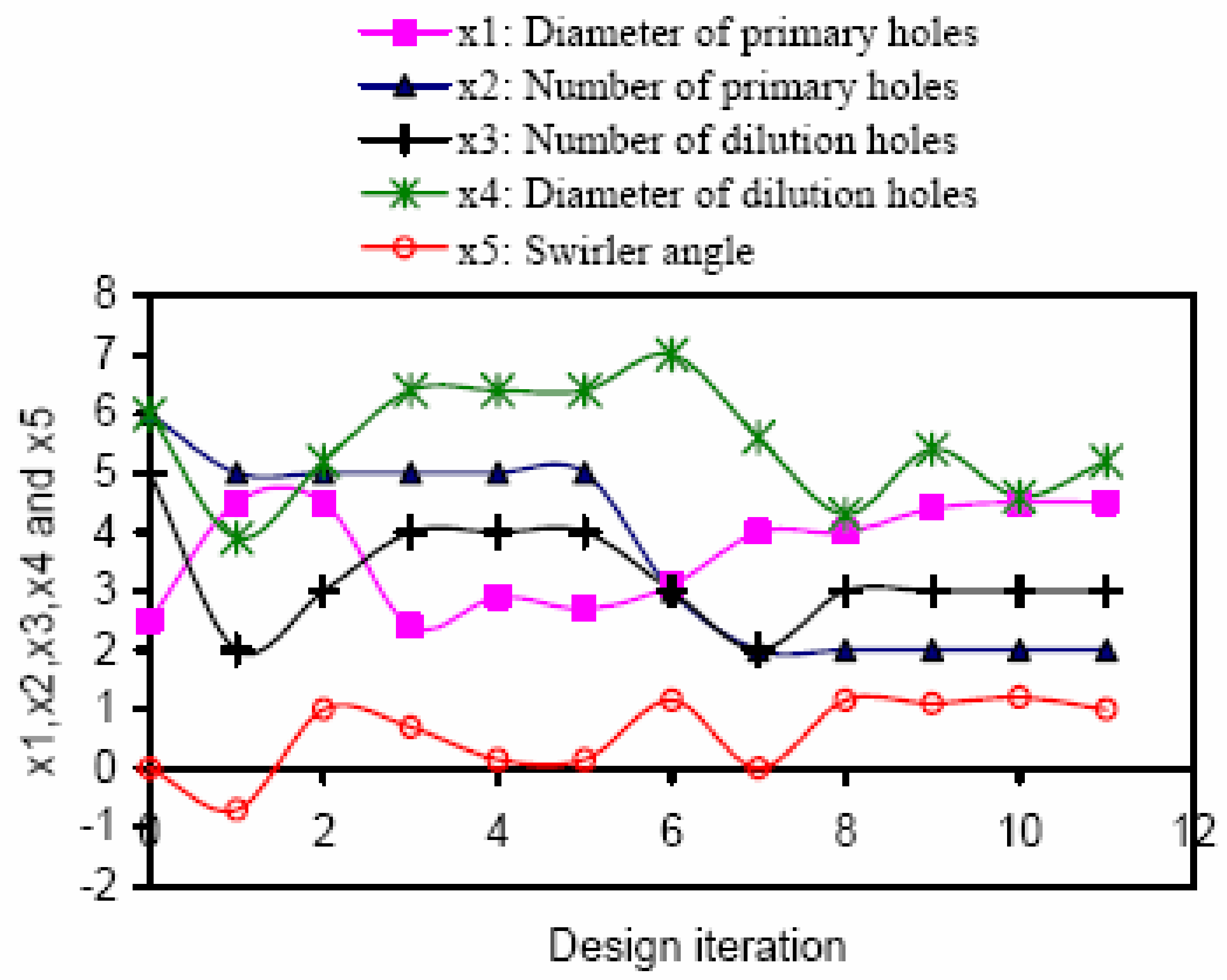
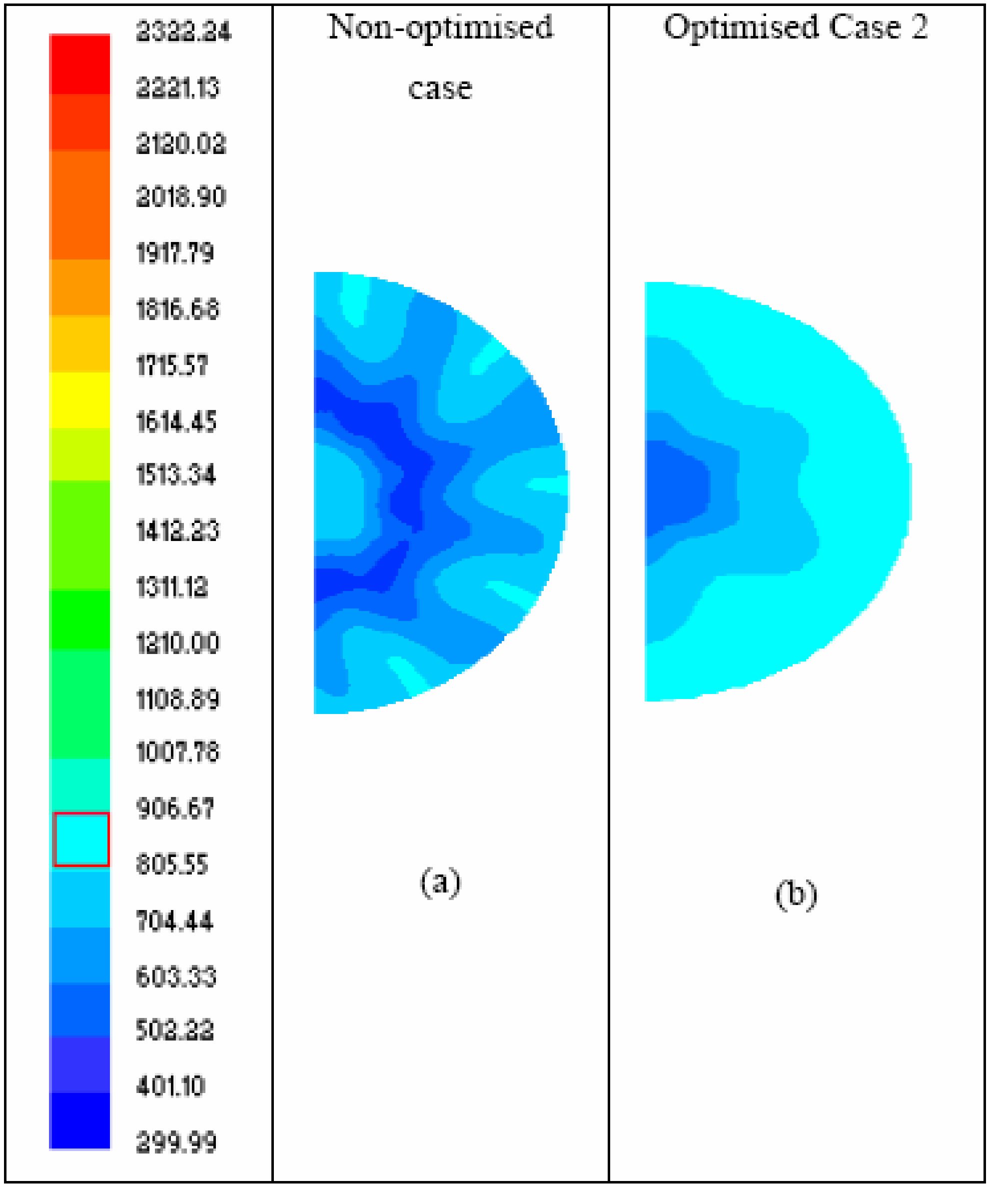


Figure 19. Optimisation history of inequality constraint (pressure drop) for Case 2

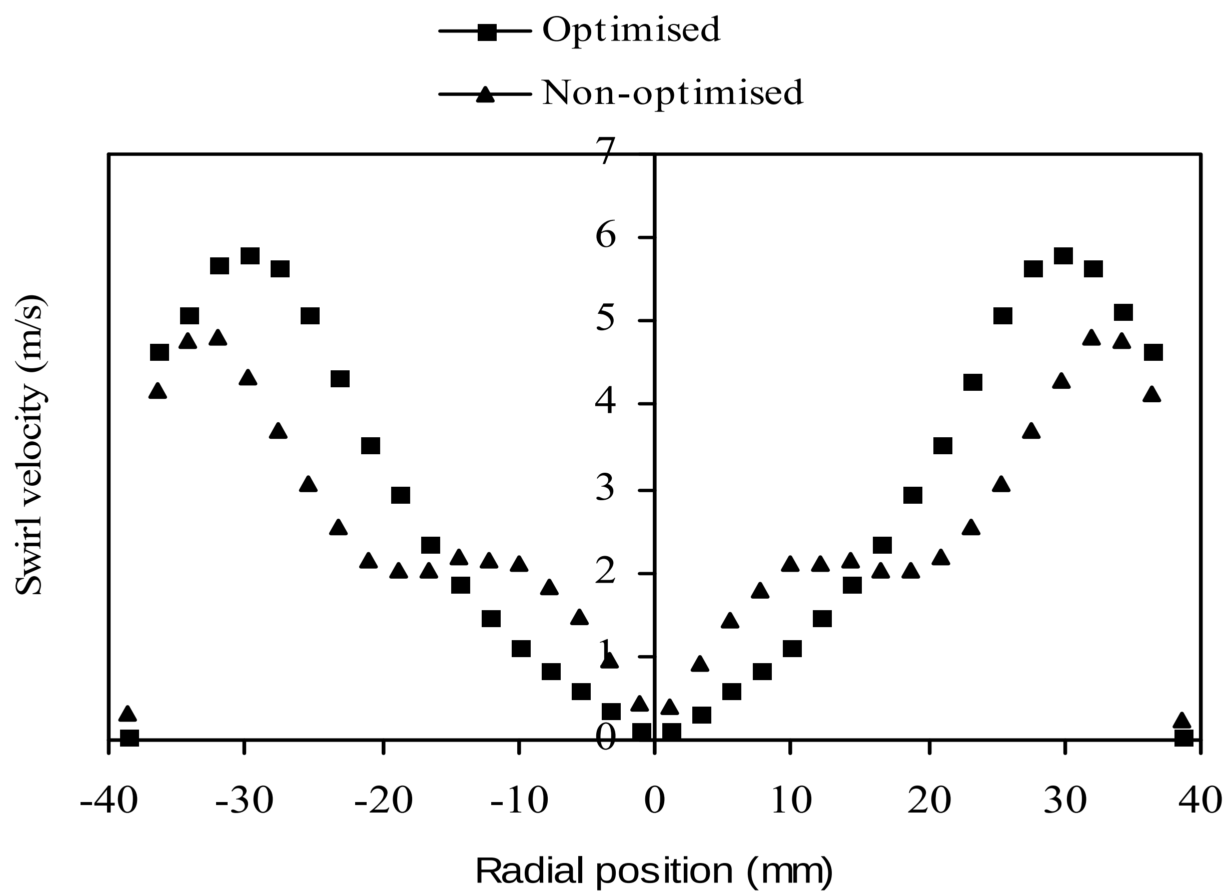
Optimisation history of design variables for case 3



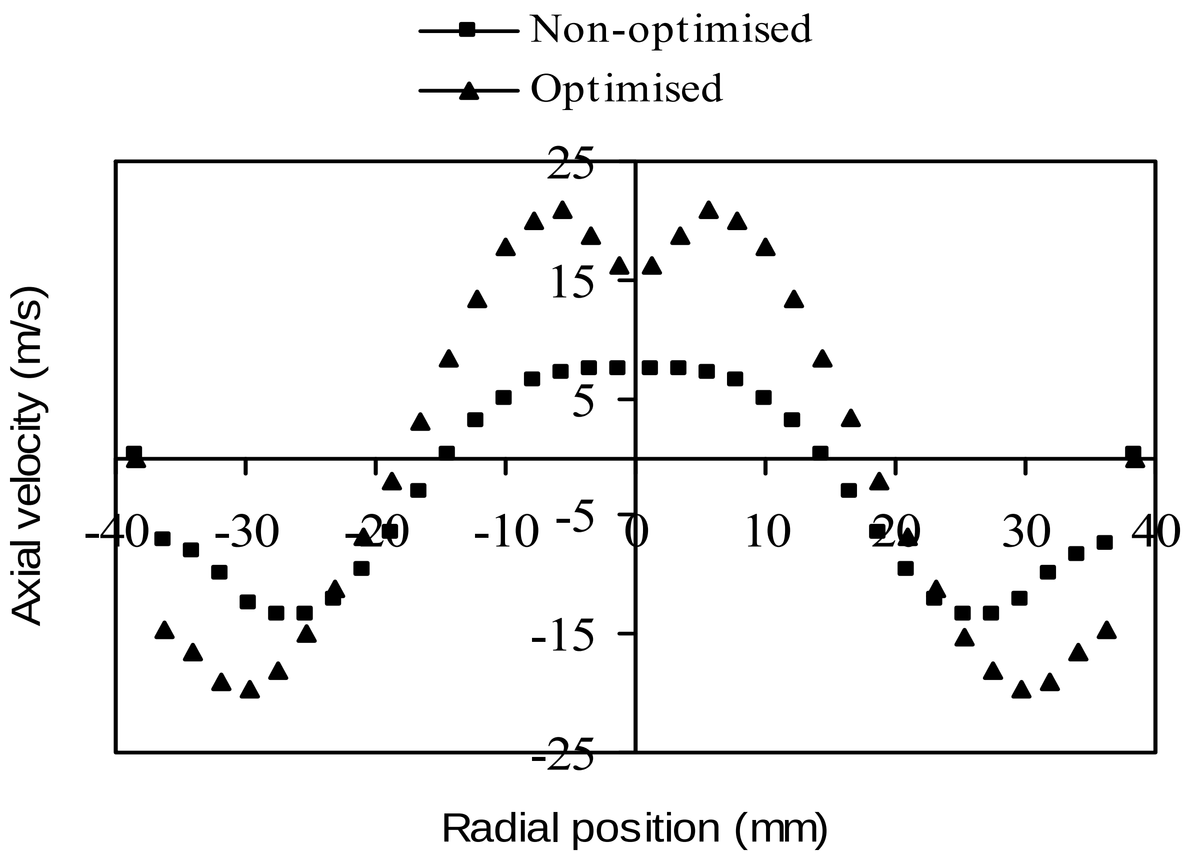
Temperature contours of the combustor exit plane for case 3



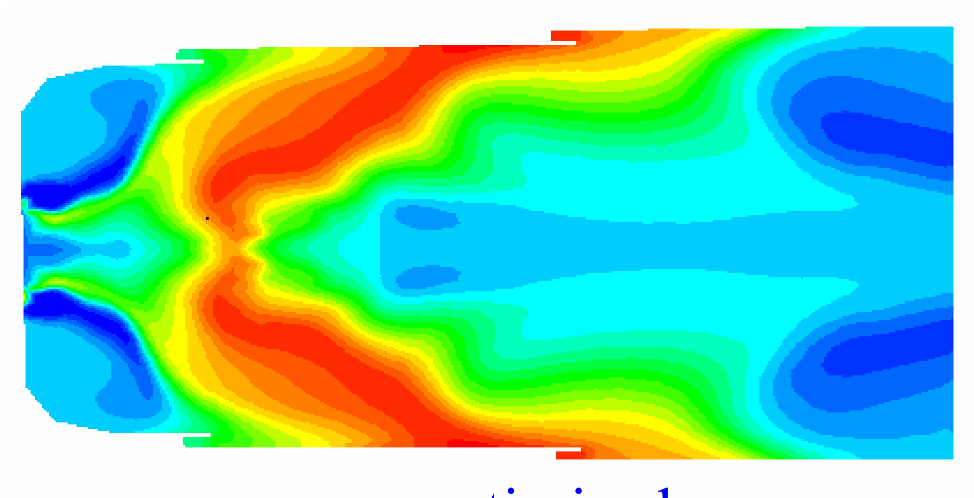
Swirl velocity at 30mm from the dome face for case 3



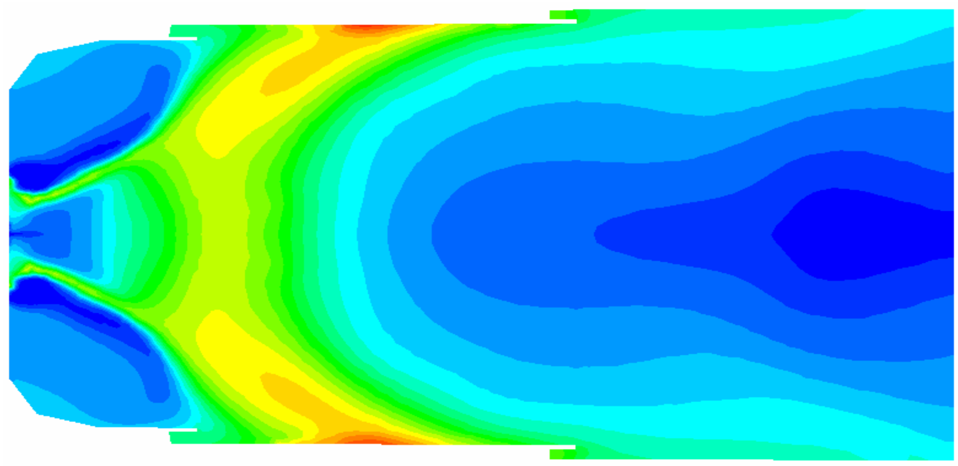
Axial velocity at 30mm from the dome face for case 3



Non-optimised and optimised temperature contours for case 3 on the symmetrical plane



non-optimised



optimised