FLOWNEX®
SIMULATION ENVIRONMENT

GAS TURBINE COMBUSTOR DESIGN

Application of the network approach to the modeling of three combustor types, i.e. two annular- and a reverse flow combustor, is discussed in this case study. The network method effectively deals with complicated and unusual geometries, is not prone to numerical difficulties, and has the advantage of rapid execution. It removes many limitations placed by conventional semi-empirical modeling techniques. It may be applied to model all conceivable combustor types. It is shown that simulation results obtained with the network approach closely match those obtained experimentally, as well as by a thoroughly validated industrial one-dimensional combustor code "CODAS".

AEROSPACE

CHALLENGE:

Gas turbine combustor design involves the calculation of parameters like gas mass flow rates, pressure drops, flame tube heat gains and losses, annulus heat addition, combustion equilibrium mixture compositions and temperatures. Preliminary design is a necessary step in the design of gas turbine combustors as its outputs serve as inputs for more thorough design methods such as computational fluid dynamics simulations (CFD) and experimental tests which are time-consuming and costly methods.

BENEFITS:

Flownex® provided the following benefits:

- The use of Flownex® allowed the optimization of combustion chambers in the preliminary design phase in rapid execution times.
- Flownex® enabled design modifications and parametric studies to easily be performed on the combustion chamber.
- Flownex® provides the capability to effectively deal with complicated and unusual geometries

SOLUTION:

The use of Flownex® in the preliminary design phase of the combustion chamber proved to be an effective tool allowing design modifications and optimization in rapid execution times which can be applied to model all conceivable combustor types. The simulation results obtained closely matched experimental results as well as results obtained by a thoroughly validated industrial one-dimensional combustor code "CODAS".

> "Flownex® allowed the optimization of combustion chambers in the preliminary design phase in rapid execution times"

INTRODUCTION

This case study demonstrates the application of the network approach in the preliminary design of gas turbine combustors, as described by Stuttaford, P.J., & Rubini, P.A., *"Preliminary Gas Turbine Combustor Design Using a Network Approach," published in the Transactions of the American Society of Mechanical Engineers, Journal of Engineering for Gas Turbines and Power, Vol 119, July 1997, pp. 546 to 552.*

Application of Flownex® to three combustors is presented, two of which are industrial annular combustors, as well as a reverse flow combustor. Due to counter flow, the reverse flow combustor is the most challenging combustor type to model as conventional semi-empirical methods fail to solve this type of flow problem.

Flownex® is used to obtain total pressures and mass flow rates of the annular and reverse flow combustors. Results for the annular combustors using Flownex® are compared with results obtained with the well verified CODAS design code and these results match satisfactorily. Results obtained for the reverse flow combustor are compared with experimental and analytical results, as CODAS is not capable of solving reverse flow problems. Reasonably accurate results are obtained for the reverse flow combustor using Flownex®.

SEMI-EMPIRICAL MODELS

Semi-empirical methods incorporate experimental data and empirically derived correlations to support simplified overall governing equations. The models may be one-dimensional or three-dimensional. One-dimensional models give reasonably accurate results rapidly, but lack the resolution of three-dimensional models.

Historic trend lines and one-dimensional models may be used for preliminary design. Three-dimensional empirical and analytical procedures may then be employed to augment the basic design. Three-dimensional models provide good qualitative analyses and satisfactory agreement with experimental results. However, they are time consuming and should only be used when the preliminary design has already been developed.

Semi-empirical models have the advantage of rapid execution times and are optimized as much as possible before the outputs are used in more thorough investigations, such as rig testing and CFD, which are time-consuming and costly.

"Results for the annular combustors using Flownex® are compared with results obtained with the well verified CODAS design code and these results match satisfactorily"

THE NETWORK APPROACH

A network consists of a number of independent sub flows linked together to model a process which is made up of a number of elements and nodes, as shown in figure 1. Elements represent physical features in the domain, for example duct sections and holes joined together by elements. Overall governing equations are solved within nodes and flow through an element may be described using semi-empirical relationships.

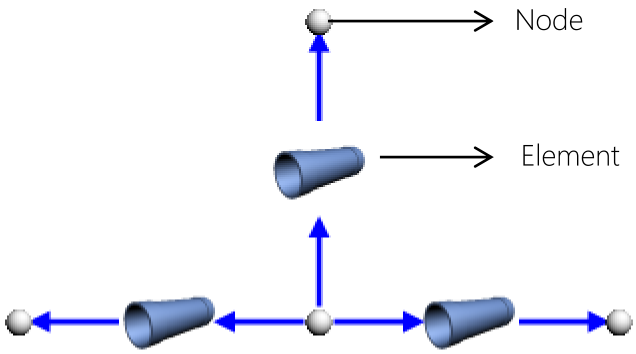

Figure 1: Network showing elements and nodes.

General advantages of the network method used in Flownex® are:

- Simple modeling of complicated and unusual geometries.
- Rapid execution times.
- The method poses little numerical difficulties.

Specific advantages of the network method with regards to preliminary gas turbine combustor designs are:

- The versatility in Flownex® benefits design of combustors, such as annular- and reverse flow combustors, and combustors with multiple combustion zones, for example double annular combustors.
- Modeled results for annular combustors show close agreement with validated data obtained by means of the well validated one-dimensional CODAS design code.
- Modeled results for reverse flow combustors show close agreement with measured and manual calculation data.
- Sub-models used in combustor preliminary designs continue to be improved, for example equilibrium-, film cooling- and radiation models.

"The versatility in Flownex® benefits design of combustors, such as annular- and reverse flow combustors, and combustors with multiple combustion zones for example double annular combustors."

THE NUMERICAL ALGORITHM

Equations that are solved are the continuity equation, equations for pressure drop and flow rate, the ideal gas state equation, energy equation and chemical equilibrium equation.

The Semi-Implicit Method for Pressure-Linked Equations ("SIMPLE" method), is used to obtain a solution to the flow equations. The governing equations are the continuity equation and a pressure drop/flow rate relationship. The functional relationships are derived from semi-empirical formulations for combustor features and internal flows.

In order to solve the ideal gas state equation, initial pressures and temperatures at nodes are predicted from which density is calculated. A predicted flow rate is calculated from the pressure drop/flow relationship. The predicted values are corrected by differentiating the pressure drop/flow equation with respect to flow and by substitution of this equation into the continuity equation. The resulting equation is solved for all the nodes in the network. Updated values for flow, pressure and density are calculated and the process is repeated until convergence is reached.

The energy equation is satisfied by ensuring an enthalpy balance at each node in the network. A semi-implicit formulation is used to compute node temperatures on boundaries or within walls. Heat transfer coefficient terms are evaluated using semi-empirical correlations and data for various cooling types found in gas turbine combustors. Film cooling has a significant effect on wall temperatures and must be accurately modeled, cooling effects include those of Z-rings, lipped-rings, slots, effusion patches and transply patches.

Radiative fluxes are accounted for by a simple empirical model. Gas emissivity is calculated using a corrected luminosity for gases containing soot clouds, in terms of pressure, luminosity, hot gas temperature, fuel-air ratio, mean beam length and the carbon/hydrogen mass ratio of fuel. Its accuracy is however limited, as luminous emissivity is highly dependent on fuel type, soot formation and oxidation. The Gauss-Seidel iterative technique with successive over-relaxation is used to solve the node temperatures. The solution of the flow- and energy equations is coupled.

A constrained equilibrium computation calculates adiabatic flame temperatures from local species concentrations at given fuel-air ratios. The temperature calculation is performed within specified elements and the resulting heat release is treated as a source term in the energy equation.

COMBUSTOR NETWORKS

Two industrial annular combustors were studied, identified as "annular combustor 1" and "annular combustor 2", as well as a reverse flow combustor. The annular combustors were selected as results obtained with the CODAS one-dimensional combustor code for these combustors have been well validated. The CODAS results served as a measure of accuracy for the network models.

The network diagram of the reverse flow combustor is shown in figure 2.

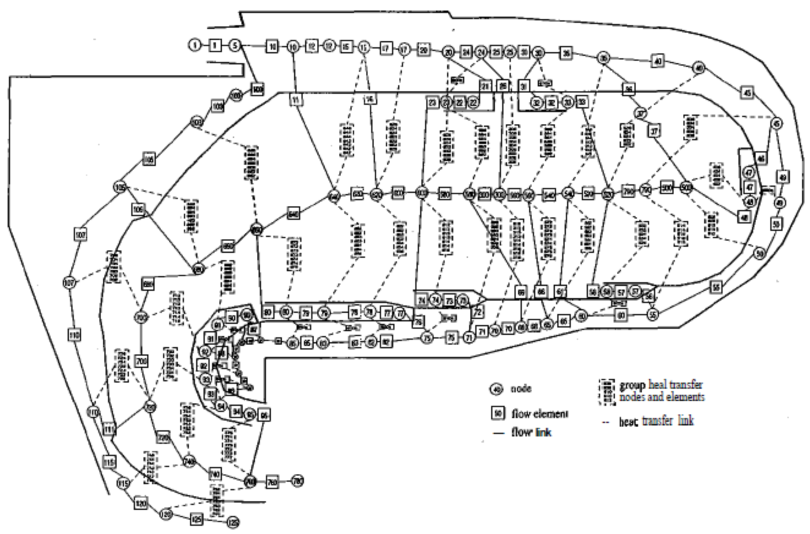

Figure 2: Network diagram for reverse flow combustor

In figure 2, numbers in circles indicate node numbers, while those in squares indicate flow elements. Solid lines connecting nodes and elements are flow links. Numbers in rectangles with dashed borders are group heat transfer nodes and elements. Dashed lines connecting group heat transfer nodes and elements are heat transfer links.

Mass flow rates and total pressure of all three of the combustors were predicted with the network method. The mass flows rates are non-dimensionalized by predicted annuli head flows, while the total pressures are non-dimensionalized by combustor total inlet pressures.

For the reverse flow combustor, an additional heat transfer analysis was coupled to the airflow analysis. External wall temperature results were obtained, to be compared with thermal paint data obtained during rig tests.

Convergence speed in the case of the annular combustors was high; in the same order as that of the simple semi-empirical models and convergence for the reverse flow combustor model was slightly slower than for the annular combustors.

VALIDATION OF COMBUSTOR NETWORK MODELS

Initial validation of the two production annular combustors was done by comparison with CODAS results. CODAS is an industrial one-dimensional combustor code, of which the results for the two annular combustors have been well validated.

A comparison with CODAS, for non-dimensional inner- and outer mass flow versus non-dimensional annuli axial position, of annular combustor 1, is shown in figure 3 which showed close agreement between the results of the network method and CODAS, for both inner and outer flows.

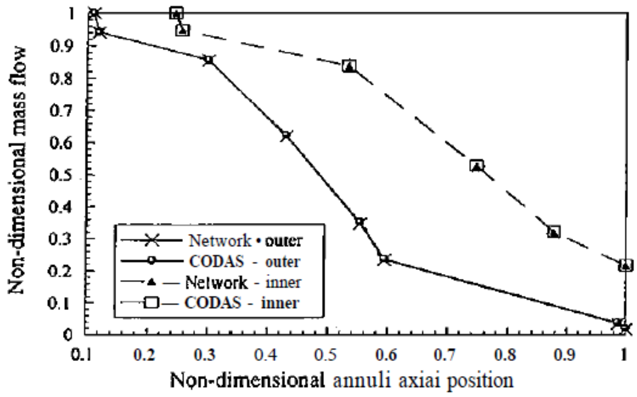

Figure 3: Annular combustor 1: Comparison between network method- and CODAS results for non-dimensional mass flow vs. non-dimensional annuli axial position.

A comparison with CODAS, for non-dimensional flame tube total pressure versus non-dimensional flame tube axial position of annular combustor 1 is shown in figure 4 method which showed close agreement with the results obtained with the CODAS combustor code.

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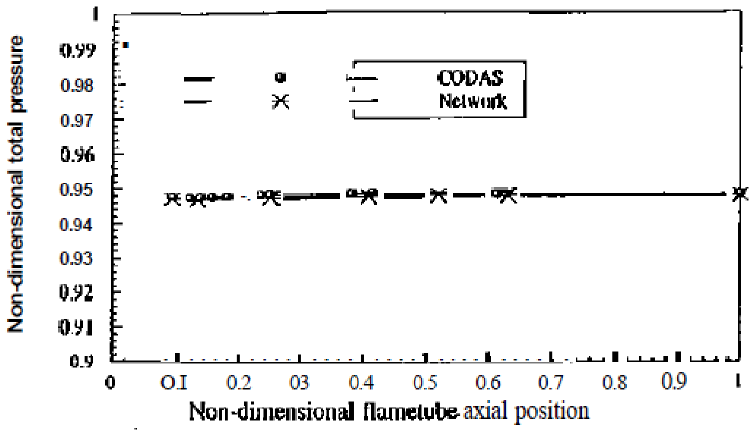

Figure 4: Annular combustor 1: Comparison between network method- and CODAS results for non-dimensional total pressure vs. non-dimensional flame tube axial position.

Validation of modeled results for annular combustor 2

A comparison with CODAS, for non-dimensional inner- and outer mass flow versus non-dimensional annuli axial position, of annular combustor 2, is shown in figure 5 which shows close agreement between the results of the network method and CODAS, for both inner and outer flows.

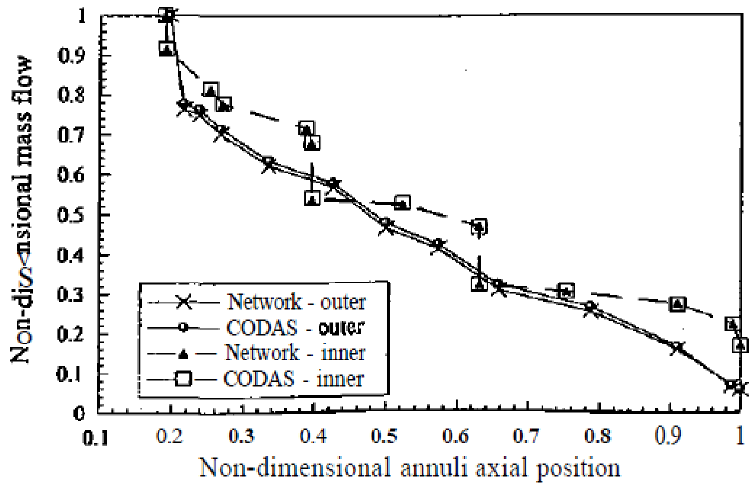

Figure 5: Annular combustor 2: Comparison between network method- and CODAS results for non-dimensional mass flow vs. non-dimensional annuli axial position.

A comparison with CODAS, for non-dimensional flame tube total pressure versus non-dimensional flame tube axial position of annular combustor 2 is shown in figure 6 which shows close agreement between the results of the network method and CODAS, for both inner and outer flows.

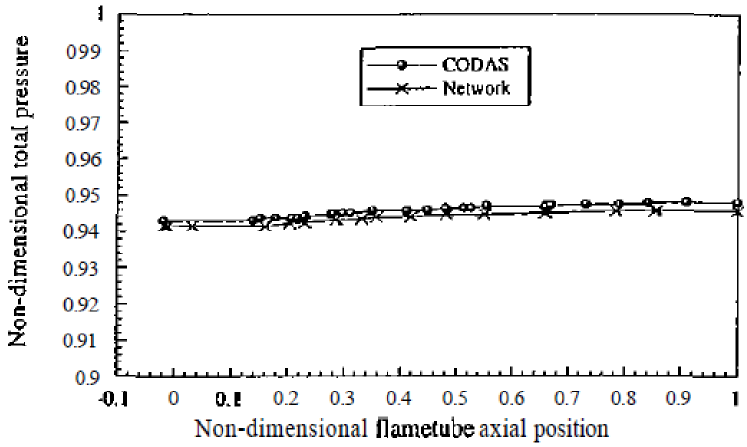

Figure 6: Annular combustor 2: Comparison between network method- and CODAS results for non-dimensional total pressure vs. non-dimensional flame tube axial position.

Validation of modeled results for reverse flow combustor

Due to reverse flow, which CODAS is not capable of modeling, results for this combustor were compared with a combination of pressure measurements and manual calculation results. Modeled pressure losses agreed within 0.1% with the measured results, while mass flows agreed within approximately 5% with the manual calculation results.

External wall temperature results generated with the network solver were compared to temperature bands obtained with the thermal paint data and reasonable agreement was achieved.

CONCLUSIONS

The network approach has been successfully applied to the preliminary design of gas turbine combustors. The method removes many limitations of models based on conventional semi-empirical analysis. It is powerful as it makes simple modeling of combustors with complicated and unusual geometries possible which may be applied to model all conceivable gas turbine combustor types.

The method poses little numerical difficulties. Its high speed of convergence is of the same order of that of simple semi-empirical models. Convergence in the case of reverse flow combustors is slightly slower.

Flownex® proved to be an accurate and versatile tool for preliminary combustor design. Modeled results showed close agreement with verified modeled and experimental data.

"Flownex® proved to be an accurate and versatile tool for preliminary combustor design."