MODELING THERMAL PERFORMANCE OF BRICK GEOMETRIES IN PACKED BED ENERGY STORAGE SYSTEMS

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Abstract: This study presents the development of a model to characterise the thermal performance of brick geometries in a packed bed thermal energy storage (TES) system. The research focuses on optimising heat transfer between ceramic clay-based bricks and molten salt heat transfer fluid (HTF) in a packed bed configuration. A single-brick heat transfer model is developed, considering factors such as void fraction, channel arrangement, and brick shape. The model employs an extended lumped capacitance method to analyse heat transfer coefficients and Biot numbers for various geometries. A case study compares the thermal performance of two brick designs, demonstrating the model's ability to estimate cooling times and heat transfer rates. The flat plate design performs better with larger heat transfer and lower pressure drop. The model provides valuable insights for early-stage brick design in packed bed TES systems. This research contributes to optimising packed bed TES systems for improved thermal performance and efficiency in solar thermal energy applications.

Keywords: Packed bed, Heat transfer, Lumped capacitance, Brick Geometry, Thermal energy storage

1. Introduction

Concentrated solar power (CSP) is able to provide dispatchable energy when combined with storage. While this significantly improves the capacity factor of the CSP plant, the addition of storage introduces a large capital cost. For a 50 MWe CSP plant with 16 hours of storage, the TES system makes up about 10% of the total plant costs, of which 60% is from the molten salt [1]. A packed bed TES system is proposed wherein cheap solid filler material replaces part of the molten salt volume in the tank. The main reason for doing so is to reduce the costs associated with the molten salt. This does introduce an additional layer of complexity to the system. The molten salt flows through the packed bed during charge and discharge cycles. Heat must be transferred sufficiently fast between the packed bed and the molten salt. If this rate is too low, the heat supply from the TES will be unable to maintain the thermal demand of the power block.

2. Objective

The study aims to develop a model that quantifies the thermal performance of a given brick design. The model will calculate the heat transfer rate of a brick in a packed bed and determine the time required to heat or cool the brick fully under specific flow conditions. A case study comparing two different brick designs will be used to demonstrate the model's capabilities.

3. Methodology

A packed bed thermal energy storage (TES) system is constructed by stacking specially designed perforated bricks up to the height of the tank. The tank is then filled with molten salt, fully immersing the bed. The perforations in the bricks allow molten salt to flow through them, transferring heat between the packed bed and the molten salt. The three main parameters investigated in the model are the heat transfer rate, the pressure drop, and the cooling/heating time for the brick.

3.1. Effective heat transfer and pressure drop correlations

Flow through a pipe (perforations in the brick) is characterised by the Nusselt number (equation 1) and the pressure drop (equation 2), reported as a head loss in meters. When the molten salt enters the tank, it expands into the large flow area made up by the numerous brick perforations. This expansion causes the velocity to decrease significantly according to the Bernoulli principle. The low velocity results in laminar throughout the tank.

For fully developed laminar flow the Nusselt number in equation 1 becomes constant as it is independent of the Reynolds or Prantl numbers that characterise the flow [2]. In this study, molten salt is used as the HTF, implying that the thermal conductivity will remain constant for all the cases. The main variable influencing the heat transfer coefficient is the hydraulic diameter of the channel. A smaller hydraulic diameter will result in a larger heat transfer coefficient and a higher heat transfer rate.

Referring to equation 2, the head loss represents the additional height a fluid needs to be raised by to overcome the friction losses in the pipe [2]. This parameter is important in quantifying the pumping power needed to operate the TES system.

$$Nu = \frac{hD}{k} \tag{1}$$

- Where h is the heat transfer coefficient, D the hydraulic diameter, and k the thermal conductivity for the molten salt.

$$h_L = \frac{\Delta P_L}{\rho g} = f \frac{L}{D}\frac{V_{avg}^2}{2g} \tag{2}$$

- Where f is the friction factor, L the channel length, V_{avg} the average fluid velocity through the channel, D the hydraulic diameter, and g the gravitational acceleration.

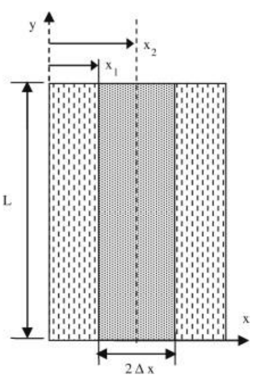

Figure 1. Model of a large plate in fluid flow. Brick material is represented by the middle grey box with fluid on either side.

The Biot number is a dimensionless parameter defined as the ratio of conduction resistance through a body to the convection resistance at its surface. When subjected to convection heat transfer at its surface, the lumped capacitance method assumes a uniform temperature throughout a body and is applicable for Bi < 0.1. Biot numbers for ceramic bricks tend to be in the order of 10 [3]. To address this, Xu et al. [4] developed effective correlations for the Biot number and the heat transfer coefficient, extending the lumped capacitance method to a Bi ≤ 100. The model implements the modification, replacing the standard heat transfer coefficient with the effective value in the lumped capacitance method. For instance, the effective heat transfer coefficient for the large flat plate is given by equation 3. Where k is the brick thermal conductivity, and x_1 and x_2 are defined as in Figure 1. Similar correlations have been developed for the other geometries.

$$\frac{1}{h_{eff}} = \frac{1}{h} + \frac{(x_2 - x_1)}{3k} \tag{3}$$

Proceeding with the lumped capacitance method, the exit temperature can be determined using equation 4. The heat transfer rate can then be determined according to equation 5. The log mean temperature, ΔT_{ln} is defined in equation 6.

$$T_e = T_s - (T_s - T_i) exp\left(\frac{-h_{eff}A_s}{\dot{m}c_P}\right) \tag{4}$$

$$\dot{Q} = h_{eff}A_s\Delta T_{ln} \tag{5}$$

$$\Delta T_{ln} = \frac{T_i - T_e}{ln\left[{(T_s - T_e)}/{(T_s - T_i)}\right]} \tag{6}$$

3.2. Estimating the packed bed cooling time

The time taken for thermal energy to be extracted from the bed needs to be equal to or shorter than the number of hours of storage for which the tank is designed. If the time is longer, the molten salt won't be able to extract thermal energy quickly enough to meet the demand of the steam generator upstream in the process. Rodriguez-Garcia et al. [5] proposed equation 7 to determine a single brick's cooling or heating time given specific flow conditions. The time can then be used to estimate the total time to cool or heat the bed. A conservative approximation is made that the bricks are cooled in succession. Thus, the time for a single brick is multiplied by the number of bricks stacked to construct the packed bed. The equation is given as:

$$hA\Delta T = \frac{(c_p\rho V)_s \Delta T}{\tau} \rightarrow \tau = \frac{(c_p\rho V)_s \Delta T}{hA\Delta T} = \frac{(c_p\rho V)_s}{hA} \tag{7}$$

- Where V is the solid volume for the brick, and A is the total heat transfer area for the brick.

The Engineering Equation Solver (EES) has been used to construct the model [6]. The model takes the brick geometry, properties, and flow conditions as inputs and returns the effective heat transfer coefficients, and associated heat transfer rate.

4. Case study: cylindrical and parallel-plate channels

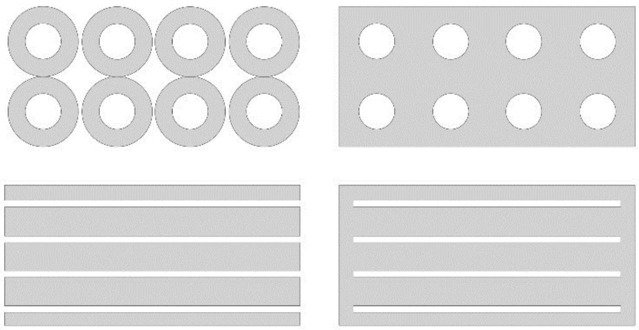

Figure 2. Bird's-eye view of the brick designs. Left: Theoretical models used for calculations. Right: Actual brick geometries approximated by the models.

The case study compares two bricks made of the same material and with the same overall dimensions. Referring to Figure 2, the first brick has cylindrical channels and the other has parallel-plate channels designed into it. The left side of the figure shows the theoretical model used for the calculations and the right side shows the actual brick it approximates. The theoretical model is necessary for the effective parameters to be applicable [4]. The brick designs are compared based on heat transfer, head loss, and cooling/heating duration. The following parameters were kept constant for the analysis.

- The inlet flow conditions to the brick.
- The void fraction: this results in the same cross-sectional area and mass flow rate for each brick.
- The material properties: clay for the bricks, and molten salt as the HTF.

Table 1 Results from the case study

Parameter	Unit	Parallel-plate	Cylindrical
D_h	mm	9.78	26.46
Q	W	2576	879.8
h_L	mm	1.24	1.74
τ	hr	3.54	21.96

Table 1 reports the hydraulic diameter (D_h) and model results. Although the flow cross-sectional area is identical for both designs, the parallel-plate design achieves a significantly higher heat transfer rate (Q) than the cylindrical design. This difference agrees with the variation in their channel hydraulic diameters. The results show a slightly lower head loss (h_L) experienced by the molten salt across the parallel-plate design, requiring less pumping power to operate the system. The cooling/heating time (τ) is also significantly shorter for the parallel-plate design than the cylindrical channel. Overall, the parallel-plate design performs better in this study.

Adding to the analysis, a packed bed TES system with dimensions of 38.5 m in diameter by 14 m in height is estimated to be able to supply thermal energy for 9 hours at a rated output of 50 MWe. The parallel-plate design's cooling/heating time meets the requirement and should theoretically be able to supply thermal energy at the required rate.

5. Conclusion

The study successfully developed a model that quantifies the heat transfer performance of a given brick design. The model provided estimates useful for comparing the thermal performance of different brick designs. These estimates assist during the early design phases of packed bed TES systems, quantifying heat transfer rates, head losses, and cooling/heating times for the bricks. These capabilities were demonstrated through a case study on a parallel-plate and a cylindrical channel brick design. The case study revealed that the parallel-plate channel design performed better in all three parameters. The results can be used to develop bricks that meet the performance requirements for packed bed TES systems and thereby create an opportunity to reduce TES system costs.

Data Availability

Data is available on request.

Author Contributions

Mu-een Khan: conceptualisation, software, methodology, validation, visualisation, writing - original draft. Stephen R. Clark: writing - review & editing. Craig McGregor: supervision, conceptualisation, writing - review & editing, resources.

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