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Consecutive Operation of a Rock Bed Thermal Energy Storage - CFD Analysis

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***Abstract*— High temperature thermal energy storage units can provide the flexibility required, by storing the excess energy in the form of heat and suppling it back either into the electric grid or as heat to any energy intense industrial process. DTU Energy has constructed a vertical flow high temperature thermal energy storage unit, which uses air as a heat transfer fluid and Swedish diabase rocks as a storage medium. This storage unit can store heat at a temperature of up to 675°C and has a thermal capacity of 1 MWh$_{th}$. The main objective of this study is to present an experimentally validated 2D time dependent computational fluid dynamics model of the rock-bed thermal energy storage developed in COMSOL Multiphysics. The results show good agreement between experimental and model data. Moreover, the overall efficiency is increased when subjected to consecutive cycling.**

Keywords*— High Temperature Thermal Energy Storage (HT-TES), packed bed, rock-bed, Computational fluid dynamics (CFD), COMSOL Introduction (Heading 1)

I. INTRODUCTION

The interest of increasing renewable production has risen sharply owing to the dangers caused by the use of fossil fuels for energy production. Wind and solar energy provide a better alternative to conventional energy production techniques, but they cannot be fully utilized because of the discrepancy between renewable energy production and energy demand [1], [2]. The rock bed high temperature based thermal energy storage (HT-TES) provides a clean and cost-effective way to store the excess amount of energy [3], [4]. This can either be coupled to an electric grid to store excess renewable production and provide additional power production during low renewable production periods or to fluctuations in heat supplied to and consumed by industrial processes using commercially available technologies [5], [6].

Schumann [7] was the first to investigate the effect of a temperature step variation between the porous medium and the flowing fluid by proposing an analytical solution. Later this analytical solution was further simplified to suit a rock-bed based thermal energy storage system, which was subjected to changing inlet temperature by Shitzer and Levy [8]. They used Duhamel's theorem to calculate the temperatures of the fluid and rock-bed, and then later validated these results with experimental data.

Recently Hänchen [9] presented a 1-D transient numerical heat transfer model between rocks and air as the heat transfer fluid (HTF). This numerical model was experimentally validated, and a parametric study was performed by changing the fluid flowrate, particle size, height of the bed and rock type to evaluate the optimal conditions. The overall efficiency was found to be above 90%. Similarly, Anderson [10] also studied the thermal behavior inside an alumina filled packed bed with air as the HTF, he presents a simplified model by coupling one-equation energy model coupled with Navier-Stokes to study the temperature profile inside the packed bed. G. Zanganeh [6] analyzed an air-based rock-bed TES by means of two-phase heat transfer model, which after validating with the experimental data was scaled up to 7.2 GWh$_{th}$. The overall thermal efficiency reached 95 %.

Later S.A. Zavattoni [11] presented a 3D time-dependent computational fluid dynamics simulation model in ANSYS Fluent software. This CFD model was validated with the reference pilot scale plant and later upscaled to 80 MW to match the demand for an industrial scale CSP plant. The thermocline and the overall efficiency were analyzed under cyclic conditions. More recently, F. Marangiu [3] developed a 2D time-dependent heat transfer model of a horizontally oriented rock-bed TES in COMSOL Multiphysics software. The developed model was verified by means of experiments performed on the pilot plant after which a parametric study was performed for a number of parameters such as particle size, flow rate, particle type and insulation material. The charge efficiency was found to be in the range of 69-96%.

This paper will present a CFD model setup of a 1MWh$_{th}$ pilot plant in COMSOL Multiphysics 5.6. This model is experimentally validated against a pilot plant for a reference test case, then the validated model is later studied for four consecutive cycles of charge, rest, and discharge. This also includes a study of partial discharging of rock-bed (till 200°C) before the start of subsequent charging cycle to increase the overall efficiency. The model is also verified for three working conditions by varying the flowrate (6-hour cycle, 12-hour cycle and 24-hour cycle).

TABLE I. PHYSICAL PHENOMENON COMPUTED IN THE SPECIFIC MODEL DOMAINS

	Central Flow Hole	*Concentric flow holes*	*Rock-bed (Porous Media)*	*Shell (Insulation and Concrete)*
Physical Phenomenon	• Free and Porous media flow. (Navier Stokes Equation) • Heat Transfer in Fluids • Non-Isothermal Flow	• Free and Porous media flow. (Navier Stokes Equation) • Heat Transfer in Fluids • Non-Isothermal Flow	• Free and Porous media flow. (Brinkman's Equation) • Heat Transfer in Solids • Non-Isothermal Flow • Local Thermal non-equilibrium	• Heat transfer in solids

II. CFD MODEL SETUP

COMSOL Multiphysics 5.6 was used to perform a detailed CFD analysis of the rock bed. Owing to the hemispherical geometry (see Figure 1), a 2D axisymmetric model geometry is used. The flow conditions used during charging, resting, and discharging in COMSOL is shown in Figure 1.

The model considers five physical phenomena which are solved to calculate the time dependent solution and their domains are given in the Table 1.

The Free and Porous Media flow module solves for the flow through the porous media (Rock-bed) using Brinkman's Equation, while using Navier Stokes Equation for the free flow areas (the pipes). For heat transfer, the local thermal non-equilibrium approach is used since the temperature of the fluid and solid is not the same, especially for higher flowrates. Figure 1 shows the computational domains and the respective boundary conditions.

The model is set up in such a way that for charging the flowrate boundary condition (BC) is applied at the outer pipe and a zero pressure BC at the center pipe. For the resting period both the inlet and outlet are closed where the only heat transfer is inside the rock-bed. Finally, for the discharging the flow condition is reversed with flowrate BC at the central pipe and zero pressure condition at the outer pipe.

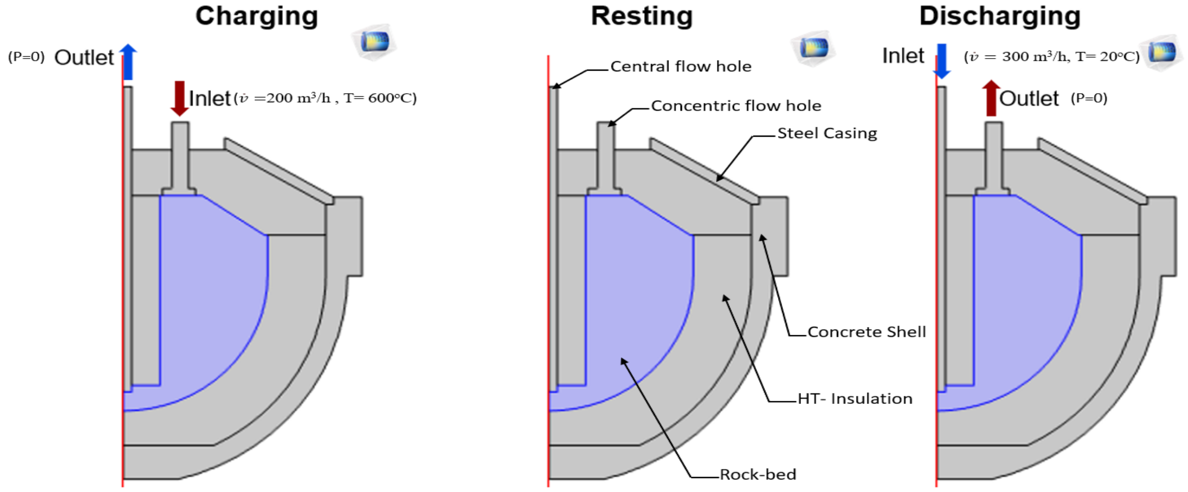

Fig. 1. CFD model geometry with labelled domains and the respective flow boundary conditions

A. Storage Material Properties:

Temperature dependent properties are considered for the storage material (rocks) and air in this study. The thermophysical properties at 500 °C are presented in Table 2. And the heat capacity is presented in the Figure 2.

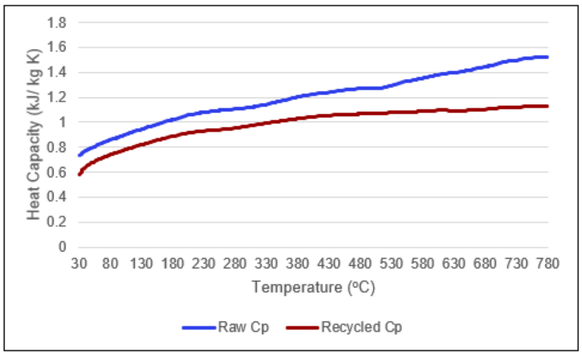

Fig. 2. Heat Capacity Cp of rock material as a function of temperature

TABLE II. THERMOPHYSICAL PROPERTIES OF THE MODELLED ROCKST AT 500 °C

Material	Density (kg/m³)	Heat Capacity (kJ/(m³K))	Thermal Conductivity (W/(m K))
Swedish Diabase	3007	3824.9	1.75

B. Heat Transfer in Porous media

For the heat transfer in the solids of the porous media, a local thermal equilibrium (LTE) between the solid and fluid can be used since the heat transfer model is designed for a macro-scale model. Here the temperatures of the porous-media matrix and the fluid flowing through it are not considered to be in equilibrium. The local thermal non-equilibrium (LTNE) approach is used, where separate energy equations will be solved for both liquid and solid phases (Eq. 1, 3) [12]. These two equations are coupled by the overall solid-fluid heat transfer, given as the first term on the right-hand side of these equations.

$$\theta_p\, C_{p,s}\, \rho_s \left(\frac{\partial T_s}{\partial t}\right) + \nabla \cdot (\, q_s) = \, q_{sf}(T_f - T_s) \quad (1)$$

$$q_s \;= -\,\theta_p\;k_s\,\nabla T_s \qquad (2)$$

$$\begin{aligned} (1-\theta_p\,)C_{p,f}\,\rho_f \left(\frac{\partial T_f}{\partial t}\right) & \\ &+ (1-\theta_p\,)C_{p,f}\,\rho_f\,u_f.\nabla T_f \\ &+ \,\nabla \cdot (\,q_f) \\ &= \,q_{sf}(T_s - T_f) \\ &+ (1-\theta_p\,)\,Q_f \end{aligned} \qquad (3)$$

$$q_f \;= -(1-\theta_p\,)\,k_f\,\nabla T_f \qquad (4)$$

The critical factor in solving the LTNE approach is the value of q_{sf}. This intestinal heat transfer is influenced by the heat transfer co-efficient (h_{sf}), the surface area (a_{sf}), and temperature difference between the solid and fluid. Dixon and Cresswell (1979) give the co-relation for a porous media which is given as follows:

$$q_{sf} = a_{sf} * h_{sf} \quad (5)$$

Where the specific surface area and overall heat transfer co-efficient are given by:

$$a_{sf} = \left(\frac{6\theta_p}{D_p}\right) \quad (6)$$

$$\frac{1}{h_{sf}} = \frac{2r_p}{Nu\, k_f} + \frac{2r_p}{\beta k_s} \quad (7)$$

Where D_p is the diameter of the particle and Nu is the Nusselt number, which can be derived by using the co-relation of spherically shaped porous bed given by Wakao and Kaguei [13]:

$$Nu = 2.0 + 1.1\,\mathrm{Pr}^{\frac{1}{3}} Re_p^{0.6} \quad (8)$$

Where Re is the Reynold number, and Pr is the Prandtl number, defined as:

$$Re = \left(\frac{d_p\, \rho_f\, u_f}{\mu}\right) \quad (9)\ (8)$$

$$Pr = \left(\frac{\mu\, c_{p,f}}{k_f}\right) \quad (10)$$

C. Flow Modelling

The flow in this study is modelled using the Navier-Stokes equation for the free flow the domains without the porous media (inside the pipes), and Brinkman's equation for the porous media flow (M.L bars et al. 2006). The overall equation for the flow is given in the Eq.

$$\frac{\rho}{\varepsilon}\left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\frac{\boldsymbol{v}}{\varepsilon}\right) = \nabla\cdot\left[-p\boldsymbol{I} + \frac{\mu}{\varepsilon}(\nabla\boldsymbol{v} + (\nabla\boldsymbol{v})^T) - \frac{2\mu}{3\varepsilon}(\nabla\cdot\boldsymbol{v})\boldsymbol{I}\right] - \left(\frac{\mu}{K} + \beta|\boldsymbol{v}|\right)v + \rho g \quad (10)$$

The equation also includes the gravity effects on the flow distribution which is given as "ρg" in the Eq.1 . One other important factor in the Eq.1 is K which is the permeability of the rock-bed. The permeability of this study is defined using the Carmen-Kozeny permeability and porosity relation, given in Eq.

$$K = \frac{\varepsilon^3}{180(1-\varepsilon)^2} D_p^2 \quad (11)$$

Where, ε is the porosity and D_p is the average diameter of the rocks. D_p is one of the most uncertain terms in the model since the rock size and shape is not uniform because the rocks are sieved within some size range. This leads to an uncertainty in the CFD model.

(5)

III. EXPERIMENTAL SETUP

The experimental packed TES system, used as a reference to validate the CFD model presented in this study, has been designed and constructed by DTU Energy. It contains 5394 kg of Swedish diabase rocks having a diameter of 8-11 mm inside a 3.2 m^3 hemi-spherically shaped steel cage, which is further covered with insulation and finally with reinforced concrete. This storage is partially buried in the ground with all the components mounted on top of the unit. Figure 3 shows the experimental setup at DTU Energy.

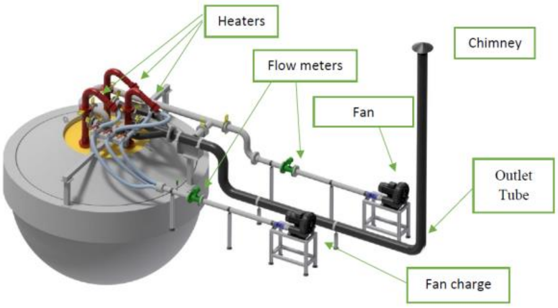

Fig. 3. CAD Model of TES unit at DTU Energy

The system presented in Figure 3 is vertically oriented; the hot air is blown into the top of the bed by the fan during charging and the cold air is blown from the fan vertically from the bottom of the rock bed during discharging. This flow direction uses the natural stratification caused by buoyancy to its advantage. The hot air blown from the top will make a flat thermocline and the cold air blown from the bottom will not destabilize the existing thermocline. This flow scheme is designed to counter the effect of buoyancy forces, which reduced the overall efficiency due to non-uniform temperature distribution in the horizontal flow rock bed [4], where the buoyancy forces will tend to transfer air to the top of the tank leaving a cold region at the bottom which will lower the overall storage efficiency

A. Reference Test Results

The reference test case used for the CFD simulation consists of a continuous charging for 24 hours at a flowrate of 200 m^3/h and heater temperature of 600^{o}C. The rock bed is equipped with thermocouples at three different radial positions R1, R2 and R3, and three axial positions at a depth of 0.3 m, 0.7 m and 1.1 m. The temperature evolution within the rock-bed during the experimentation of the standard test is shown in the Figure 4.

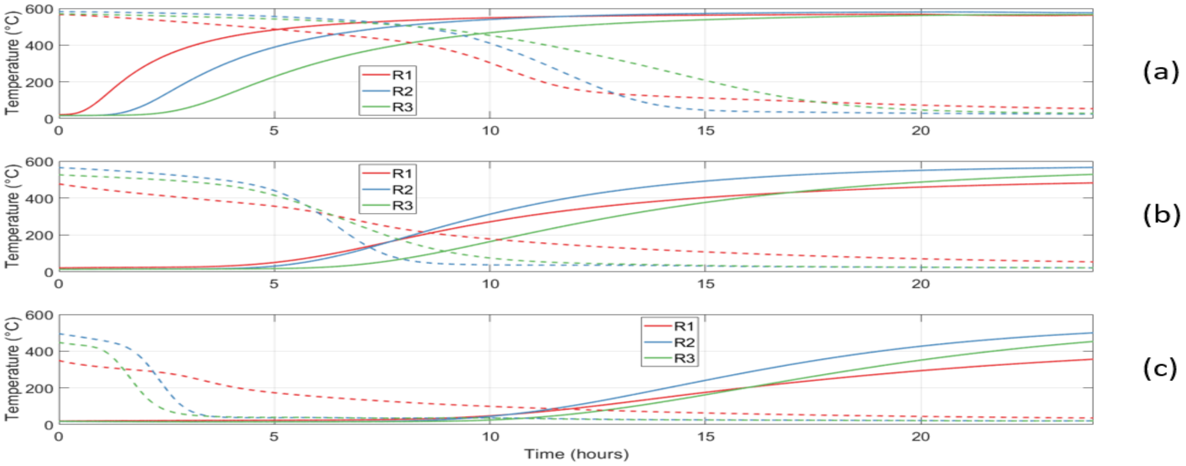

Fig. 4. Temperature evolution at the thermal probes in the rock-bed during the experiment at a depth of (a) 0.3 m, (b) 0.7 m and (c) 1.1 m. Charging is denoted by solid line at 600 °C and 200 m^3/h and discharging is denoted by dashed line at 300 m^3/h.

B. Validation of the CFD Model

The CFD model was satisfactory validated by the experimental data in this study. The thermocouples present in the rock-bed are compared to the COMSOL model at two radial positions, R2 and R3 during the charge phase at 1, 5, 10, 15 and 20 hours of charging. R2 is the center of the rock-bed going downwards and R3 is the radial position close to the outer periphery of the rock-bed.

In this analysis, a temperature with respect to time with a radial coordinate set is assumed to be equal to those considered using COMSOL. Then the model's expected temperature profile should move through the group's three temperature readings. The uncertainty was also considered and corresponds to the uncertainty as to the position of the thermocouples within the bed along the vertical direction (horizontal error bars), the uncertainty as to the temperature value reported due to the thermocouple accuracy (vertical error bars) and, finally, the uncertainty along the horizontal direction was expressed by two additional curves (dashed lines) which were the temperature readings 5 cm to the right and left of the thermocouple locations, Figure 5.

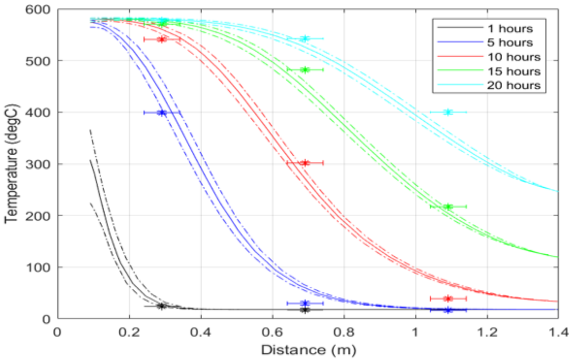

Fig. 5. Comparison of model results with the experimental data

IV. NUMERICAL ANALYSIS UNDER CYCLIC CONDITION (CHARGE-REST-DISCHARGE)

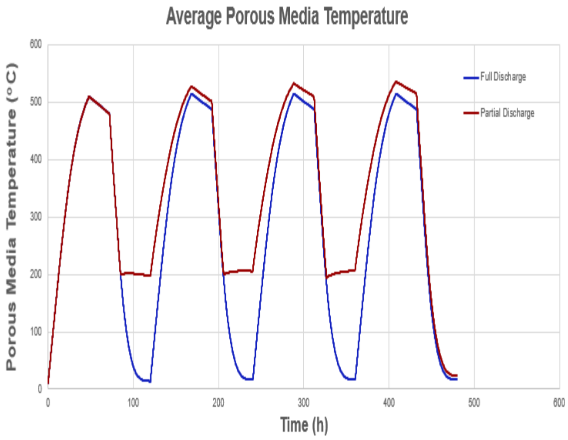

Fig. 6. Average porous media temperature of 4 consecutive cycles

The Figure 6 presents the average porous media temperature during the 4 consecutive cycles with full discharge and partial discharge. The results presented are for 48 hours of charging, 24 hours of resting and finally discharging for 48 hours. This process is then repeated for 3 more cycles. The blue line represents the cycles where continuous discharging takes place for 48 hours before the start of next cycle. Whereas the orange line represents the process where the discharging is stopped at 200°C, since the HT-TES mainly supplies the high-grade heat and rested for the remaining of the discharged time then finally starting the charge cycle along with the full discharge cycle. Here we can already see an increase in the average porous media temperature with every cycle which will yield better charge efficiency.

One other thing worth noting is that the average porous media temperature during the rest period after partial discharge increases rather than decreasing or staying constant. This is due to the residual heat in the surrounding material which flows back towards the rock-bed during this rest period. This residual heat will result in higher overall efficiency of the system which would have been wasted during full discharging.

V. NUMERICAL ANALYSIS UNDER DIFFERENT FLOW CONDITIONS

For the rock-bed to be competitive in terms of fast charging and discharging it has to be able to run shorter cycles of 6 and 12 hours. The flowrate in the pilot plant is limited to 325 m^3/h by the fans installed. After adjusting the mass flowrate of the air inlet by using the Equation () which will give the mass flow of air required to charge the rock-bed in that specific period of time and 600 °C as heater temperature, the validated model is run for shorter cycles and the results are presented in Figure 6 and 7 for respectively 6 and 12 hours charging, resting and discharging periods.

$$m_{air} = \frac{P}{c_P\left(T_f - T_i\right)} \qquad (12)$$

Where P is the heater power required to heat up the rock-bed in a specific time period.

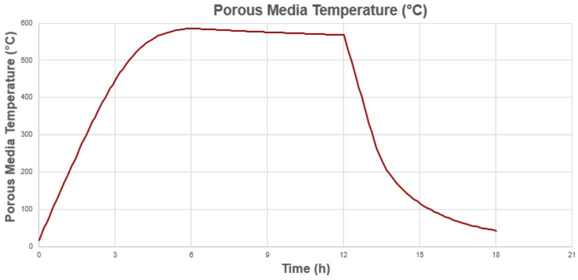

Fig. 7. Average porous media temperature for 6 hours charging, 6 hours resting and 6 hours discharging.

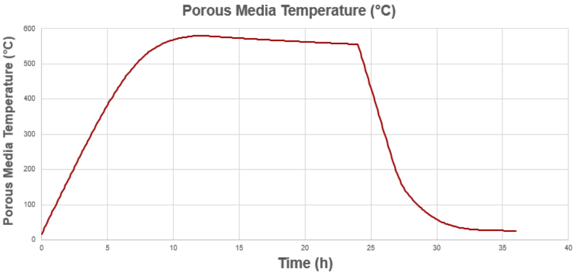

Fig. 8. Average porous media temperature for 12 hours charging, 12 hours resting and 12 hours discharging.

It is observed from the Figure 7 and 8 that the TES unit can be fully charged and discharged within shorter intervals by increasing the flow rate of air and power of heaters.

VI. CONCLUSION

This work developed a time-dependent 2D axisymmetric CFD model of a rock-bed thermal energy storage that was validated by the experimental data obtained from a 1MWh$_{th}$ pilot plant constructed at DTU Energy. Good agreement is reached between the experimental data and the data obtained from the model throughout the depth of the bed. Even with non-uniform shapes and sizes of rock, the porous heat transfer and flow model presented in this paper provides a good estimation of the thermocline inside the rock-bed.

During cycling, if the discharging is stopped at 200°C, the successive cycles will show better performances because the residual heat from the insulation migrates back to the rock-bed during the resting phase which is otherwise not utilized during full discharging and the thermocline is also observed to become flatter because of the buoyancy effect. Both these factors will tend to speed up the charging process for the subsequent cycle, which will help in increase the overall efficiency of the rock-bed. Moreover, by adjusting the mass flow and power of heaters the unit can be charged and discharged for a shorter cycle of 6 hours and 12 hours.

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