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Modelling of a cross flow evaporator for CSP application: Analysis of the use of different two phase heat transfer and pressure drop correlations

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ABSTRACT

Heat exchangers consisting of bundles of horizontal plain tubes with boiling on the shell side are widely used in industrial and energy systems applications. A recent particular specific interest for the use of this special heat exchanger is in connection with Concentrated Solar Power (CSP) applications. Heat transfer and pressure drop prediction methods are an important tool for design and modelling of diabatic, two-phase, shell-side flow over a horizontal plain tubes bundle for a vertical up-flow evaporator. With the objective of developing a model for a specific type of cross flow evaporator for a coil type steam generator specifically designed for solar applications, this paper analyzes the use of several heat transfer, void fraction and pressure drop correlations for the modelling the operation of such a type of steam generator.

The paper after a brief review of the literature about the available correlations for the definition of two-phase flow heat transfer, void fraction and pressure drop in connection with the operation of steam generators, focuses attention on a comparison of the results obtained using several different models resulting by different combination of correlations. The influence on the analysis of the performance of the evaporator, their impact on significant design variables and the effective lifetime of critical components in different operating conditions, simulating the daily start-up procedures of the steam generator is evaluated. The importance of a good calibration of the model based on the comparison with some experimental data is recognised.

1. Introduction

In recent years the power generation industry has been affected by a significant growth of small capacity intermittent renewable on-site power plants. In such a new distributed energy scenario, concentrated solar power (CSP) plants can surely play an important role, in the near future.

Concentrating solar is a promising technology, but it still has open operational issues that are a challenge compared with other rival technologies. Considering the discontinuous nature of the power source [1], the analysis of solar plant operation has to consider not only the design of the components, but also the analysis of the performance of the system under different operating conditions. Very fast transients may occur and all the operation units may have shorter life cycles for strong dynamics and frequent changes of operating conditions.

For this reason, from the process viewpoint, it is necessary to go through a dynamic modelling simulation phase. This is particularly important for systems involving strong dynamics and for particular components, like the steam generator.

The steam cycle involves components similar to those operating in a conventional power plant. With focus on the dynamic performance of these, the steam generator is the most important one. The operation of these components will be constrained by the allowable temperature and pressure gradients during the start-up and shut-down phase causing pressure and thermal stresses.

In this case the simulation of the various operating condition is important not only in order to evaluate the performance of the system, but also for evaluating the expected lifetime of the

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components operating under strong transient conditions. In recent times several dynamic simulations were performed to improve the knowledge and to assess the effectiveness of the various components of solar plants under design and to monitor, predict and control the operation of them [2–4].

Solar thermal power plants undergo lengthy start-up and shut-down operations due to the variation of solar radiation during the day. Therefore, valid modelling of their performance must address those transient conditions in order to accurately model the daily performance of a solar thermal power plant including start-up and shut-down operations and for this reason the various components involved, must be studied [5,6].

Unfortunately there are limits on how fast a thermal power plant can be started-up. The importance of a quick start-up (producing power some minutes earlier) has a specific value in CSP plants. In general if it is not possible to have a quick start-up of the plant, as the sun rises, the energy will be lost. A faster start-up means therefore higher daily energy production.

A steam generator of the coil type or a cross flow evaporator working in transient conditions are interesting for a large range of engineering applications; in particular for CSP applications.

For the design of a cross-flow evaporator working in transient conditions, a dynamic study is of primary importance. This is true both in applications referred to conventional thermal power plants, because in recent times they are subject to frequent load changes in order to be regulated according to the electricity grid requirements and also for systems like CSP applications, in which the steam generation system works in highly transient conditions, both during the aforementioned daily start-up and shut-down phase and due to the possible variation of the input heat source, mainly due to cloud passing, [7]. In this case the flexibility of the evaporator is extremely important in order to be able to operate the power plant with maximum efficiency in the limited daily amount of sun hours. To design and optimize a CSP it is essential to know the performances of the different subsystems and components. Dynamic modelling tools have recently been used to assess the performance of solar systems under transient conditions but obviously each specific component requires a specific tool.

A mathematical model to simulate the operation of the steam generator and of the evaporator has to consider the heat transfer between the liquid–vapour side and on the oil side. Several studies have been developed on the dynamic aspects of two-phase flow on the shell side of staggered and in-line horizontal plain tube bundles, such as the evaluation of void fraction, two-phase flow behaviour, two-phase pressure gradients and heat transfer prediction methods on tube bundles in cross-flow. These prediction methods are generally based on the calibration of an analytical model with experimental results. In general, noticeable discrepancies between the prediction and the experimental results are exhibited [8,9]. But an accurate idea about the differences that can be associated to the use of different modelling approaches is surely a preliminary step. Several mathematical models of key unit operations are developed and available in the literature to study the dynamic behaviour of solar plants to characterize their operations and to improve the reliability of the plant as well as to identify the main critical aspects in operating the plant. But even if the topic is well covered in reduced attention is given to specific elements like the definition of the heat transfer coefficients and the friction factors. A lot of work is generally needed to adapt the available codes for calculation to specific features and specific needs of each project.

The difficulty of getting proper insight into the boiling over tube bundles in industrial heat exchangers is due mainly to the heat transfer model; on the other hand industrial scale experiments are difficult to carry out [8].

In a recent paper, the authors have analysed a new type of evaporator in which the coil-type evaporator does not have thick tube plates and in which the hot oil flows are distributed to the heat transfer tube bank via a circular manifold, [6]. According to previous experience on CSP plants the cross flow evaporator represent the critical component and the great advantage of the innovative Coil Steam Generator, is represented by the new design of the oil collectors as cylindrical headers in the cross flow evaporator in order to lower the thermal stresses that seriously affects the lifetime of the component.

The objective of this paper is to define criteria and guidelines for a semi-dynamic fluid and thermo-mechanical model for the cross flow evaporator for CSP applications. The structure of the model has already been discussed in [5,6] but in this paper the aim is to present the impact, of implementing different correlations in the model, on the results of the simulations over a wide range of operating conditions. The main objective of this study is the particular analysis and modelling of the evaporator section. This, as already seen in [6], requires a preliminary analysis concerning the correct selection of the correlation for two phase heat transfer coefficient void fraction and pressure drop in boiling conditions.

A further objective is to investigate in detail how the cross flow evaporator of the Coil Steam Generator, specially designed for CSP applications, can be modelled in order to be able to evaluate its thermal performance and the fatigue life and damage in connection with daily start-up routines and the uncertainties connected to the modelling.

The paper is structured in two parts: in the first part a preliminary analysis about steam generators for utilization in CSP in the different load conditions and a discussion of the available correlations that can be used in the model is presented. In the second part a sensitivity analysis connected with the simulation of various different operating conditions of the steam generator will be shown and finally examples of the application of the model in order to predict the life of the evaporator under highly transient operating conditions is presented.

2. System description and general elements for modelling

The specific object of the analysis is a cross flow heat exchanger, included in the two shells of a Steam Generator of the coil type, specially designed for solar applications by the company Aalborg CSP A/S [10] and schematically represented in Fig. 1. From this point it will be referred to as Coil Steam Generator (CSG). The coil steam generator consists of two evaporators in parallel that are cross flow

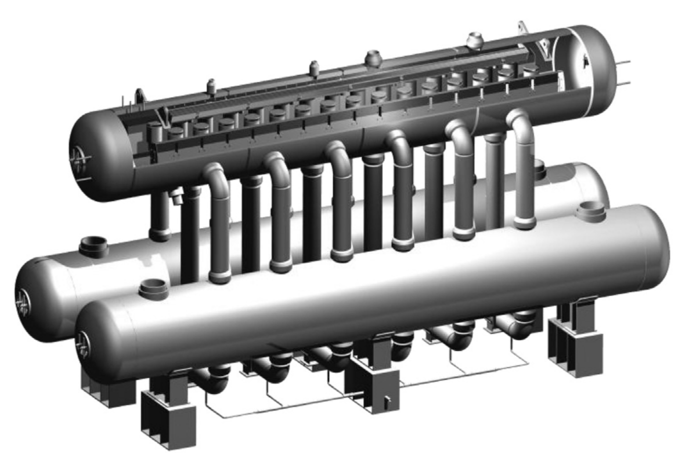

Fig. 1. Steam generation system of the CSP plant [10].