3-D CFD ANALYSIS OF THERMAL STRATIFICATION IN AN AIR THERMOCLINE TANK ANALYSIS USING COPPER SLAGS AS FILLER MATERIAL

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Summary

The present study describes a CFD based methodology for the analysis of temperature stratification in an air thermocline tank using a three-dimensional model developed in ANSYS CFX. This particular case considers copper slags as filler material, allowing to simulate its behavior as a coupled solid-fluid interface system. The charging and standby phases are simulated using a coupled CFD model to capture the heat transfer mechanisms between the solid-fluid region to assess the effect of including a copper slag rock bed inside the tank. The transient temperature profile along the tank height is obtained for charging and standby process in order to analyze the thermal behavior of the rock bed during different stages in every process.

Keywords: CFD Simulation, Thermocline Tank, Thermal Stratification, Stratification Efficiency

1. Introduction

Thermal energy storage (TES) applied to concentrated solar power (CSP) provides clean and cost-competitive technology for commercial and large-scale heat and power generation, increasing the plant's dispatchability and operational flexibility. TES tanks have been pointed out as a low-cost and high-efficiency solution for thermal energy storage. However, some studies had suggested that a single tank system (dual medium-based thermocline tank) and a two-tank system show that a single tank system has the potential of reducing 33% of storage cost when compared to an equally sized two-tank system as described by Angelini et al. (2013). Thermocline storage filler materials are widely used due to its high heat capacity, where the most common materials are silica sand and quartzite which withstands and retains molten salts thermal properties during charging and discharging cycles. Packed-bed filler materials for a thermocline TES model taking into account parameters such as inlet velocity, tank height, and porosity were reported by Nandi et al. (2018). The transport phenomena within the packed-bed molten salt tank strictly depends on a three-directional heat transfer model to realistically represent the thermocline development and stability during the charging/discharging cycles. Since molten salts are used in many applications, they present many chemical and thermal instabilities at high-temperature applications. To avoid these issues, air is considered as heat transfer fluid. Therefore, the aim of this study is to further develop the analysis of an air thermocline tank with copper slags as filler materials by developing a transient 3D laminar-turbulent model, allowing to study and analyze the impact of using copper slags (and other mining by-products) as filler materials in packed bed air thermocline tanks and its behaviour in high temperature conditions. The methodology developed aims to emulate through a computational model, various technical gaps limiting large scale applications of this technology as detailed by Xu et al. (2012a, 2012b). The main aiming of this paper is to test the thermal behavior of the discretized copper slags bed and its effects on the thermal stratification inside the tank.

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2. System Description

The simulated system consists of a thermocline tank filled with a cylinder-shaped distribution of spherical rocks. Each pebble has a diameter of d=0.025 m, with a dx=0.075 m of gap between every pebble. The initial temperature of the air within the tank is 25°C. The tank is filled with air at 600°C from top-height inlet which allows mixing well hot and cold air to get the thermal stratification. The charging process consists of loading the tank with hot air as cold air, located at the bottom of the tank is being extracted. The standby process consists of no flow being loaded to the tank leading heat exchange to occur due to the air density variations.

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3. Methodology

This research develops a 3-D CFD model using ANSYS FLUENT/CFX 19.0 for the simulation of an air thermocline tank operation cycle (charge/standby/discharge). The main objective is to study the transient thermal stratification process during the different operational stages. Since developing a transient 3-D model is very complex, a detailed physical-mathematical model with specific boundary conditions is proposed, as shown Figure 1, in order to capture the proper heat transfer phenomenon which drives the thermal stratification process inside the tank.

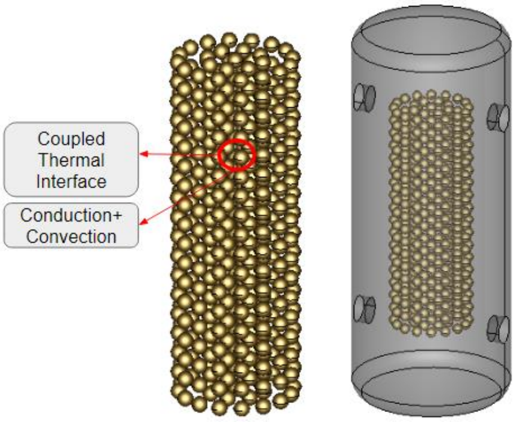

Fig. 1: Thermocline tank system with copper slags rock bed.

This study considers the porous bed discretization in spherical shaped rocks, in order to get a better approach on the thermal behavior of the copper slags within the tank. This means that the solid body representation of slag should consider the convective heat transfer on the solid surface and conductive heat transfer inside the rock body. The geometry of the tank is treated by cutting the sphere's volume from inside the tank, which allows creating the contact surface of the rock that is surrounded by hot air. This common surface will be defined as an interface between the solid and fluid domain, which is specified by checking the System-coupled boundary condition in ANSYS. The temperature profile along the tank is obtained by solving continuity, momentum, and energy equations for the fluid domain, during the charging and standby process. To obtain the one-dimensional temperature profile along with the tank height, a volume-averaged calculation of temperature is made for each cell on the computational domain.

3.1 *Boundary Conditions*

This section describes every aspect and consideration taken to set a physical model that captures the main heat transfer mechanism for charging, and the standby process. Every stage simulated considers different thermo-physical models (turbulence models for charging/discharging process, Boussinesq/density-driven buoyancy forces for the standby phase) and boundary conditions as shown in Figure 2. It is necessary to specify that the temperature distribution at the end of the charging process, corresponds to the temperature initial condition at the begin of the standby process, but switching from a pressure-linked equations based solver to a density-based solver to properly capture the buoyancy effects during standby phase.

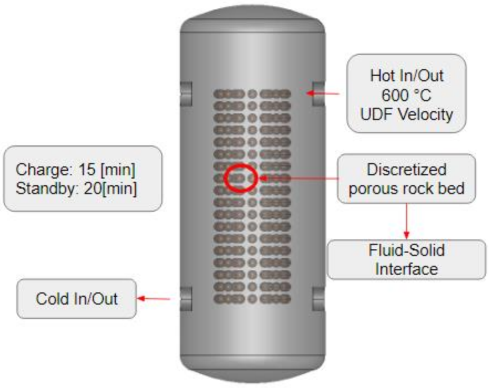

Fig. 2: Thermocline system and operating conditions

3.2 *Geometry*

A single geometry of an air thermocline tank is used to carry out every simulation stage. In order to allow the thermal stratification to develop in an easier way, and aspect ratio of 2.1 is considered for a tank diameter of D=0.6 m. To replicate the geometry of commercially distributed tanks, a scaled torispherical head (Klopper-head) DIN-28011 is located at the top and bottom part of the geometry. In order to achieve proper mixing of the hot and cold fluid, the hot air inlet of diameter l=0.05 m is located at the top-height of the tank. The system geometry consists of two bodies: the tank body and the rock-bed body which are connected by an interpolation surface.

3.3 CFD Setup

Transient simulations were carried out using ANSYS 19.02, and then post-processed in Matlab 2019b. To simulate the thermocline tank operation, a 600°C air inlet is considered using two UDF for the velocity profile which considers a velocity of v=0.1 m/s and v=0.25 [m/s] and pressure-outlet during 15 [min] and v= 0 m/s during next 20 [min] to simulate the standby/cooldown process. Considering the airflow interaction with the solid rocks, which are incomplete stagnation will produce vortex shedding, a two-equation k-omega turbulence model is selected to capture the near-wall behavior of the flow. For the fluid domain discretization, tetrahedral mesh with 5.500.000 elements is used. Near-wall regions were refined using first-layer thickness inflation to capture the boundary layer region. The solid-fluid interfaces were set with a coupled-interface condition, to consider conductive heat transfer in the common region between solid and fluid.

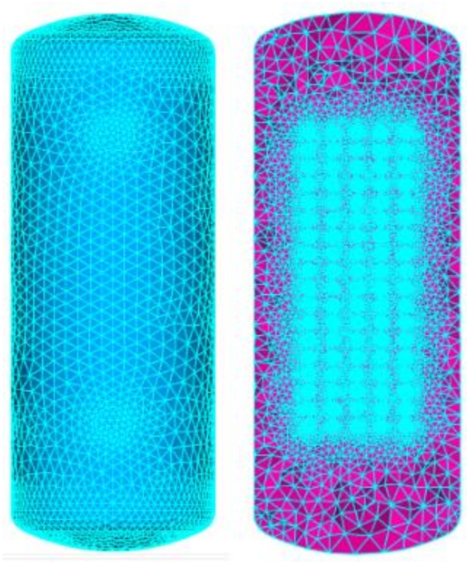

Fig.3: Tank outer mesh density (left), Tank inner mesh density (right)

The simulation time-step selected corresponds to dt=0.0005 [s] which is calculated with the smallest element size, in order to achieve a Courant number of 0.7 through each time-step to avoid numerical convergence issues.

4. Results and Analysis

4.1 *Temperature profile*

CFD simulations results are obtained under the framework described in the methodology section in order to obtain the one-dimensional temperature distribution along with the tank height. Figures 4 and 5 show the temperature profile for the tank height at different time-steps of the charging and standby phases, respectively. For the charging process, the temperature profile is obtained every 5 minutes to capture the maximum temperature gradient between hot and cold air. As Figure 4 shows, the temperature gradient for the first 5 minutes of the charging process is 45°C, which is 10% higher than the temperature gradient at 15 minutes of the charging process, which corresponds to the final time-step of the charging process. As the charging process ends, the thermal stratification process takes place during the standby phase and its temperature distribution is shown in Figure 5. The results for the standby phase shows that the cooldown process is slow until 20 minutes of the standby phase and that the temperature gradient variations are negligible during this stage. This behavior can be explained by the temperature distribution inside the spherical rocks bodies, which have interacted with the hot air inlet and are easily heated by the airflow, due to the solid's thermophysical properties. During the standby process, no hot air is being loaded to the tank, which allows the air located at the top-height of the tank, exchanges heat with the cold air mass while it interacts with the previously heated rocks (which begins to heat up the surrounding air). To capture the previously described situation, the rock-bed height is referenced in Figures 3 and 4 to locate the averaged temperature distribution inside the rock-bed. Consequently, the rock-bed region presents the most pronounced variations within the temperature profile during the end of the charging process.

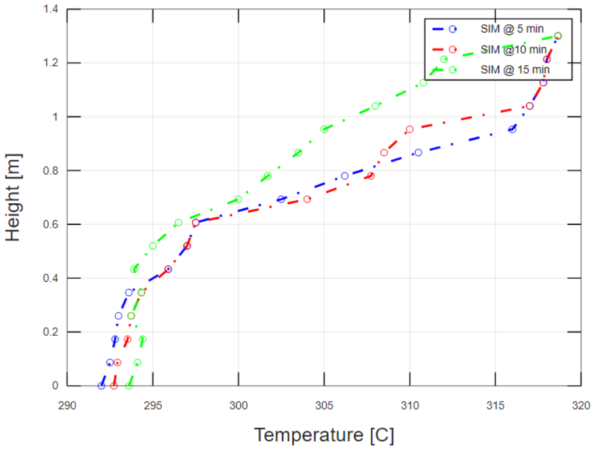

Fig. 4: Temperature distribution, charging proces, v=0.01 [m/s]s

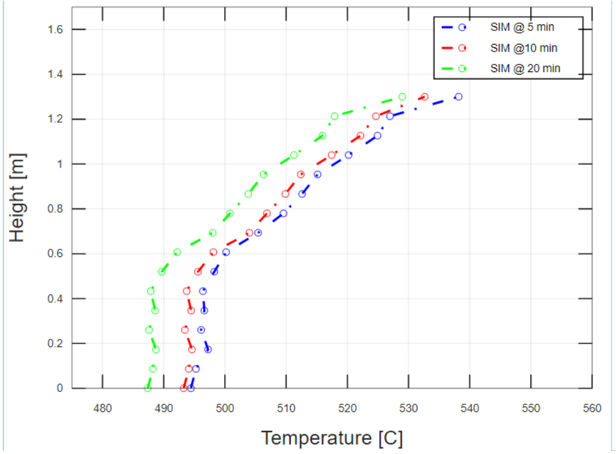

Fig. 5: Temperature distribution , standby process, v(t=900 s)=0 [m/s] for charging.

It is important to note that comparing the temperature distribution at 15 minutes of the charging process is very similar to the profile obtained after 5 minutes of the standby phase, which indicates that coupling a turbulent/buoyancy models and solvers to capture the different stages of the tank operation seems appropriate to get the expected behaviour of thermal stratification..

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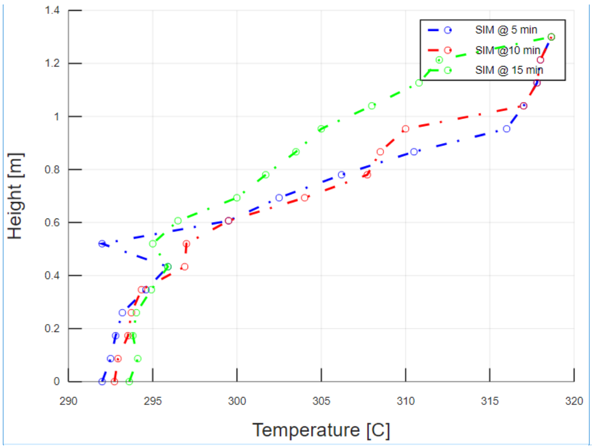

Fig. 6: Temperature profile, charging process, v=0.03[m/s].

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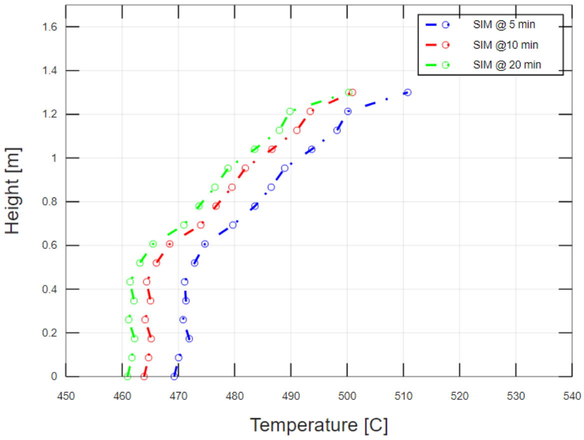

Fig. 7: Temperature profile, standby process, v(t=900 s)=0.

The temperature profile for a higher velocity airflow inlet is shown in figures 6 and 7.showing the same behavior on the thermal stratification inside the tank during the charging process. A wider temperature range can be obtained by increasing the flow inlet velocity. Nevertheless, the maximum temperature at a higher velocity inlet decreases by 5.6%.

5. Conclusions

In the present investigation, charging and cooling down processes of a thermocline tank were simulated in order to get the temperature distribution along with the air tank height. The methodology for developing the CFD model aims to capture the effects of the solid-fluid interaction effects on the temperature distribution, which allows quantifying the stratification efficiency considering the thermal behavior of copper slags within the tank. This paper considers the transient temperature profile along with the tank height as the main objective in order to lay the foundations of an exergy-based method to assess thermocline tanks with filler materials operation and optimization. The conclusions referent to the previously described results are described as follows:

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The effect of heated rocks is that the transition from cold to hot air temperature is less smooth inside the rock-bed region for the first minutes of the charging phase due to the rocks being heated up. As the CFD model considers an initial temperature of the rock bed, the temperature distribution within the rock bed has a notorious temperature gradient, which causes that the one-dimensional profile obtained has more variations due to its calculation from a three-dimensional distribution using a cell volume-average approach.

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With the proposed operation conditions, the results show to have a temperature gradient of 45°C during the charging process and having less than 7.5% of variations for the standby/cooldown process. This can be explained by the effects of the heated rock pebbles which begins to lose heat to the surrounding air. Since the rock-bed height corresponds to 40% of the tank height, this causes that most of the air mass near, and in between the rock walls, is being heated after the charging process. This also causes the cooldown process to slow down, since the air it's not immediately losing heat through the tank walls, but being heated up by the rock pebbles instead.

Although this study has not been validated with an experimental setup, the proposed CFD model seems to be suitable for simulating a charging/standby process of a tank, and its interaction with a heated rock-bed since the thermal stratification with a stable temperature gradient is achieved.

The results show that including copper slags in thermocline tanks for high-temperature applications, may improve the thermal storage systems and in consequence, the dispatchability of a concentrated solar power plant allowing to store high-temperature air with a slowed-down cooldown process. This presents a great opportunity for developing cost-effective solutions to make CSP plants more competitive in terms of energy availability and energy prices. In terms of quantifying the tank stratification efficiency, a more deep analysis of exergy destruction must be made in order to minimize the heat losses. Future works consider the assessment of stratification efficiency, based on a second-law analysis which allows quantifying the stratification efficiency based on entropy production theory. Including and exergy analysis allows us to achieve a better assessment of how thermal energy is being seized or destroyed during the tank operation.

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6. References

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