Optimisation Techniques for Combustor Design

By

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Overview

- Introduction and Objectives
- Design Methodology
  - CFD Modelling
    - Background
    - Validation
  - Mathematical Optimisation
    - Background
    - Dynamic Algorithm
- 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
    Holdeman et al (1997)
    & Tangarila et al (2000)

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.

![Diagram of burner geometry with dimensions and labels: 761 mm, 382 mm, 1066.8 mm, 343 mm, 109 mm, 27 mm, measurement locations (distance from quarl exit).]
Validation of CFD Models

Axial velocity at 27 mm from the quarl exit
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:

\[ \min_x f(x); \; x = [x_1, x_2, \ldots, x_i, \ldots, x_n]^T, x_i \in R \]

\[ s.t. \; g_j(x) \leq 0; \; j = 1, \ldots, m \]

\[ h_k(x) = 0; \; k = 1, \ldots, p < n \]

\[ x^* = [x_1^*, x_2^*, \ldots, x_n^*]^T \]
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
Constrained optimisation with approximated objective function

And analytical constraint

Approximated unconstraint subproblem, $f(x)$ due to penalty function

Approximated constraint subproblem

Dynamic-Q-Quadratic subproblems - cont..

Feasible Region $g(x) \leq 0$
Flow chart of Optimisation run

Starting design \( x^1, i:=1 \)

Pre-processing
- Gambit journal file

Optimum \( x^* := x^{*(i)} \)

Next iteration \( i:=i+1 = x^{*(i-1)} \)

Yes

Converged

No

CFD simulations

Optimisation
- Set up and solve approximate optimisation subproblem \( P(i) \) to give \( x^{*(i)} \)

Numerical integration
- Evaluate objective and constraint functions

Post-processing
- Process and extract data
Non-Optimised Combustor Numerical Flow Fields

Primary injections

CRZ CTRZ

Sec injections

Dilution injections

Velocity vectors on the half plane
Non-Optimised Combustor Flow Fields – cont..

Temperature contours on the half plane
Optimisation Problem Definition

- Target temp. = mass-weighted temp: can also be derived from a simple thermodynamic relationship
- The shaded area in the figure was derived by Trapezoidal rule
- 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
- Target and non-optimised temperature profile
- 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 $f(x) = \text{shaded area}$

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

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 $f(x) = \text{shaded area}$ such that:

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

$$k_1 = x_1 x_2 - 37.5 = 0 \quad \text{(equality constraint)}$$

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

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

where $x_j^{\text{min}}$ and $x_j^{\text{max}}$ 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 $x_1$, $x_4 \in \mathbb{R}$

<table>
<thead>
<tr>
<th></th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
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<td>5</td>
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<td><strong>Upper limit</strong></td>
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<td>10</td>
<td>7</td>
<td>8</td>
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</table>

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 \( f(x) = \text{shaded area} \)
such that:

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

\[
g_j = -x_j + x_j^{\text{min}} \leq 0, \quad j = 1, 2, \ldots, 5
\]

\[
g_{j+2} = -x_j - x_j^{\text{max}} \leq 0, \quad j = 1, 2, \ldots, 5
\]

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

Here \( x_2, x_3 \) are integers, and \( x_1, x_4, x_5 \in \mathbb{R} \)

\( x_1 \) 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 \( x_1, x_4, x_5 \in \mathbb{R} \)

<table>
<thead>
<tr>
<th></th>
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<td><strong>Lower limit</strong></td>
<td>2.3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>45</td>
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<tr>
<td><strong>Upper limit</strong></td>
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<td>6</td>
<td>7</td>
<td>8</td>
<td>65</td>
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</tbody>
</table>
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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- 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

Colour Map

Non-optimised case

(a)

Optimised Case1

(b)
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 graph]

- **Feasible value, F=4.6**
- **Lower infeasible value, F=4.2**

Design iteration vs. $f(x)$
Optimisation history of the design variables for case 2

![Graph showing the optimisation history of 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
Figure 19. Optimisation history of inequality constraint (pressure drop) for Case 2
Optimisation history of design variables for case 3

- $x_1$: Diameter of primary holes
- $x_2$: Number of primary holes
- $x_3$: Number of dilution holes
- $x_4$: Diameter of dilution holes
- $x_5$: Swirler angle

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

non-optimised

optimised