8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineeering (ECCOMAS 2008)
June 30 – July 5, 2008
Venice, Italy

A CFD MODEL FOR REAL GAS EFFECTS IN TURBOMACHINERY

Filippo Rubechini[1], **Michele Marconcini**[1], * **Andrea Arnone**[1]

[1] "Sergio Stecco" Dept. of Energy Engineering - University of Florence
via di Santa Marta, 3, 50139, Firenze, Italy
Filippo.Rubechini@arnone.de.unifi.it
http://www-pgtu.de.unifi.it/CFDBranch

Key Words: *Real gas, Turbomachinery.*

ABSTRACT

In the design of industrial turbines and compressors, different evolving fluids are encountered, working over a wide range of thermodynamic operating conditions. In most cases, the perfect gas model is accurate enough to describe the physical characteristics of the fluid. However, there is a number of applications for which such an approach is not satisfactory. In steam turbine LP stages, thermodynamic transformations occur near or above the saturation curve of steam, where a bi-phasic fluid is present. Also some centrifugal cryogenic compressors make use of complex mixtures of gases, whose behavior at operating conditions is far from ideal. As far as gas turbines are concerned, the behavior of the combustion products deviates from that of a perfect gas basically from a caloric point of view, and is well represented by the ideal gas equation of state so that the gas model should only account for the variation of specific heat with temperature.
A numerical model to account for real gas effects was included in the TRAF code (Arnone [1]), a three-dimensional viscous steady and unsteady RANS solver. In this model the behavior of real gases, gas mixtures or steam is reproduced by replacing analytic relationships of the perfect gas with the use of gas property tables. A detailed description of the numerical model is given in [2]. The real gas model is generally applicable to any working fluid, and extends property evaluations into saturated and superheated regions. To reduce computational costs, gas tables are generated off-line to be used in CFD solution. Accessing these tables proved to be much faster than evaluating thermodynamic properties directly by means of an analytical equation of state. The gas database is external to the flow solver, and can be generated using either commercial or in-house developed specific tools. The method consists of a local fitting of gas data to provide the thermodynamic property required by the solver in each solution step. Using two-variable formulations, a number of thermodynamic functions and different couples of independent variables are identified to be used in computations, like for example $T(h,s)$, $s(p,\rho)$, $h(p,s)$ and others. Values of these functions are provided by gas tables over a range of thermodynamic states which is set by the user, depending on the physical problem to be investigated. Considering a generic thermodynamic function $z(x,y)$, values of this function are known at each node of a structured grid of points, identified by two indices i and j ($1 \le i \le nx$; $1 \le j \le ny$). Given a thermodynamic state of the system (x_0, y_0), the property of interest $z_0 = z(x_0, y_0)$ is computed by local interpolation once the grid cell containing the point (x_0, y_0) is found. If the grid is regular, orthogonal to x and y axes, and equally spaced, indices i_0 and j_0 of this cell are easily found via the analytical search formula:

$$i_0 = \text{int}[(x_0 - x_{min})/(x_{max} - x_{min})] + 1 \quad ; \quad j_0 = \text{int}[(y_0 - y_{min})/(y_{max} - y_{min})] + 1 \qquad (1)$$

where $x_{min}, x_{max}, y_{min}, y_{max}$ are minimum and maximum values of variables x and y stored in the gas table. In addition to regular and equally spaced gas tables, clustered tables can also be used. Clustering allows one to adopt local very fine cell spacing where high accuracy is needed, without requiring too many grid points far from the physical region of interest. In the present model gas tables are clustered using the following transformation:

$$\tilde{\xi} = \frac{\xi_0}{A} \cdot \{\sinh\left[(\xi - x_0)\beta\right] + A\} \tag{2}$$

where $\xi = (i-1)/(n-1)$ is the uniform linear distribution, $\beta > 0$ is the degree of clustering, ξ_0 is the normalized position where clustering has to be imposed, and x_0 and A are functions of β and ξ_0 [3]. Analogous expressions hold for clustering in the j direction. The index i_0 of the computational cell used for interpolation is again found via an analytical search formula:

$$i_0 = \text{int}\left[x_0 + \frac{1}{\beta}\ln\left(\hat{\xi} + \sqrt{1+\hat{\xi}^2}\right)\right] \quad ; \quad \hat{\xi} = A\left(\frac{\tilde{\xi}}{\xi_0} - 1\right) \tag{3}$$

As an example, gas tables used for computations of LP steam turbines are clustered in the vicinity of the saturation line, to ensure high accuracy in the evaluation of thermodynamic properties in a region where abrupt changes of these variables occur. The increase in computational time with respect to the perfect gas model, is about 20% for equally spaced tables and 30% for clustered ones. As a major result, the analytical search formulas make computational time independent of table dimensions.

The real gas model was applied to the analysis of turbomachines representative of common industrial problems in which the working fluid modeling affects performance prediction, like LP steam turbines [3], cooled gas turbines [4] and centrifugal cryogenic compressors [2].

The proposed approach presents several characteristics which make it attractive as a design tool for industrial applications. First of all, the implementation of the method in the solver is simple and straightforward, since it does not require relevant changes in the solver structure. Moreover, it is based on a low-computational-cost algorithm, which prevents a considerable increase in the overall computational time. Finally, the approach is completely general, since it allows one to handle any type of gas, gas mixture or steam over a wide operative range.

REFERENCES

[1] Arnone, A., 1994, "Viscous Analysis of Three–Dimensional Rotor Flow Using a Multigrid Method". ASME Journal of Turbomachinery, **116** (3), pp. 435–445.

[2] Boncinelli, P., Rubechini, F., Arnone, A., Cecconi, M., and Cortese, C., 2004, "Real Gas Effects in Turbomachinery Flows: a CFD Model for Fast Computations". ASME Journal of Turbomachinery, **126** (2), pp. 268–276.

[3] Rubechini, F., Marconcini, M., Arnone, A., Cecchi, S., and Daccà, F., 2007, "Some Aspects of CFD Modeling in the Analysis of a Low-Pressure Steam Turbine". ASME paper GT2007-27235, ASME Turbo Expo, May 14–17, Montreal, Canada.

[4] Rubechini, F., Marconcini, M., Arnone, A., Maritano, M., and Cecchi, S., 2006, "The Impact of Gas Modeling in the Numerical Analysis of a Multistage Gas Turbine". ASME paper GT2006-90129, ASME Turbo Expo, May 8–11, Barcelona, Spain (accepted for ASME Journal of Turbomachinery).