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Heat transfer correlation between Molten Salts and helical-coil tube bundle Steam Generator

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ABSTRACT

A Computational Fluid Dynamic (CFD) modelling able to describe a discharge process of a Molten Salts (MS) Thermal Energy Storage system with integrated Steam Generator (TES-SG) is presented in this paper. This simulation model has been validated with experimental results obtained at the PCS Facility located at the ENEA Casaccia Research Centre in Rome. The numerical results of this model (MS velocities, temperatures and boundary heat flux distributions within the SG) have been used to derive a dimensionless form for describing fluid flow, by Reynolds number, Re, and heat transfer between MS and helical-coil tube bundle SG, by Nusselt number, Nu. The obtained correlation is: $Nu = 0.3146Re^{0.54}Pr^{0.36}$, where Re and Nu are based on the outer diameter of the helical coils. It is valid for 400 to 1200 Reynolds numbers, 4 to 11 Prandtl numbers, an average winding angle of 2° and an outer diameter of the helical coils of 0.0127 m. The correlation here proposed can be very useful for sizing a vertical helical-coil tube bundle SG immersed in a Molten Salts tank of a commercial CSP plant for a specific nominal power.

1. Introduction

Thermal Energy Storage (TES) systems are an added value for Concentrating Solar Power (CSP) technologies since they buffer the transient weather conditions, improve their dispatchability, increase their annual capacity factor and allow a more even distribution of electricity production [1,2]. The objective of OPTS project (Optimization of a Thermal Energy Storage system with integrated Steam Generator, 2011–2014, FP7 funded project under 283138 Contract) has been to provide the efficient and techno-economic viability of a new TES concept for the next CSP plants generation, based on:

- The use of Molten Salts (MS) as heat transfer fluid & storage medium.
- The use of a single tank (or thermocline tank) instead of the traditional two-tank configuration.
- The integration of the Steam Generator (SG) that feeds the power block within the storage tank.

One of the OPTS tasks aimed at estimating heat transfer correlations needed for the simulation of a helical-coil tube bundle SG in contact with MS, under defined working conditions on the water-steam side and natural or assisted convection on the MS side. The scope of this paper is the heat transfer in the MS side, since the correlations found in the literature for helical-coil tube bundles [3–5] are not adequate for the OPTS configuration because, they are either not suitable for MS as heat transfer medium or the heat exchanger designs are different enough to influence the heat transfer process.

For this purpose, a Computational Fluid Dynamic (CFD) model of the $300kW_{th}$ MS prototype erected in the Casaccia Research Centre of ENEA (Italy) has been carried out, which has been validated with the experimental data obtained during one of its discharge tests.

The advantage of CFD techniques is to contribute with a detailed description of the thermo-hydraulic behaviour of systems. In the ENEA prototype at issue, these simulations have been able to

Abbreviations: CFD, Computational Fluid Dynamical; MS, Molten Salts; TES-SG, Thermal Energy Storage system with integrated Steam Generator; PCS, Prova Colletori Solari; ENEA, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile; SG, Steam Generator; TES, Thermal Energy Storage; CSP, Concentrating Solar Power; OPTS, Optimization of a Thermal Energy Storage system with integrated Steam Generator; OECD, Organisation for Economic Co-operation and Development; CAD, Computer Aided Design; SIMPLE, Semi-Implicit Method for Pressure Linked Equations; RANS, Reynolds-Average Navier–Stokes; K–E, K–epsilon; CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas; UDF, User Defined Function; CPU, Central Processing Unit; UTRINN-STD, Technical Unit for Renewable Energy Sources-Solar Thermodynamic Laboratory; MAPE, Mean Absolute Percentage Error; MADP, Mean Absolute Deviation Percent.

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Nomenclature

Re	Reynolds number
Nu	Nusselt number
d_o	outer diameter
d_h	hydraulic diameter
Δs	cell size
Δt	time step
Pr_T	turbulent Prandtl number
Pr	molecular Prandtl number
f_g	buoyancy force
C_p	heat capacity
$\overline{Cp}$	average heat capacity
$\dot{Q}$	power
$\dot{m}$	mass flow rate
H	enthalpy
T	temperature
h	heat transfer coefficient
$\bar{h}$	local heat transfer coefficient
ΔS	surface element
v	velocity

Greek symbols

ρ	density
β	thermal expansion coefficient
κ	thermal conductivity
μ	dynamic viscosity

Subscripts

m	mth helical turn
n	nth helical turn in a uniformly distributed subset of them
MS	molten salts
WS	water steam
OUT	outlet condition
IN	inlet condition
∞	bulk
w	wall

provide the MS velocities, temperatures and boundary heat flux distributions within the SG needed to explain the heat transfer in the MS. This kind of information cannot be obtained by means of more simplified simulations [6], neither examining prototype experimental data [7].

The commercial code STAR-CCM+8.04.010® (based on finite volume method [8]) has been used as CFD tool.

The conducted layout is as follows: in the next section, a literature survey of heat transfer correlations for helical-coil tube bundles is presented. In Section 3, the ENEA prototype is introduced and in Section 4 the CFD model that describes the MS behaviour during its discharge is described, both the pre-processing – establishing the geometry, meshing, and simulation model – as the processing. In Section 5 the model is validated in terms of both numerical parameters and experimental data. From the numerical results, in Section 6 a methodology for calculating the local heat transfer coefficients along the SG is established and in Section 7, these coefficients are linked with representative dimensionless numbers, so a new heat transfer correlation for MS is proposed and discussed. In the last section, the main conclusions of the study are included.

2. Literature survey of heat transfer correlations for helical-coil tube bundles

Studies on convective heat transfer in helical coil heat exchangers on the shell-side are scarce in the literature and the reported configurations are limited to very specific situations and configurations. Messa et al. [3], proposed several heat transfer correlations founded on an experimental work with six different kind of helical coil heat exchangers of winding angles from 4° 30′ up to 18° 30′. Smith [4], carried out a thermal design using the data of one OECD Dragon helium-steam heat exchanger. Abadzic [4], examined the heat transfer data from different sources and recommended three correlations for an extended range of Reynolds numbers, Re. Most of the data correlated correspond to non-uniform helical-coil bundles with mean winding angles of 9°. Genić et al. [5], have recently presented a new correlation founded on an experimental research with three helical heat exchangers of different winding angles (from 4° 26′ up to 42° 28′). The first correlations are based on the outer diameter, d_o, and the last in the hydraulic diameter, d_h.

He et al. [31], studied convective heat transfer of MS around a tube bundle, proposing a correlation valid for Prandtl numbers, Pr, between 20 to 100 and 0.0432 m hydraulic diameter, d_h.

In the following table, Table 1, correlations mentioned in the previous works are summarized.

Smith's and Abadzic's correlations are only suitable for gases ($Pr \sim 1$) and Messa et al.'s (1), (3), (4), (5) and (6) are suitable for gases and liquids with low Pr number (up to 2.6).

He et al.'s correlation, that, despite it is suitable for MS, the heat exchanger configuration for which was validated (a common tube bundle) is less effective in transferring heat that the helical-coil tube bundle configuration.

3. ENEA prototype

The TES-SG prototype is based on a joint patent between the company Ansaldo Nucleare S.p.A (Italy) and ENEA Research Centre (Italy), [9].

It is a stainless steel tank, of nearly 2 m diameter and 2.8 m height covered by an insulating layer, which contain 12,000 kg of molten solar salt (60% weight $NaNO_3$ + 40% weight KNO_3).

SG is integrated vertically at one side of the tank and is composed by three concentric and uniform helical coils (of 65 helical turns), an insulating blanket around them, a downcomer in their core and an opening and a diffuser through which the MS enter and leave the SG respectively (Fig. 1, [10]).

During TES discharge, saturated water goes through the Steam Generator, along the downcomer and is distributed through the three helical coils that are born at the end of the downcomer. Along these three helical coils MS exchange their energy with the water flowing up to the helical coils, becoming steam and inducing a self-sustaining flow by natural convection in the MS side.

This process causes the stratification in the Molten Salts bulk (outside the SG), i.e., originates the appearance of a cold zone at the bottom of the tank, from the MS which have flowed through the SG exchanging heat, a hot zone at the top of the tank, and an intermediate zone between them. As discharge progresses the bulk MS stratification changes.

The 300kW$_{th}$ ENEA prototype has different temperature gauges (TI.), placed in the physical media (MS, water-steam and air) and at various positions of walls (tank, SG shell, central helical coil);