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Thermal Shield Design for Molten Salt Reactors

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1. Introduction

The Molten Salt Reactor(MSR) is one of the most advanced reactor types (Generation-IV) under investigation in many countries, including the United States, Russia, and Japan [1]. The MSRE was developed at Oak Ridge National Laboratory in the late 1960s as an experimental reactor using molten salt as both coolant and fuel [2]. This reactor presents several advantages over traditional solid-fuel reactors, particularly in terms of safety and efficiency. However, effective and safe operation of MSRE necessitates appropriate thermal insulation design.

2. Thermal Shield for MSR

2.1 Molten Salt Reactor Experiment(MSRE) Design

The 8-MW MSRE operated by transferring thermal energy through high-temperature molten salt. This design leverages the high thermal conductivity of molten salt to effectively dissipate heat, distinguishing it fundamentally from solid-fuel reactor systems. Insulation objectives primarily focus on achieving minimal thermal conductivity, maximizing thermal resistance, and ensuring chemical stability. Figure 1 illustrates the thermal shield design for the MSRE, where the primary function is to mitigate radiation damage to the reactor containment vessel. According to ORNL-TM-728 [2], the thermal shield reduces neutron dosage inside the containment vessel by approximately a factor of 10^4 and attenuates the gamma irradiation by a factor of 10^3.

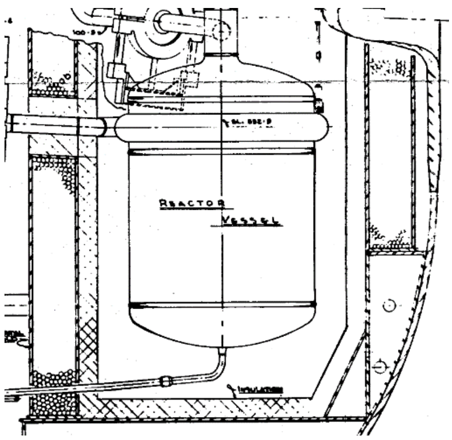


Fig. 1. Thermal Shield Design for MSRE [2]

The thermal shield is a water-cooled, steel- and water-filled container that completely encases the reactor vessel. With an exterior diameter of about 10.4 ft, an interior diameter of 7.8 ft, and an overall height of 12.5 ft, the shield features a 14-inch wide annular space filled with 1-inch diameter carbon steel balls. Through these interstitial spaces, cooling water circulates to enhance the shield's thermal efficiency. Constructed with a 1-inch thick plate, the shield maintains a thickness of 16 inches, consisting of 50% iron and 50% water. Notably, the annular space between the reactor furnace and the thermal shield wall is insulated to a built-up thickness of 6 inches.

2.2 Conductivity for Steel Materials

For the MSRE project, they chose a carbon steel- and water-filled container for the neutron shield. Because carbon material is susceptible to corrosion, we think to use stainless steel such as 316H [4] instead for a new MSR design. Thermal conductivity data of carbon steel from EN 1993-1-2 [3] and stainless steel from ASME SEC-II Part D [4] as a function of temperature are compared as shown in Fig. 2.

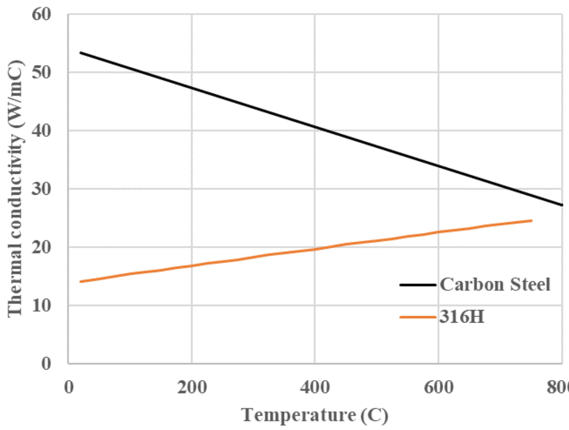
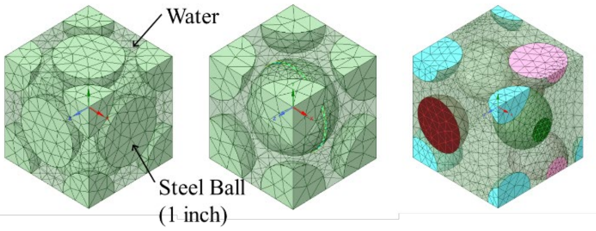


Fig. 2. Thermal Conductivity of Carbon Steel and 316H as A Function of Temperature

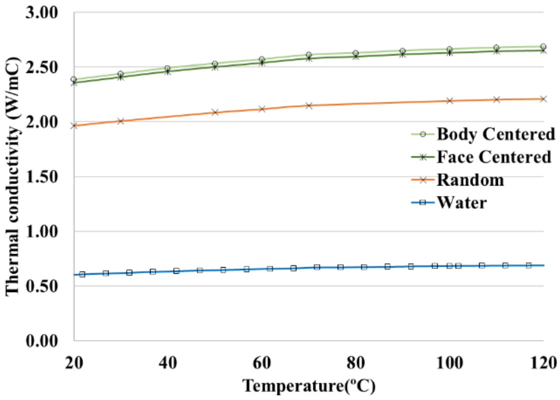
Notably, the thermal conductivity trends of the two steel materials diverge with temperature variations. Stainless steel exhibits an increase in thermal conductivity with rising temperature, whereas carbon steel demonstrates a decrease.

2.3 Conductivity for Steel and Water Filled Container

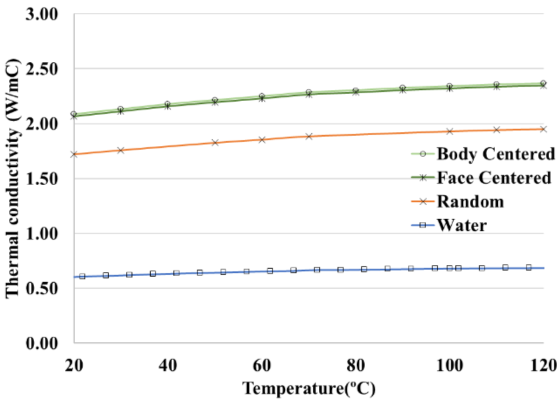
The thermal conductivity of the steel- and water-filled container can be determined based on the steel ball and water volume fraction. Figure 3 presents a numerical model of the mixed zone with a volume fraction of 0.5. Thermal conductivity modeling and calculations for the steel ball and water-filled container were conducted using the commercial software ANSYS Workbench [5]. As shown in the figure, the thermal conductivity was calculated using the Face Centered model with a total of possible 12 contacts between steel balls, the Body Centered model with a total of possible 8 contacts between balls, and the randomly distributed steel ball model.



(a) Face Centered (b) Body Centered (c) Random
Fig. 3. Comparison of Steel Ball Model



(a) Carbon Steel



(b) 316H
Fig. 4. Thermal Conductivity of Steel Ball and Water Filled Container

Figure 4 illustrates these three models considering temperature and the thermal conductivity values for water and both carbon steel and 316H. Specifically, water demonstrates the lowest thermal conductivity, referred to the literature [6]. The thermal conductivity of the Body Centered and Face Centered models are comparable, although the Random model shows reduced thermal conductivity. It is critical to note that increasing the steel volume fraction enhances thermal conductivity, with the Face Centered model (12 contacts) resulting higher thermal conductivity than the Body Centered model (8 contacts).

3. Conclusions

The thermal shield, primarily constituted of a container filled with steel and water, plays a critical role in mitigating neutron and gamma radiation damage. This study undertakes a comparative analysis of carbon steel and stainless steel with respect to their thermal conductivity properties. The findings indicate that stainless steel emerges as a potential alternative, attributed to its superior corrosion resistance. The thermal conductivity of the container is observed to be somewhat higher when filled with carbon steel balls compared to stainless steel balls. However, an increase in the volumetric fraction of steel within the container is associated with an enhancement in thermal conductivity.

ACKNOWLEDGEMENTS

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