A NOVEL METHOD FOR THE COMPUTATION OF CONJUGATE HEAT TRANSFER WITH COUPLED SOLVERS

Verstraete Tom* and Rene Van den Braembussche
Turbomachinery Department
Von Karman Institute for Fluid Dynamics
Waterloosesteenweg 72, 1640 Sint-Genesius-Rode, Belgium
(* Corresponding author: verstraete@vki.ac.be)

Two main strategies exist in solving the Conjugate Heat transfer (CHT) problem, depending on how the continuity of temperature and heat flux are imposed on the common wall between fluid and solid.
One approach integrates the entire set of equations in the fluid and solid as a single system and treats the continuity of temperature and heat flux implicitly. The full coupled system of equations is solved together. This approach, in literature referred to as the *conjugate method*, is computationally efficient, but requires that both the fluid and solid are handled by a similar numerical approach and put together into a unified framework.
A second approach calculates separately the flow and the thermal field with a coupling provided by the boundary conditions at the interface. This approach allows different stand-alone flow and solid platforms to be used within an iterative procedure to obtain the continuity of temperature and heat flux. The drawback of this approach, known as the *coupled method*, is the need for sequential iterations between the two platforms and interpolation of the boundary conditions from one grid to the other.
This paper compares several methods known from literature for the second approach. A new stability criterion for these methods is derived from a simple one-dimensional CHT problem. A novel approach with enhanced stability properties is presented.

STABILITY OF THE COUPLED METHODS

Consider the 1D conjugate heat transfer problem sketched in Fig. 1. A temperature T_s is specified at one boundary of a solid, while at the other wall a fluid flows, and thus heat is transferred by convection. Suppose the fluid temperature T_{fluid} and the heat transfer coefficient h are known. The problem consists in finding the wall heat flux q_{wall} and temperature T_{wall} at the interface.
Following equations define the 1D conjugate heat transfer problem:

$$q_{wall} = \frac{\lambda_s}{L}\left(T_s - T_{wall}\right) \quad \text{on } \Omega_s \tag{1}$$

$$q_{wall} = h\left(T_{wall} - T_{fluid}\right) \quad \text{on } \Omega_f \tag{2}$$

The solution of this simple problem is given by Eqn. (3):

$$T_{wall} = \frac{T_s + Bi \cdot T_{fluid}}{1 + Bi} \tag{3}$$

with

$$Bi = \frac{hL}{\lambda_s} \tag{4}$$

the Biot number.

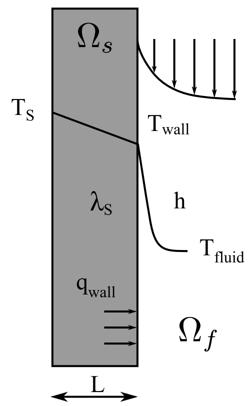

Figure 1. The one-dimensional conjugate heat transfer problem.

In the paper it will be shown that the Flux Forward Temperature Back (FFTB) method (e.g. Verdicchio et al. 2001, and Illingworth et al. 2005) , in which the wall heat flux is transferred from the fluid to the solid computation, and the wall temperature is returned from the solid computation to the fluid one, is stable for Biot numbers below one:

$$|Bi| < 1 \tag{5}$$

For the Temperature Forward Flux Back method (e.g. Divo et al. 2003, Heidmann et al. 2003, and He et al. 1995), which is the opposite of the FFTB method, the coupling algorithm is stable for Biot numbers above one:

$$|Bi| > 1 \tag{6}$$

The heat transfer coefficient (h) Forward Temperature Back (hFTB) method (e.g. Amano et al. 1994, Montenay et al 2000, Veredicchio et al. 2001, and Heselhaus 1998) is different from both previous mentioned methods as it uses a Robin boundary condition for the solid domain. A virtual heat transfer coefficient $\widetilde{h}$ and fluid temperature $\widetilde{T}_{fluid}$ are computed from the results of the fluid computations and imposed at the solid wall for the solid computation. The resulting solid wall temperature is returned to the fluid domain. It is shown that the coupling algorithm is stable for:

$$\widetilde{h} > \frac{h}{2} \tag{7}$$

A forth new method is presented in the present paper and is named the heat transfer coefficient (h) Forward Flux Back (hFFB) method. It is similar to the hFTB method but returns the heat flux at the solid wall to the fluid computation. It is shown to be stable for

$$\widetilde{h} < 2h \tag{8}$$

RESULTS

The four different methods are compared to each other for the two-dimensional flat plate test case. The derived stability criteria are validated. Finally, the new method has been validated on a 3D turbine blade test case, for which the temperature result is presented in Fig. 2.

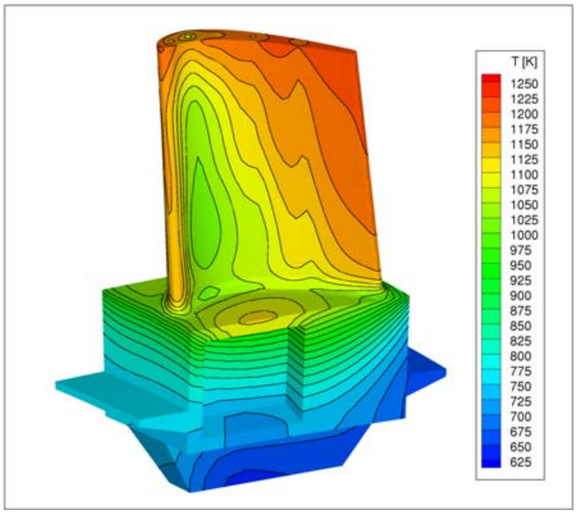

Figure 2. Temperature distribution of a turbine blade with internal cooling channels.

REFERENCES

R. S. Amano [1994]. A Study of Rotor Cavities and Heat Transfer in a Cooling Process in a Gas Turbine. ASME Journal of Turbomachinery, 116:333–338

E. Divo, E. Steinthorsson, F. Rodriguez, A. J. Kassab, and J. S. Kapat [2003]. Glenn-HT/BEM Conjugate Heat Transfer Solver for Large-Scale Turbomachinery Models. NASA-Report CR 212195.

M. He, A. J. Kassab, P. J. Bishop, and A. Minardi [1995]. An Iterative FDM/BEM Method for the Conjugate Heat Transfer Problem – Parallel Plate Channel with Constant Outside Temperature. Engineering Analysis with Boundary Elements,15(1):43–50.

J. D. Heidmann, A. J. Kassab, E. A. Divo, F. Rodriguez, and E. Steinthorsson [2003]. Conjugate Heat Transfer Effects on a Realistic Film-cooled Turbine Vane. In ASME TURBO EXPO, Atlanta, Georgia. Paper No. GT2003-38553.

A. Heselhaus [1998]. A Hybrid Coupling Scheme and Stability Analysis for Coupled Solid/Fluid Turbine Blade Temperature Calculations. In ASME TURBO EXPO. Paper No. 98-GT-88.

J. B. Illingworth, N. J. Hills, and C. J. Barnes [2005]. 3D Fluid-Solid Heat Transfer Coupling of an Aero Engine Pre-Swirl System. In ASME TURBO EXPO, Reno Tahoe, Nevada. Paper No. GT2005-68939.

A. Montenay, L. Pate, and J. Duboue [2000]. Conjugate Heat Transfer Analysis of an Engine Internal Cavity. In ASME TURBO EXPO, Munich, Germany.Paper No. 2000-GT-282.

J. A. Verdicchio, J. W. Chew, and N. J. Hills [2001]. Coupled Fluid/Solid Heat Transfer Computation for Turbine Discs. In ASME TURBO EXPO, New Orleans, Luisiana. Paper No. 2001-GT-0205.