International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 12, Number 9 (2019), pp. 1389-1393
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Estimation of Optimal Insulation Thickness for a Cylindrical Ceramic Crucible

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Abstract:

High temperature thermal energy storage (TES) systems have the capacity to achieve high thermal efficiencies due to their high operating temperatures. However, they tend to experience higher thermal losses which adversely affect their thermal cycles. This paper focuses on heat loss estimation from a TES system operating at 800 ℃, insulated in a cylindrical ceramic crucible, and the determination of the optimal insulation thickness of the crucible. Parameters affecting heat loss such as thermal conductivity of the ceramic material and convective heat transfer coefficient were simulated. It was observed that the thermal conductivity of the crucible had a greater effect on the rate of heat loss than the convective heat transfer coefficient. Furthermore, an increase in the length of the crucible increased the thermal mass of the crucible causing it to lose heat at higher rate. The deduced optimal radial thickness for the operating temperature range was 0.075 m. In conclusion, addition of more refractories beyond the optimal radius will not significantly reduce the rate of heat loss and will make the insulating crucible bulkier.

Keyword: Thermal energy storage, heat loss estimation, optimal insulation thickness, cylindrical ceramic crucible.

1. INTRODUCTION

One of the trending topics in energy storage and efficiency is how thermal energy can be captured and stored as applicable to concepts of renewable energy and waste heat recovery. [1] Thermal energy storage (TES) systems are being employed to reduce wastage by storing generated or excess heat until it is utilized. [2-3] TES systems have been reported has been reported to be one of the relatively least expensive energy storage systems having a large range of applications, from building applications (district heating, domestic hot water supply and cooking) to generation of electricity using concentrated solar power plants. [4] In addition to reducing the variance between demand and supply, TES systems also improve the thermal reliability of the system and performance of the system. [5] TES systems operating at high temperature are able to achieve high thermal efficiencies. [6] However, high temperature TES systems have the tendency to lose thermal energy at higher rates due to their elevated temperatures. Effective storage of thermal energy in the high temperature TES system is feasible if only optimal insulation exists. The insulation serves to retard the rate of flow of heat from the TES material to the environment in order to conserve the stored energy for a period. There are several insulating materials with different thermophysical properties used for different applications, nevertheless, a TES system operating at high temperatures (above 500 ℃) requires an insulating material which can withstand high temperatures during the charging process without undergoing any chemical or physical change. Also, the thermal insulating material should be inexpensive to economically justify the operation of the TES system at high temperatures.

According the Thermal Insulation Association of Canada, thermal insulation refers to materials within temperatures ranging from -75 ℃ to 815 ℃, while materials operating above 815 ℃ are called refractory. [7] Since the TES system is designed to reach a temperature of 1200 ℃, refractory was selected as the thermal insulating material because of its ability to withstand such temperatures. Due to their suitable thermal and mechanical properties, and low costs, refractories are employed in the construction of high temperature application-specific areas or surfaces such as in furnaces or boilers in order to minimize heat loss through the structure. Even when in contact with molten slag, metal and gases, refractories can withstand elevated temperatures and sudden temperature changes without undergoing physical or chemical change. These high temperatures range from 1540 ℃ for materials made from fireclay to 2800 ℃ for materials made from magnesium oxide.

The suitability of refractories for the insulation of TES systems have been investigated and different refractory materials have been reported to perform better within certain temperature ranges. [6-12] Besides selecting a suitable material for insulation, other factors to be considered in the design of the thermal insulating system include the shape, size, weight and thickness of insulation. [13]

The aim of this research is to estimate the expected heat loss from a high temperature TES system insulated in a portable ceramic crucible which will be fabricated using available refractory materials in Nigeria, and to determine the optimal thickness of the crucible.

2. MATERIALS AND METHOD

2.1. Material Selection for the Crucible

The suitability of the material for the high temperature TES system is very essential for excellent insulating properties and long operational life. Due to the upper temperature limit of the TES, availability and cost of insulating material, kaolin was selected as it is readily available especially in Nigeria. Its plasticity also allows easy fabrication of the cylindrical crucibles. Kaolin (Aluminosilicate; $Al_2Si_2O_5(OH)_4$) has been reported to withstand temperature up to 1700 ℃ while having thermal conductivity values ranging from 0.03 W/mK at room temperature to 0.3 W/mK at 1050 ℃. [14] Also, kaolin is able to maintain thermal stability at high temperature making it suitable for use in a continuous heating and cooling cycle. In addition to its insulating properties, kaolin has the advantage of resisting contamination of the material with which it comes into contact.

The thermal conductivity of kaolin can be further reduced by increasing its porosity which can be achieved by mixing it with combustible materials such as rice husks prepared like sawdust. Upon firing the clay, the fillers will burn off leaving tiny holes which will improve its insulating properties. However, care should be taken to not excessively increase the porosity so that it does not considerably affect the mechanical strength.

2.2. Computational Analysis

The rate of heat transfer from the thermal energy storage (TES) material to the cylindrical thermal insulation material by conduction and to the surrounding fluid by convection is expressed as: [15]

$$Q = \frac{T_1 - T_\infty}{R_{cond} + R_{conv}} = \frac{T_1 - T_\infty}{\frac{\ln(r_2/r_1)}{2\pi Lk} + \frac{1}{h(2\pi r_2 L)}} \qquad (1)$$

where Q is the rate of heat transfer, T_1 is the temperature of the TES material/ inner temperature of the crucible, T_∞ is the ambient temperature of the fluid surrounding the crucible, R_{cond} and R_{conv} are the conductive and convective resistances respectively, r_1 is the inner radius of the crucible, r_2 is the outer radius of the crucible, L is the crucible length/ height, k is the thermal conductivity of the insulating material and h is the convective heat transfer coefficient.

Using Microsoft Excel, the parameters in equation (1) were varied to assess their effect on the rate of heat loss from the TES material to the environment. The control values of the parameters are defined thus; the outer radius r2, of the cylindrical crucible was varied between 0.04 to 0.45 m while the inner radius r_1, was kept at a constant value of 0.04 m to determine the optimum thickness of the cylinder. The inner temperature T_1 was set to 800 ℃, which is within the operating temperature range of the TES material, while the outer temperature T_∞ was set 27 ℃ (room temperature). An arbitrary cylindrical length of 0.108 m was selected and a convective heat transfer coefficient value of 25 W/m^2K was used. The theoretical thermal conductivity value of 0.3 W/mK for kaolin obtained from [14] was used for the simulation. The critical radius of insulation of the material was also computed. Other parameters which were varied include inner temperature of the cylindrical crucible T_1 (at 200 ℃, 500 ℃ and 800 ℃), temperature of the surrounding T_∞ (at 0 ℃, 20 ℃ and 40 ℃), length of the crucible *L* (at 0.1 m and 0.2 m), thermal conductivity of the material *k* (at 0.03 W/mK and 0.3 W/mK) and convective heat transfer coefficient *h* (at 20 W/m^2K and 40 W/m^2K). When any parameter was varied, the other parameters maintained their control values.

3. RESULTS AND DISCUSSION

3.1. Simulation Results

The critical radius of insulation is a necessary parameter for determining the optimum thickness of insulation. However, the inner radius of the insulating crucible is larger than the critical radius computed for the material, therefore it is unnecessary to apply the concept. This is because, in this case, any addition of insulation will automatically result in an increase in the thermal resistance of the system. In Fig 1, the plot of the heat loss rate from the TES material to the thermal insulating material and the surrounding against the change in the outer radius of the refractory is presented. The rate of energy loss is highest when the TES system is bare and sharply declines as the thickness of the refractory increases. As insulation is added, the curve of the rate of heat loss becomes asymptotic as the heat loss rate barely changes and the system reaches a thermal equilibrium. It is evident that at higher temperature, the rate of heat loss from the TES to the refractory will be higher; thus, the inner temperature in the core the refractory crucible was reduced to check how the system would behave if the temperature of the TES material was lower. This variation is shown in Fig 2. It is seen that the rate of heat loss is significantly lower at 200 ℃ and increases as the inner temperature of the crucible is increased.

Although the rate of heat loss to the surrounding changes when the inner temperature changes, this is not the case when the temperature of the fluid surrounding the insulating crucible changes as seen in Fig 3. There is no significant change in the rate of heat loss with changes in the temperature of the surrounding. The insignificant change could be attributed to the fact that the variation in the ambient temperature simulated is not large. Thus, within the specified range, changes in ambient temperature does not contribute much to the rate of heat loss. The insignificant contribution of the variation in the ambient temperature (from 0 ℃ to 40 ℃), on the rate of heat loss depicts that the crucible can be used in tropical climates as well as during winter without modification in the design.

The effect of the variation of the height of the insulating crucible on the rate of heat loss from the TES was also checked (Fig 4). It is observed that the heat loss rate from the crucible is affected by a change in the height of the crucible. This is most likely due to an increase in the thermal mass of the crucible as its height increases. It is also observed that the height of the cylinder has a greater influence on the rate of heat loss than the change in the inner temperature of the crucible.

The thermal conductivity of the material which is one the most important parameters which determines the rate at which is transferred through the crucible to the surrounding was varied. Since the thermal conductivity of the insulator increases as the temperature of its material increases, values of kaolin at room temperature and at a temperature of 1050 ℃ were used. As expected, the rate of heat transfer is lower at the thermal conductivity value of 0.03 W/mK (Fig 5). However, the temperature of the inner core of the crucible will fluctuate between these values as it is charged and discharged, thus, the rate at which heat is conducted through the material will vary. The effect of the convective heat transfer coefficient on the rate of heat transfer is also observed. It is expected that an increase in the convective heat transfer coefficient, will result in an increased rate of heat transfer by convection. However, in Fig 6, it is observed that the effect of the changes in the convective heat transfer coefficient becomes less significant on the heat loss rate as the thickness of the cylindrical crucible increases. From the simulated result, we see that above 0.075 m outer radius, the effect of the convective heat transfer is no longer substantial. Thus, we assert that the convective heat loss no longer contributes greatly to heat loss at a radial thickness >0.075 m.

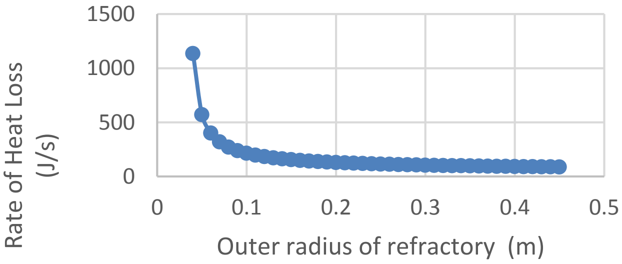

Fig 1. Variation of rate of heat loss with thickness of refractory

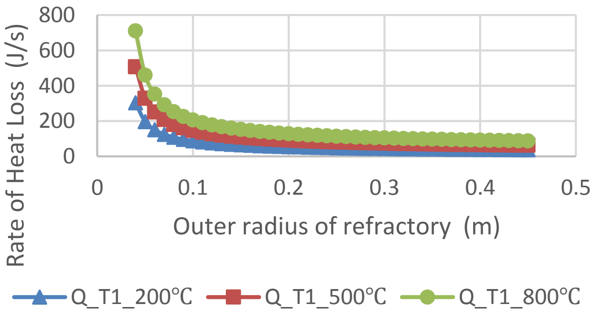

Fig 2. Effect of temperature of TES material on rate of heat loss

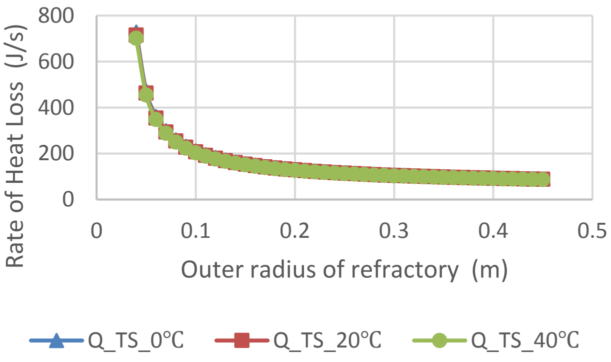

Fig 3. Effect of surrounding temperature on the rate of heat loss

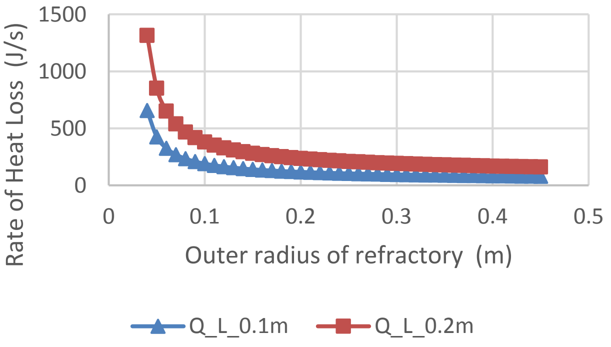

Fig 4. Effect of height of cylindrical crucible on the rate of heat loss

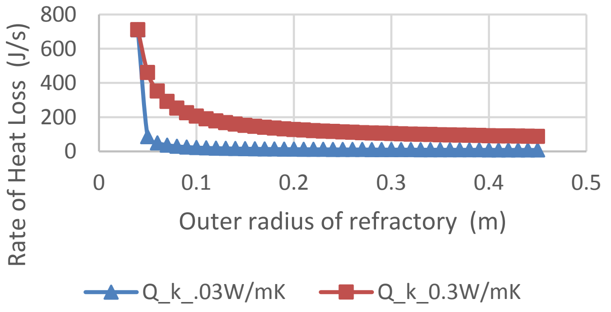

Fig 5. Effect of thermal conductivity of the crucible on the rate of heat loss

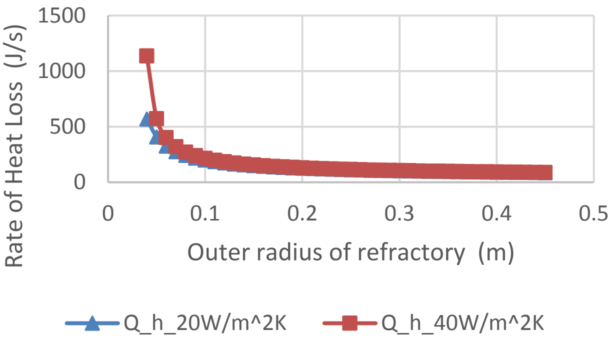

Fig 6. Effect of convective heat transfer coefficient on the rate of heat loss

4. CONCLUSION

The effects of the parameters affecting the rate of heat loss from a thermal energy storage (TES) insulator was simulated using Microsoft Excel. The optimal insulating thickness of the cylindrical ceramic crucible was determined from the simulation. Results revealed that variations in the thermal conductivity of the insulating material had the greatest effect on the rate of heat loss from the TES material and should be taken into account during the transient state (charging and discharging). It was observed that increasing the length of the crucible from 0.1 m to 0.2 m did not affect the rate of heat loss, however, it increased the thermal mass of the crucible. From the simulations, the radial thickness at which convective heat transfer becomes less effective is 0.075 m. Addition of more refractories beyond the optimal radius will not significantly reduce the rate of heat loss but will make the insulating crucible bulkier. Thus, an optimal outer radial thickness of 0.076 m was used in the design considerations of the fabricated crucibles.

Acknowledgement

The authors appreciate the Covenant University Management through the Covenant University Center for Research, Innovation and Discovery (CUCRID) for financial support.

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