A Conjugate Heat Transfer Model for Heat Load Prediction in Combustion Devices

M. Bahador and B. Sundén
Important Characteristics of Combustors - General

- **Layout and Overall Running Condition**
  - Industrial, 10-40 Bar and 1780 K at Turbine Inlet
  - Aero, 20-40 Bar and 1870 K at Turbine Inlet
  - Microturbine, 4-6 Bar and 1300 K at Turbine Inlet

- **Performance**
  - High Combustion Efficiency
  - Wide Range of Stability
  - Suitable Pattern Factor
  - Low Pressure Drop

- **Cooling**

- **Emissions**
Different Combustors Layouts

**Annular Combustor**

![Annular Combustor Diagram](image1)

*CP6-50 annular combustor (courtesy General Electric Company).*

**Tiled Combustor**

![Tiled Combustor Diagram](image2)

*PW V-2500 tiled combustor.*

**Industrial Trent DLE Combustor**

![Industrial Trent DLE Combustor Diagram](image3)

*Industrial Trent DLE combustor (courtesy Rolls Royce plc).*

**Tubular Combustor**

![Tubular Combustor Diagram](image4)

Why Liner Cooling Is Needed?

Thermal tolerances of materials and extremely long operating intervals of combustors are the main reasons for cooling. These problems often make buckling and cracking in liners.

VT4400 Cooled and Non-cooled Cases

Source: Volvo Aero Corporation
Common Mechanisms of Liner Cooling

- Simple Convective Cooling
- Ribbed Wall
- Film Cooling
- Impingement Cooling
- Effusion Cooling
- Thermal Barrier Coating (TBC)
Mechanisms of Heat Transfer in Liner Walls

Cold Region in Cooling Channel

- Convection Flux to Cold Fluid Flow
- Radiative Flux to Casing
- Convection Flux from Hot Fluid Flow
- Conduction Flux through Wall
- Radiative Flux from Hot Fluid Flow

Hot Region in Liner
Modeling of Heat Transfer in Liner by a Conjugate Approach and Its Difficulties

Heat transfer from hot region to the cold region of the liner, can be modeled by Computational Fluid Dynamics (CFD) together with a conjugate heat transfer approach. Some difficulties in modeling of a liner heat transfer are:

- Modeling of High Turbulent Flow in the Inner and Outer Side of the Liner and Near the Liner Wall Regions,
- Selection of Proper Wall Treatments for the Convective Heat Transfer,
- Modeling of Radiative Heat Transfer
A Conjugate Heat Transfer Model for Prediction of Temperature and Heat Loads in Combustors

A lean pre-mixed combustor, with two different simple convective cooling and ribbed cooling arrangements with TBC have been modeled by CFD and conjugate heat transfer approach. The general combustor data are:

- Swirl number = 0.6
- Liner Conductivity = 25 W/mK
- TBC Conductivity = 1.3 W/mK

Inlet (Air+Fuel)
1.57 kg/s Air + Methane
A/F=28.9

The Model for the Case of Ribbed Duct Cooling
Model Description

- Using a 2D Axi-Symmetric geometry
- Simplification of the Complex Swirl system
- Using Multiblock Structured grid
  - 42580 Cells for Simple Cooling Duct
  - 70090 Cells for Ribbed Cooling Duct and TBC
Solution Method and Boundary Conditions (BC)

1) Flow Field

- Solving the Time Averaged Continuity and Navier-Stokes Equations.
- Using SIMPLE Algorithm for the Pressure and Velocity Couplings.
- Assume that the Density Is Temperature Dependent.
- Solving the Transport Equations for the Turbulent Kinetic Energy and Turbulent Dissipation, Using the Standard $k$-$\epsilon$ Model.
- Using Inlet and Pressure BCs for Inlets and Outlets and Periodic and Symmetry BCs on the $r$-$z$ Faces in the Liner and Cooling Duct, respectively.
Solution Method and Boundary Conditions (BC)

2) Energy Equation

- Using the Enthalpy Form of Energy Equation.
- Solving the Energy Equation in Both Fluid and Solid Domains.
- Involving The Radiative Heat Transfer As Source Terms of Energy Equation.
- Modeling of Combustion By Assumption of One Step Burning of Methane and Using The Eddy Dissipation Concept (EDC).
- Using Polynomial Correlation of Cp versus Temperature.
Using the Standard Wall Function Approach on Both Hot and Cold Sides.

Modeling Radiative Heat Transfer on the Hot Side by:

- The S4 – Discrete Ordinates Method with 24 Directions.
- The Spectral Line Weighted Sum of Grey Gases (SLW), With 5 Optimised Gray Gases for Modeling of CO$_2$ and H$_2$O Mixture.
Other Solution Considerations

- The Computational Fluid Dynamics Code, STAR-CD now STAR CCM+ was used.
- The Second Order Monotone Advection and Reconstruction Scheme (MARS), was used.
- Convergence criteria were set on $1.0 \times 10^{-4}$ for normalized global residuals and besides that, the temperature data at some boundaries were controlled.
Results of Flow and Temperature Fields

Temperature Field Near to the Ribbed Liner Wall

Velocity Field Near to the Ribbed Liner Wall

Temperature Field in the Ribbed Wall

Temperature Field in the Simple Wall
Results of Flow Field and Temperature in the Liner (Simple Cooling Duct Without Radiation)

Zero Axial Velocity at the Liner Wall

Variation of Temperature Near the Liner Wall
Results of Temperature Field in the Simple Cooling Duct

Temperature Distribution at the Inner Wall

Temperature Distribution at the Outer Wall

Notes:

- Position of maximum temperature is the same with zero axial velocity.
- The average temperature data without radiation increased about 33 K by adding the radiative heat transfer.
- Good agreement at the liner inlet has been obtained whereas the predictions became worse along the liner length.
Results of Temperature Field in the Ribbed Cooling Duct and TBC

Notes:

- Because of extended heat transfer surfaces, the temperature varies along the liner length.
- The average temperature data without radiation increased about 40 K by adding the radiative heat transfer.
- Good agreement has been found in the mid part and also there are some uncertainty about two end points of experimental data.
Results of Predicted Heat Loads

Notes:

- Radiation increases the amount of heat load more in the cold zones.
- Average heat load by radiation has increased by 8 and 7 percent in the simple and ribbed cooling ducts, respectively.
- Nearly constant heat load at mid part of simple cooling duct has been predicted.
Conclusions

With some simplifications, by CFD, temperatures and heat loads in a combustor liner have been predicted. Following conclusions were obtained:

- Generally the trends of the temperature variations were captured and in some points the predictions were good.
- In addition, by adding the radiative heat transfer to the model, in the simple and ribbed duct cooling schemes the average inner wall temperature increased by 33 and 40 K, respectively.

As an extension of this study, accuracy of the model can be investigated by using different wall treatment such as a two layer wall function approach or by applying a low Reynolds number turbulence model.