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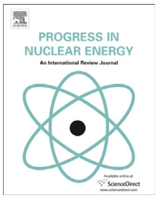

Analysis of heat source distribution in internal circulating surface heat transfer molten salt reactor

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ABSTRACT

The Molten Salt Reactor (MSR) is one of the Generation IV nuclear reactor concepts that were selected by the Generation IV International Forum in 2000. The concept is based on liquid fuel instead of solid fuel assemblies. Besides the advantages, there are several aspects of operation that can hinder the realization of this reactor concept. In this paper, the authors investigate the neutronics behaviour of a new sub-concept that offers solutions for many of the technical problems. The analysis was performed using the particle transport code MCNPX 2.7. The paper focuses on the short-term and steady state heat source distribution in the fuel salt and in the graphite moderator. Accordingly, neither burn-up effects nor reactivity transients are considered. The sensitivity of the effective multiplication factor on different geometrical and material parameters was studied. The results obtained indicate that the main region of heat deposition is in the internal and external channels of the graphite moderator. Only a few percent of the total heat power is released in the graphite moderator, where the gamma and neutron related heat deposition is on the same scale. The results also prove that the heat source distribution does not change drastically upon the actuation of the control rods.

1. Introduction

The first MSR was built at Oak Ridge National Laboratory (ORNL) during the Aircraft Reactor Experiment (ARE) in the 1950s. It operated until 1955 at approximately 2.5 MW thermal power and a maximum temperature of 860 °C (Bettis et al., 1957). Almost ten years passed until the next series of studies, i.e. the Molten Salt Reactor Experiment (MSRE) was carried out at ORNL. The MSRE reactor operated for almost five years, producing thermal power of 8 MW. The fuel was mainly $^{235}UF_4 - {}^{233}UF_4$ solved in a mixture of molten BeF_2 and LiF (LeBlanc, 2010). With the experience gathered during these two experimental programs, a new concept was designed at ORNL between 1970 and 1976. The name of the concept was Molten Salt Breeder Reactor (MSBR) and its nominal power was 1 GW_e equipped with a supercritical steam cycle. In 1976 the project was terminated because the liquid sodium cooled nuclear reactor concept seemed a more favourable alternative (MacPherson, 1985). Since then the original molten salt reactor (MSR) concept has been divided into two sub-concept groups. Reactors that belong to the first group operate with thermal neutron spectrum and have large graphite moderator blocks in their cores. Examples for this type of MSR are the liquid fuelled Japanese FUJI (Fiorina et al., 2013) and the FHR, which is a solid fuelled, molten salt cooled concept (Scarlat and Peterson, 2014; Wang et al., 2014). The reactors belonging to the second sub-concept group operate with fast neutron spectrum and have no moderator in their core. The French MSFR and the Russian MOSART concepts are examples for this type of MSR (Ignatiev et al., 2014; Ishiguro et al., 2014). There are many differences between the groups but the main attribute of the reactors, i.e. the fact that they use liquid fuel, can be observed with almost every sub-concept. The significant disadvantages of the use of molten salt as liquid fuel in reactors are the following.

i. Since the nuclear fuel has to be cooled outside the reactor core in external heat exchangers, a certain (significant) portion of the delayed neutron precursors escape from the core (Zhang et al., 2015). In transients, such as pump start-up, this can cause reactivity oscillations (Kópházi, 2010).
ii. The highly radioactive fuel salt is present not only in the reactor core but also in the entire primary circuit. Accordingly, the whole primary circuit becomes rather activated

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and therefore cannot be maintained easily due to dosimetry aspects (Kamei, 2012).

iii. Many concepts contain two molten salt loops: a primary fuel salt and a secondary salt, the latter containing no fissile material. Since there is no phase transition in the salts, the pipe-wall thickness of the heat exchangers is made rather small in order to ensure proper heat transfer between the two salt loops. Due to the highly corrosive environment, the operation time of the heat exchangers decreases significantly (Kamei, 2012).

Due to the above disadvantages (Kamei, 2012), proposes a new MSR concept called Internal Circulating Surface Heat Transfer Molten Salt Reactor (ICSHT-MSR). Although this concept does not fit the electricity generation systems used today, which are currently dominated by large scale production power plants, it may suit a decentralized energy system. The aim of this paper is to investigate the new concept, mainly with respect to the steady state heat source distribution and the global neutronics behaviour of the reactor.

2. The concept of the new ICSHT-MSR

The main difference between the ICSHT-MSR and the other MSR concepts resides in the flow of the fuel salt within the reactor core. The flow in the core of the ICSHT-MSR is natural circulation (buoyancy driven) instead of the typical forced flow of other MSR concepts. Fig. 1 shows the schematics of the new MSR concept. The core of the reactor consists of two main domains, i.e. the liquid fuel salt and the graphite moderator. The space where the molten salt flows in can be divided into three main sub-regions: the channels within the inner graphite moderator block, a peripheral channel between the inner graphite moderator block and the outer graphite reflector, and the mixing spaces over the top and under the bottom of the inner graphite moderator block.

During operation the temperature of the molten salt increases in the inner graphite channels because of the higher neutron flux and fission density. As the temperature of the salt increases, its density decreases and due to the buoyancy force it ascends to the top of the reactor. From the top mixing tank it flows into the peripheral graphite channel where it cools down and descends into the bottom mixing tank. The generated heat is absorbed by the forced gas convection outside the reactor vessel, using helium or nitrogen as coolant. There are external reflector blocks outside the vessel, which are used for reactivity control purposes. By decreasing neutron leakage, the insertion of these reflector blocks leads to increased reactivity of the system. A drain tank is also equipped below the reactor vessel for emergency situations. A gas layer is located above the molten salt volume in order to ensure that the molten salt can expand when the temperature increases. If the inner pressure exceeds a certain threshold, a fraction of the gas can be released.

Based on the different thermal-hydraulics and neutronics behaviour (Kamei), proposes four different configurations for this MSR concept. Fig. 2 shows the vertical cross-section of the core of these reactor configurations with designations of dimensions, while the parameters of the different configurations are listed in Table 1.

Paper (Kamei, 2012) mentions only one fuel salt composition, which is 71.76 LiF, 16 BeF_2, 12 ThF_4, 0.24 UF_4 in mol %. This composition melts at 772 K and boils at 1703 K. The reactor is designed for a thermal output of 2.2 MW_{th}, while the electric output of the equipped gas turbine can be around 1 MW_e (this corresponds to almost 40% overall efficiency). With its small electricity output it could supply a few households in a decentralized energy system.

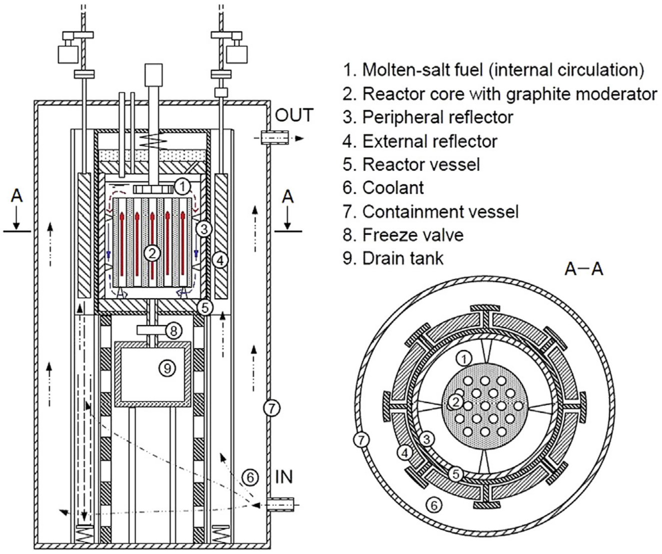

Fig. 1. Schematics of the ISCHT-MSR (Kamei, 2012).

3. Computational models and results

The first step of the feasibility study was the calculation of the effective multiplication factor of different configurations. Based on the results, one configuration was selected for further investigation. The next steps were the sensitivity study of the effective multiplication factor and the investigation of the heat source distribution that was essential for further CFD calculations.

3.1. Effective multiplication factor (k_{eff})

The MCNPX model consists of one quarter of the reactor due to symmetry considerations. On the boundary where quarters of the reactor would normally connect, reflective boundary conditions were given. The authors investigated the effective multiplication

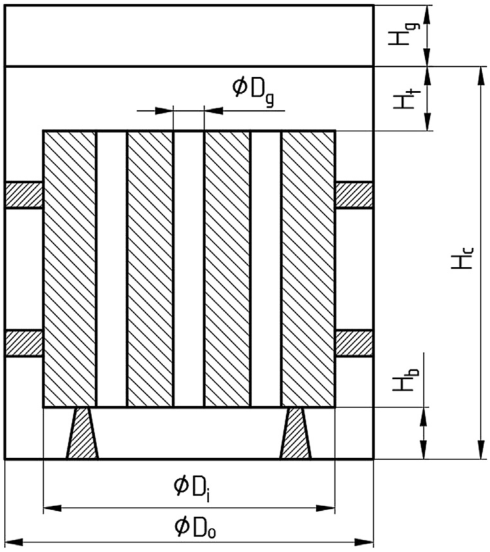

Fig. 2. Schematic vertical section of the ISCHT-MSR core with designations of dimensions.