



Full conjugate heat transfer modelling for steam turbines in transient operations

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ABSTRACT

Steam turbines are increasingly required to operate more flexibly, leading to a need for more detailed calculations and design considerations of the thermal conditions during transient operations. A major challenge in transient thermal designs is the time scale disparity. For the natural cooling of a turbine, the physical process is typically in hours or tens of hours, but on the other hand, the time step sizes typically usable tend to be very small, in seconds or sub-seconds, due to the numerical stability requirement for natural convection as often encountered.

The present paper reports a validation and demonstration study of a new loosely coupled conjugate heat transfer (CHT) approach developed for efficient and accurate simulations of steam turbine transient operations (Shut-down/Natural cooling). The verification and validation have been carried out for a complex 3D geometry configuration with attributes of realistic but geometrically simplified full-scale steam turbines and compared with a well-established simplified working method backed up by experimental data. Further comparisons are made against a direct baseline CHT method. The present results demonstrate a generally good agreement with the simplified working method. The new loosely coupled method is shown to give a marked speed-up (by a factor of 240) compared to the baseline directly coupled method with the same accuracy. It thus offers the potential for significant improvement in predicting the long-duration transient natural convection conjugate heat transfer problems of steam turbines in terms of computational efficiency and accuracy.

1. Introduction

In the past decades steam turbines typically operated as base-load machines with constant operating conditions and a relatively low amount of start and stop cycles. In the meantime, combined cycle machines did show relatively stable operating regimes. Accordingly, the designs and their lifetime were based on large field experience of the OEM's fleet. This also enabled to develop and establish highly robust and fast design methods. In the most recent years, the market significantly changed, with the generic global target of decarbonization for environmental reasons, an increasing amount of more volatile contributors to the electric grid appeared and therefore demand for more flexible operation of the classical fossil machines [1] and [2]. In the mid-term future, the fossil machines will still exist and are required to balance the disadvantages of the current renewable technologies until they are fully established and provide stable energy at any time. Also for environmental reasons, the fossil machines have to show increased efficiencies. For the benefit of cycle efficiency during the past years, the steam turbine inlet temperatures have been further increased and show

nowadays up to 620 °C, which will in near future be increased even further.

Additional to increasing steam turbine inlet temperatures, further efficiency increasing design options are developed like machines for double reheat cycles or further reduction of clearances to further reduce leakage losses. Besides operational flexibility and high turbine efficiencies, the current market is extremely competitive and therefore customer investments must be reduced as far as possible, but still maintaining a high machine value represented by high lifetime and high availability.

To keep the power plant operator investments low, the turbine designs have to be kept simple but still robust and the material grade has to be selected in a smart way to fulfil the above requirements but with the lowest possible degree of overdesigning the components. Such challenging designs can only be developed with the help of a large and long-term field experience in combination with development processes and tools which are accurate and enable deep insight into the physics of the design during operation.

For lifetime and availability, there is a little possibility of an

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accurate quantitative calculation for free convection phenomena in the cavities of heat engines, and primarily in gas and steam turbines, where their role is all the more important due to the temperature increase of the working medium. It is therefore not possible to make a proper evaluation of temperature distributions in units and components operating in the hottest zone, where temperature non-uniformities may lead to very considerable supplementary stresses, the permissible value of which is also determined by the temperature level. Moreover, in certain cases an underestimate of the effectiveness of convective heat removal may lead to structural complications due to the introduction of special artificial cooling, to avoid this, the thermal expansion behaviour must be understood for all occurring operating conditions, steady state as well as transient, hence start-up and shutdown [3].

Unsteady stresses in metal elements as well as temporal expansions (absolute and relative) of the turbine outer casing, inner casing, blade carriers, balance piston glands, outer shaft glands and turbine rotor during the start-up and shut-down are very crucial to determine steam turbines lifetime. Here i.e. the temperature gradients between cold and warm condition are relevant which means a start from cold conditions consumes more turbine life than from hot condition [4]. Therefore, between shut-down and re-start the component temperatures become of interest. While typically the rotor with the first moving blade row groove forms the weakest part of the turbine and hence requires accurate prediction methods for the lifetime.

The formulation of the problem of free convection in steam turbines cavities is extremely complicated, mainly because of the diversity of cavity shapes and temperature boundary conditions. This leads to a very low efficiency of the experimental methods of investigation, since the results obtained may be applied only to a narrow range of problems. In fact, both the geometrical size of the cavity and the temperature conditions at its boundaries must be similar to those involved in the test.

A number of efforts have been made to develop modelling based methods for prediction of turbine shutdown and cooling processes where understanding the cooling-down thermo-fluid physics is important as it directly impacts thermal designs of the rotating and stationary components. Stein et al. [5] have shown that for high cycling turbines as used in solar applications, other components like the inner casing may also become critical with respect to lifetime and require accurate assessment methods. Born et al. [6] have shown that for steady state operating conditions even complex CFD/CHT calculations of nearly full steam turbines can be executed nowadays with high accuracy against validation measurements of full-scale machines. Mohr & Ruffino [7] measured in a full-scale turbine the hot rotor surface temperature of a standard, combined cycle, intermediate pressure steam turbine using optical probes. The same data have been used by Marinescu et al. [8] for development of a full transient 2D method to calculate transient HP/IP steam turbine operations. Also, Marinescu has shown that the flow field can be captured even by using a Finite Element calculation method and treating the convective heat transfer as well as radiation by means of an adapted conductivity, which he called over-conductivity. This method was shown to be sufficiently precise and very robust against various measured designs [9]. In the first version, the over-conductivity function was calibrated against the measurements presented in Ref. [7]. In a later step, the computational domain was extended from 2D to 3D and split into regions to better distinguish the separate natural convection and radiation mechanisms. Here the equations to determine the over-conductivity for the separate mechanisms was taken from literature, and a later validation against measurements also confirmed a good agreement of the more generic method [10].

The above-described methods are shown to already enable with a certain accuracy and confidence temperature predictions for transient turbine operations. However, they rely on considerable simplifications in the calculation models and therefore require strong validations for each application. As consequence, the generic applicability and the

large design changes are challenging for these types of methods.

High fidelity CFD for steam turbine applications shows the potential to massively increase the generic applicability of a design tool and this for much larger design changes. However, a CFD/CHT method, based on convective heat transfer analysis for determination of the heat transfer coefficient (HTC) of the flow field throughout turbine cavity with an assumption that HTC is largely invariant with respect to wall temperature. In such systems, generic spatiotemporal variation in the flow give rise to variation in the heat flux for a given fluid-solid temperature difference, which can be interpreted as spatiotemporal fluctuation of the instantaneous heat transfer coefficient.

For a natural convection problem of the present interest, the near-wall flow is dominantly driven by the wall temperature, making a HTC based approach even more difficult. This strong dependence of flow on the wall thermal condition in natural convection presents a strong case for pursuing conjugate heat transfer (CHT) solutions for coupled fluid-solid domains.

For general CHT method developments and applications, the time scale disparity between the fluid and solid parts as a fundamental feature must be recognized. The ratio between the two-time scales can be up to 10^4 for gas turbine blades, as pointed out by He and Oldfield [10]. This time scale disparity presents a challenge for numerical solution methods adopted for the two domains as well as for the interface treatment between them. Fully coupled unsteady CHT simulations using the same discretization in space and time for both fluid and solid domains can be prohibitively expensive when a practical application such as a turbine flexible operation is to be dealt with. The problem would be difficult for URANS based CHT methods.

On the other hand, the time scale disparity can also serve as a justification for using a quasi-steady coupling approach for transient CHT, i.e. coupling an unsteady solid solver with a steady fluid solver at each time step. The quasi-steady based loosely coupled CHT methods have been actively developed and applied to forced convection heat transfer for turbine configurations and others, e.g. Refs. [11] [12], [13], [14]. For natural convection, there have been some attempts to use the direct coupled CHT solutions, e.g. Refs. [15] and [16], known to be computationally time-consuming. However, the present authors are not aware of any efforts of using a loosely coupled CHT approach for natural convection.

A particularly relevant issue as has been observed is related to time step size allowable in natural convection simulations with common commercial codes (e.g. FLUENT, CFX and COMSOL). The numerical stability requirement tends to restrict the time step size to a very small value (typically sub-seconds), e.g. Refs. [17] [18], [19] [20], [21] [22] [23], and [26]. When a transient CHT solution for natural convection is pursued, this time step limit can be particularly restrictive, given the time scale disparity between the fluid and solid domain.

The present effort is chiefly motivated to investigate the applicability of a new URANS based loosely coupled CHT method for transient natural convection, relevant to steam turbine flexible operations. There are several related questions in this regard:

- a) Validation and demonstration of the new loosely coupled procedure for solving transient conjugate heat transfer problems for natural convection, based on the recent efforts ([24] and [25]) and Multi-scale Time Integration for Transient Conjugate Heat Transfer, with an emphasis on a complex 3D configuration and long-time scales typical of realistic steam turbine natural cooling processes.
- b) Cross-validation between the present high-fidelity CFD and the over conductivity approach.

The coupling method is described in detail; the baseline solution results are then contrasted with the present source term based dual time stepping solver enabling a much larger time-step compared against others like direct coupled and over-conductivity.

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