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Analysis of Steam Turbine by Using Finite Element Model

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Abstract

The growing share of renewable energy sources in the market and solar thermal energy applications have established high requirements on steam turbine operation. These requirements are related to flexibility in customers. The key to this type of flexibility is the ability to start fast. Due to the changing temperature gradient during start-up, the starting speed of the turbine is limited by thermal pressure and differential expansion. These events can lead to machine failure if the lifespan of the component is consumed or not handled carefully. To get started fast while maintaining life requirements, it is important to evaluate the thermal behavior of the machine. To this end, a temporary thermal model has been developed with a view to adapting to different turbine sizes and geometries. The model allows for a simple and rapid estimation of thermo-mechanical properties within the turbine metal, in particular, the temperature distribution and the corresponding thermal expansion.

The next step in this work is to validate the model's estimates and simplifications. This study and the comparison of the two turbines were conducted against the operational data measured from the respective power plants. In addition, there are also comparisons related to the level of geometric detail of the model in validation studies. Overall, the comparison results showed a great deal of agreement between the measured data and the levels of geometric detail.A validated model has been applied in studies related to minimizing start time and maximum differential extension. To this end, the potential effects of turbine temperature-management changes are investigated and calculated. Among the modifications studied were: an increase in glandular vapor pressure, an increase in posterior pressure, and an increase in systolic motion. Significant improvements in results were achieved, starting with 9.5% at start-up and 7% at interoperability.Keywordssteam turbines, transients, start-up, finite element model, heat transfer.

1 Introduction

In general, steam turbines are complex machines in which a wide range of multidisciplinary mechanisms interact. The fundamental working principle of steam turbines is comprised in the expansion of the incoming steam, as it is through this expansion and using impulse to generate shaft power that the energy conversion from heat to electricity occurs. In addition, other relevant thermal processes within a steam turbine are those of gland steam sealing and losses due to friction and fanning.

Future scenarios of the primary energy mix for 2050 expect that fossil fuels will remain a dominant source but that growth rates will be highest for renewable energy sources with increases in the global share of 5-10% [1]. The increased penetration of renewables in the grid implies that the operation of steam turbines is required to be more flexible. The requirements are mainly related to fast cycling capabilities for frequency control as well as flexibility for start-up and shut-down.

Furthermore, the deployment of renewable technologies based on steam cycles also poses higher requirements on steam turbine flexibility during start-up. An example of this is the operation of steam turbines in concentrating solar power plants (CSPPs). Due to the fluctuating nature of the solar supply, the number of start-up cycles endured by solar steam turbines is greater than those in base load plants [2], with multiple starts possible during a 24h period.

The aforementioned requirements on steam turbine operation are related to flexibility during transient operation, especially during start- up. A key aspect sought of such flexibility is the capability for fast starts. There are two main types of operating conditions a turbine can be subject to: steady state and transient. The latter occurs when the conditions under which the turbine is operating are variable. The most intrinsic transient condition of a turbine is the start-up phase [3]. This is due to the fact that start-up conditions are characterized by high thermal stress states which compromise the lifetime of the turbine [4]. In addition, differential thermal expansion is another phenomenon of concern during

start-up. If not carefully controlled, axial rubbing may occur between the moving and stationary parts of the turbine, resulting in machine failure.

To avoid excessive thermal stresses during start-up, the manufacturer may specify start-up curves which limit the rate at which the turbines can reach full load. The purpose of the curves is to maintain thermal stresses under a given temperature dependent limit [5]. The start-up time of a turbine is determined by the permissible initial temperature step and the subsequently permissible temperature transient [6]. What this translates to is that, as a general rule, the warmer a turbine is before start the faster the startup can be [3].

In order to accomplish faster startup speeds while still ensuring safe operation of the turbine it is important to understand the thermal characteristics of the machine. As thermal stresses and start-up curves are temperature dependent, accurate prediction of the temperature gradients within the steam turbines is thus necessary to be able to optimize the operation of existing steam turbines, as well as improve the flexibility of the next generation of turbines. It is therefore very important to develop tools that can predict and give insight on the induced temperature gradients.

Models for thermal analysis of steam turbines have been developed and implemented in other works [7][8][9]. Similarly, previous work performed at the Division of Heat and Power Technology at KTH also focused on the development of a model for the overall prediction of temperature distributions within the turbine [10].

2 LITERATURE REVIEW

One of these models consisted of a mixed 2D-3D FE approach calibrated with transient temperature measurements of the steam path [7]. In this model the numerical modeling scheme was directly dependent on instrumenting the studied turbine, something that is not always plausible and not generally applicable. The other model consisted of a 3D FE approach using empirical correlations for the heat transfer zones [9]. However, the different turbine components were developed under large computational dimensionality and they had to be considered separately. By doing this, component interactions were not fully captured in accordance with physical assumptions. The model developed previously within KTH consisted of a full 2D axisymmetric that comprised the interaction of all turbine components. However, this model was developed for a single turbine without considerations of adaptability to other turbines for future studies. Other drawbacks of the model wererelated to the level of detail of the implemented boundary conditions and the calibration of the heat transfer coefficients with the use of correction factors.

In this work, the KTH thermal turbine model has been taken as a reference for developing an improved modeling tool. The previous model has been modified and refined in terms of geometric adaptability and heat transfer assumptions. Similar to the preceding model, the newly developed modeling tool consists of an integrated approach of steam and heat transfer calculations performed on a full 2D axisymmetric turbine geometry. However, the integration of a modular geometric modeling approach allows the new model to be adaptable to various turbines. Furthermore, other important changes consisted of including more accurate heat transfer correlations and refining the implementation of the boundary conditions to the model with respect to the mode of operation of the turbine. These modifications were done with the focus of delivering a fast calculating tool of sufficient level of detail to capture turbine transient behavior.

Also in this work, the general applicability and accuracy of the model have been evaluated in validation studies. The validation was performed differently than the previous study from KTH as the heat transfer coefficients were not corrected with weighting factors. Instead, the developed modeling scheme was implemented in two different turbine models while maintaining the same approach and assumptions. Finally, the validated model has been implemented in parametric studies related to steam turbine start-up improvements. The improvements were obtained through the implementation of operational modifications different from those studied previously [11].

3. Methodology

In order to achieve the aforementioned objectives, the method of investigation that was carried out consisted of three steps, namely: development, validation and implementation of the model.

The development of the modeling tool was done with the scope of achieving sufficient level of detail of the turbine while keeping fast calculation times. This was achieved with a 2D axisymmetric heat conduction model with heat transfer coefficients (HTCs) based on empirical heat transfer correlations. In general, the modeling scheme was based in previous work performed at KTH. However, several changes and improvements were performed to that model. One of main change was to supplement the existing model with a COMSOL-based finite element (FE) heat conduction model. Integration of COMSOL allowed for more flexibility, including multi-physics applications. In parallel, the model was also made more flexible with respect to the geometric modeling approach. The previous model was tied to one specific turbine geometry, and was thus cumbersome to use for the evaluation of alternative turbines. Other very important changes consisted of including other relevant heat transfer correlations and refining the boundary conditions (BCs) implementation to the model with respect to the mode of operation of the turbine.

The range of applicability and accuracy of the model was then evaluated in the validation process. The validation focused on two main aspects of the model: the geometric simplifications and the BC assumptions. In order to validate these, comparisons were made against measured operational data and other numerical models of higher geometric dimensions. The former served to understand the range of applicability of the BCs while the latter helped in the understanding of the impact of the geometric simplifications.

Once having validated the model, the next step was to implement the model. Parametric studies were carried out in order to investigate the impact of three temperature maintaining modifications in the thermal behavior of the turbine during transients. The studies were focused on

improving turbine response during start-up conditions. This was analyzed calculating reductions on start-up time and differential expansion.

3.1 Structure

This paper begins with a first introductory chapter, in which the background, the objectives and the method of investigation are presented. Chapter 2 consists of explaining the fundamentals of steam turbine technology which are relevant to the work performed in subsequent chapters. Chapter 3 elaborates on the modeling approach developed to simulate the transient thermal behavior of steam turbines. Chapter 4 presents the obtained results for the validation of the model and its implementation in studies for the improvement of steam turbine operational flexibility. Finally, Chapter 5 concludes the work in this thesis and describes future work to be performed.

3.2 Thermal Processes

In general, steam turbines are complex machines in which a wide range of multidisciplinary mechanisms interact. This section highlights only the processes which are of importance and more relevance to the work performed in subsequent chapters in relation to the modeling approach.

3.2 Steam Expansion

The fundamental working principle of steam turbines is comprised in the expansion of the incoming steam, as it is through this thermal process that the energy conversion from heat to electricity occurs. This energy transformation occurs within a turbine stage, which is composed of a static blade row, denoted as stator, and a rotating blade row, denoted as rotor. Essentially, the internal energy of the steam is transformed into kinetic energy, and the latter in turn is transformed into mechanical work that rotates the turbine shaft [16].

$$\Delta h_0 = u_{in} c_{\theta,in} - u_{out} c_{\theta,out} \qquad (1)$$

3.3 Friction and Fanning

Among the external efficiency losses that occur in a turbine stage, there are losses due to friction and ventilation. These take place in the blades and discs of the turbine. As a turbine disc rotates in space, aerodynamic resistance forces from the surrounding fluid act upon it [19]. In the gaps between the rotor and stator discs, recirculating steam flow creates friction with the moving disc surfaces (Figure 3a). The energy dissipated due to friction is proportional to the steam density ρ, the square of the disc diameter d_d and the cube of the circular speed u and as shown in Equation (5) [16].In addition, friction work is also dependent on an empirical friction factor K_{fr} which is defined by geometric parameters of the disc and the rotational Reynolds number, Equation (6).

$$W_{fr} = \frac{1}{2} K_{fr} \cdot \rho \cdot d_d^2 \cdot u^3 \qquad (2)$$

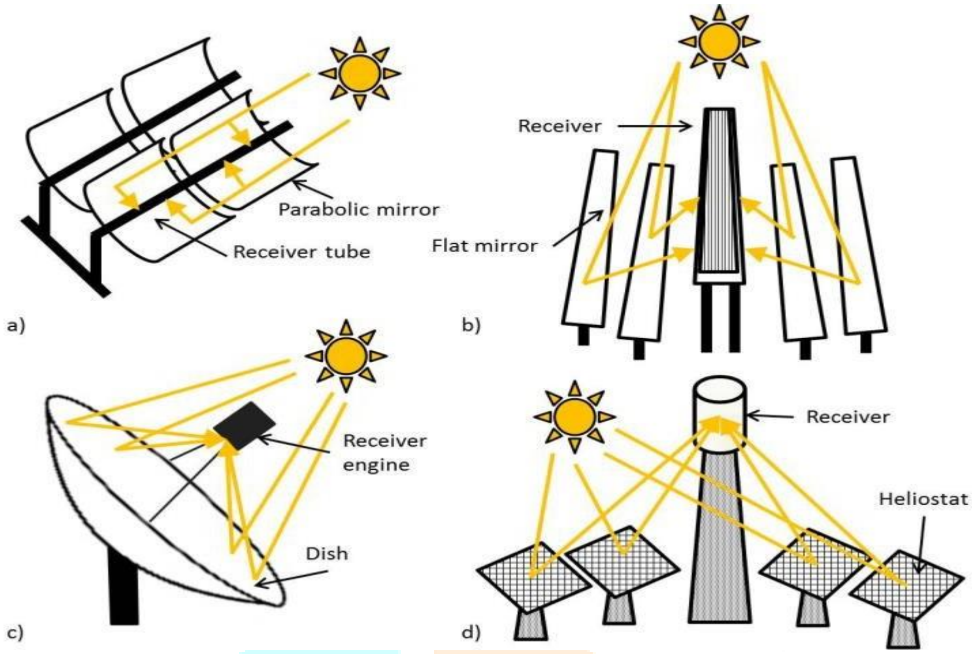

Figure 1: CSP Technologies: (a) parabolic trough (b) linear Fresnel (c) parabolic dish (d) Central tower.

3.4 Turbine Transients and Cyclic Operation

There are two main types of operating conditions a turbine can be subject to: steady state and transient. The latter occurs when the conditions under which the turbine is operating are variable. Chronologically, transients are a required phase of operation in order to reach steady-state conditions. The most intrinsic transient condition of a turbine is the start-up phase [3].

A steam turbine start consists of three stages: pre-warming, rolling up and loading [3]. During the stage of pre-warming the turbine is rotated by the turning gear and the only admission of steam into the turbine iswarming steam. Depending on the application and size of the turbine the pre-warming phase is implemented differently. The rolling up phase consists of a controllable raise of the rotation speed of the turbine up the nominal value. At this point, a small amount of steam is admitted into the turbine. Finally, the loading phase increases the steam mass flow and properties until nominal conditions are reached.

3.5 Differential Expansion

Thermal expansion is mainly caused by the axial temperature changes in a turbine component and can have different effects depending on how a component is heated or fixed in space. In general, the amount of free thermal expansion being heated up to a certain temperature T can be calculated using equation (12), where l_i is the initial length of the component.

Steam Turbine Transient Thermal Model

During transient operation, the varying inlet conditions generate uneven temperature distributions in the turbine metal. As mentioned earlier, it is due to this distribution that negative and life consuming effects occur, especially during start-up. It is therefore very important to develop tools that can predict and give insight on the induced gradients.

4 Results

4.1 Model Validation

The first step before actually implementing the turbine model for differential expansion studies was to validate it. This was done by performing studies on two turbines, each of which is employed in a different application and is of different dimensions. The validation work on each turbine consisted on performing two comparisons.

The two comparisons were carried out as independent studies. However, they both contribute to the validation of the turbine models in different aspects. These aspects are related to the BCs and geometric simplifications implemented in the model. More importantly, the comparison studies not only contribute to the general validation of the modeling tool but also help in the evaluation of the thermal prediction quality of the model and eventually strengthen its capabilities for further analysis in locations of interest within the turbine. The following sections elaborate about each of the studies in more detail.

Under the continuous approach, the rotor, casing and blades of the turbine are each represented with their own geometric block (see Figure 7b). This approach keeps a true representation of the actual 2D turbine geometry, ensuring that the temperature predictions at every metal location are made with an adequate precision level. The scaled geometries derived for the continuous approach are shown in Figure 10a.

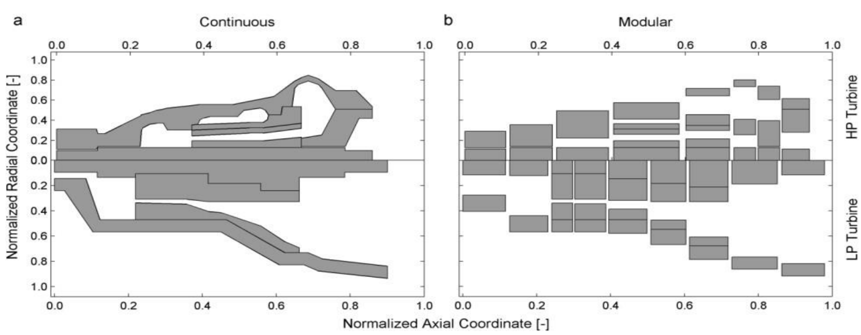

Figure 2 (a) Continuous geometry approach for the LPT and HPT units; (b) Modular geometry approach for the LPT and HPT units.

However, with the continuous approach, the geometry must be reformulated for each steam turbine studied. To define the continuous geometry of the turbines, it is required to have knowledge of the entire turbine specific shapes and dimensions. It is not simple to access this information, making the continuous approach inflexible and cumbersome to adapt to new geometries. Since a wide range of steam turbine configurations exist, there is a need for an approach that can be adaptedto different turbine geometries.

A first comparison was made concerning the temperature distribution at nominal conditions. Figure 3 shows the normalized temperature distributions obtained at nominal operating conditions.

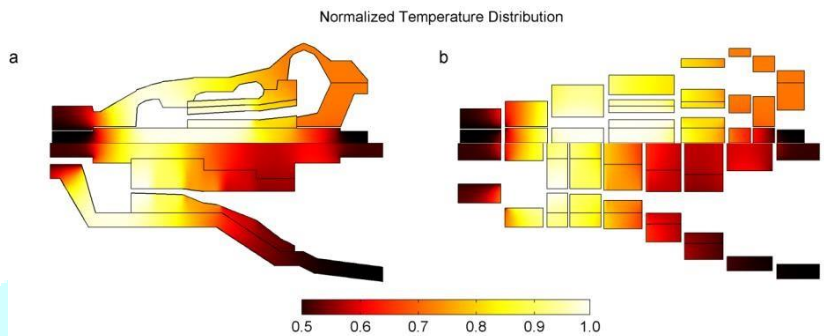

Figure 3 Normalized temperature distributions on the (a) continuous and (b) modular approaches for turbine nominal operating conditions.

. Figure 4 shows the measured inlet steam conditions, for both the live and gland steams. In this figure the variable

operation to which the steam turbine of the CSPP is subjected is clearly portrayed.

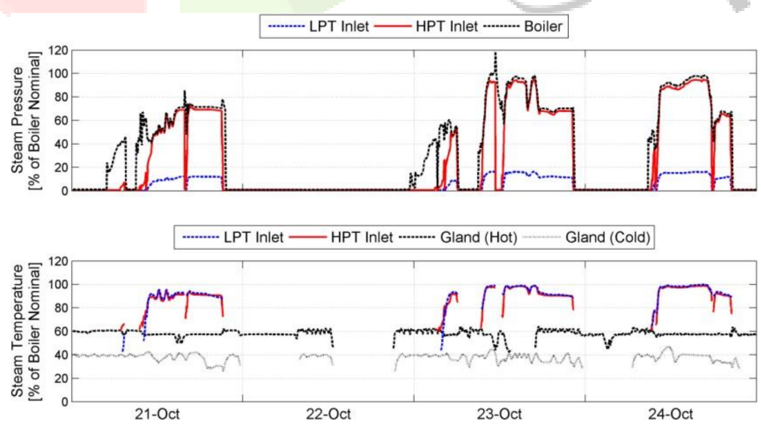

Figure 4 Pressure and temperature measured data for the live and gland steam given as a percentage of nominal boiler values

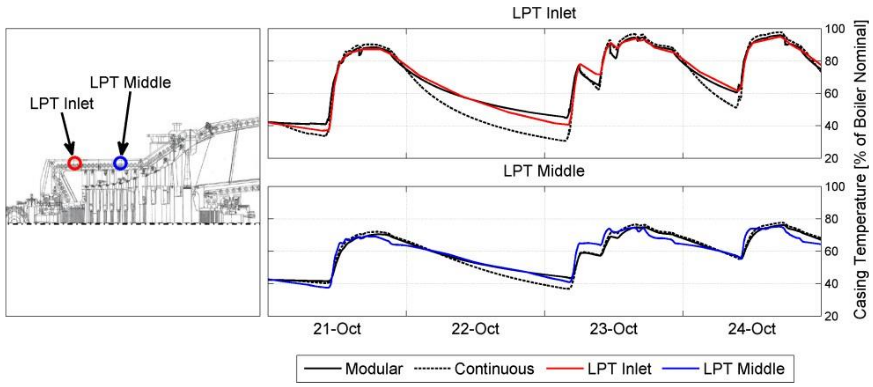

Figure 5: Measured and simulated temperatures at two points in the casing of the LPT given as a percentage of nominal boiler value.

Differential Expansion Reduction

The sensitivity studies performed in this section were oriented towards reducing the maximum differential expansion that occurs during the rolling up phase of the start, as observed in Figure 6

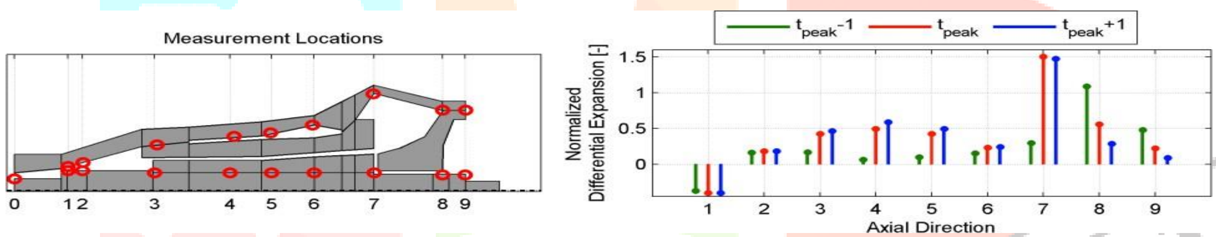

Fig 6 Measurement locations of axial displacement in turbine geometry (left) Individual differential expansion at measurement locations for time instants in the vicinity ofthe peak value of differential expansion during rolling-up.

5 Conclusions

Current power plant operation requires more dynamic steam turbine components. This raises the interest of achieving faster turbine start-ups in order to adapt quickly to the fluctuations in energy supply to the market. Turbine start-ups are governed by curves which limit the time it takes for the turbine to reach nominal load and speed. The main objective of the start-up curves is to protect the turbine component from detrimental phenomena which occur as a consequence of transient operation. Radial thermal stresses in thick walled components and axial rubbing between stationary and rotating parts due to relative axial expansion are among these negative phenomena.

In this work, a turbine thermal model was validated and implemented in parametric studies concerning improvements of the thermal behavior during start-up conditions. These sensitivity studies were performed in order to understand existing constraints of turbine start. In order to perform such studies a turbine thermal model was developed based upon previous work from KTH [10]. The previous model was modified and refined in terms of geometric adaptability and heat transfer assumptions. This was done in order to deliver a fast calculating tool of sufficient level of detail to accurately capture transient behavior of all turbine components. Furthermore, it was also desirable for the modeling scheme to be easily adaptable to other turbine models for future work. The developed modeling tool also differed from other works as it did not comprise calibration with instrumented turbines [7] [8] orcomputationally cumbersome CFD calculations [9].

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