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Technical note

Design parameters in an annular, prismatic HTGR for passive decay heat removal

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ABSTRACT

We studied the capability of an annular, prismatic HTGR to remove decay heat passively. The purpose of the study was to obtain the design parameters relationship of the annular, prismatic HTGR with passive decay heat removal depending on power density profile and to compare them with those for solid cylinder one. The results showed that the safety feature of the annular reactor is improved a lot compared with that of cylinder one. The safety margin could be increased further by flattening the power density profile. Then fundamental neutronic analysis was performed for the annular reactor whose design parameters are obtained from the condition.

1. Introduction

Reactor design idea which does not rely on the active safety system for reactor safety condition is growing up. This idea or reactor design idea with passive safety system is one of the main features for new generation IV reactor concepts. High-temperature gas-cooled reactors (HTGRs) as base of the very high temperature reactor (VHTR) concept have several inherent safety features such as high-integrity of coated fuel particles (CFPs) up to 1873 K, high-heat-capacity graphite core and support structures and inert helium coolant. Furthermore it is said that the integrity of the CFPs are highly dependent on the following safety functions to be assured: core heat removal, control of heat generation and limitation of chemical corrosion. Among those functions the most important one is successful removal of core heat after reactor shutdown (Hicks et al., 2011; Kroeger, 1990; Hayashi et al., 1989).

In our previous papers, we studied the dependence of design parameters of solid cylinder HTGRs which can remove decay heat by passive ways (Odmaa and Obara, 2014, 2015a,b, 2016). This relationship was restrained by design limits of the fuel and structural temperatures and the capability of the reactor to remove decay heat was limited only by the passive ways considering three main mechanisms as thermal conduction, radiation and convection. The severest condition was assumed for the previous papers in which all cooling systems including active and passive ones were completely lost their performance due to natural disaster.

In this paper, we extended the research by choosing the annular cylinder, prismatic HTGRs in which the fuel blocks at the core center region are replaced by graphite blocks. Since there is no heat source in inner reflector for annular cylinder core and graphite has high heat capacity, some amount of heat in core could be transferred into the inner graphite reflector during operation and after shutdown. Therefore, it is expected that the safety feature of the annular HTGRs would be improved due to the maximum fuel temperature of the core is reduced. Then, by taking into account the above advantage of the annular core, it is possible to enhance the reactor power. So, in the present work we have studied the capability of an above-ground, annular, prismatic HTGR to remove decay heat passively by obtaining quantitative relationship between reactor design parameters. The power density profile throughout reactor core is considered as flattened or unflattened. The purpose of the present study is to reveal the impact of inner reflector on the annular cylinder reactor safety feature by confirming the reduction of the maximum fuel temperature of annular cylinder core, to obtain the design parameters relationship of an above-ground, annular, prismatic HTGR with passive decay heat removal depending on power density profiles and to compare them with those for solid cylinder, prismatic HTGR. Therefore, fundamental neutronic

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analysis for the annular reactor whose design parameters are obtained from the condition was performed to confirm its long-term operation without refueling and its higher fuel burnup.

2. Design concept

We studied the design of solid cylinder HTGR with passive decay heat removal in our previous works (Odmaa and Obara, 2014, 2015a,b, 2016). The reactor core designs in previous and present works are based on the Japanese prismatic HTTR as a reference (Saito et al., 1991, 1994; Shiozowa et al., 2004; Evaluation of HTGR Performance, 2003). The general layouts of the both solid and annular reactor designs are illustrated in Fig. 1a and b respectively. Here other compartments of the design except core with reflector are the same with these for the solid cylinder reactor. In solid cylinder reactor, the core has only outer reflector as shown in Fig. 1a while annular core has both inner and outer reflectors as in Fig. 1b. Compartments in both reactor are the same as those being in HTTR. As illustrated in Fig. 1, the decay heat transfers through the solid structural domains by heat conduction mechanism and through air domains by thermal radiation. Finally, the heat is dissipated through the air on the reactor building wall by both outside natural convection and thermal radiation. Table 1 compares the dimensions of the HTTR with thermal power of 30 MW_t (Saito et al., 1991, 1994; Shiozowa and et al., 2004; Evaluation of HTGR Performance, 2003) and both the reference designs of solid cylinder and annular reactor with thermal power of 200 MW_t and average power density of 0.82 W/cm^3. The reference design for solid cylinder reactor shown in Table 1 was chosen for our previous paper (Odmaa and Obara, 2016) and in this work, we have chosen the annular cylinder reactor with the same thermal power and average power density for comparison of results to be obtained in this work.

In our previous works (Odmaa and Obara, 2014; Odmaa and Obara, 2016) the decay heat transfer analyses were performed for both types of prismatic and pebble bed HTGRs to choose the optimal ratio of core radius and height by comparing the obtained the peak core temperatures after shutdown for the same power reactors with different ratio and without changing the core volume. The ratio of radius to height corresponded to the highest peak core temperature is considered as the worst one which was between 0.46 and 0.55 depending on reactor power and core temperature at shutdown. So, for barrel type of solid cylindrical prismatic and pebble bed HTGRs, the optimal ratio of core radius and height was chosen as 0.4 and kept this ratio for the future analyses for parametric conditions in order to reduce the number of considerable parameters on comparison of similarity or difference between the conditions for annular and solid cylindrical reactors. So, the same ratio of core radius and height as 0.4, the same materials for the corresponding domains, and the same physical characteristics of region materials applied in previous works (Odmaa and Obara, 2014, 2015a,b, 2016) are used in the decay heat transfer calculations in the present work.

3. Methodology

As mentioned in introduction section, it is expected that the safety feature of annular cylinder reactor would be improved because of existence of inner reflector since graphite has high heat capacity. In order to study the impact of the inner reflector on passive decay heat removal feature of the annular cylinder reactor, we conducted the reactor design analyses in which the methodology for decay heat transfer was analogous to those performed in previous works (Odmaa and Obara, 2014, 2015a,b, 2016). The heat transfer analyses was based on fundamental heat transfer phenomena using the natural laws of physics and all calculations were performed using the heat transfer module of COMSOL multiphysics software (COMSOL AB, 2015). Previously, the several studies on core heat transfer analyses for MTHGR (Seker et al., 2012) and Pebble bed Reactor (Peter, 2013) as well as hot channel thermo-hydraulic analyses for prismatic and pebble bed type of HTGR (Irwanto and Obara, 2013; Triniruk and Obara, 2014) were performed using Comsol multiphysics software.

As illustrated in Fig. 1, the residual decay heat in the core after reactor shutdown is transferred from the core through solid structural walls by heat conduction mechanism as #3. Between solid domains, the regions are occupied by the air and the heat transfers through those gaseous domains by thermal radiation as #2 in Fig. 1. So, the surface-to-surface radiation boundary condition between structural walls was used. Finally, the heat was considered to be removed by external natural convection as #1 in Fig. 1 and thermal radiation from the reactor building wall for an above-ground reactor. From the reactor building bottom, the heat transfers through the soil by the conduction #3 in Fig. 1. From

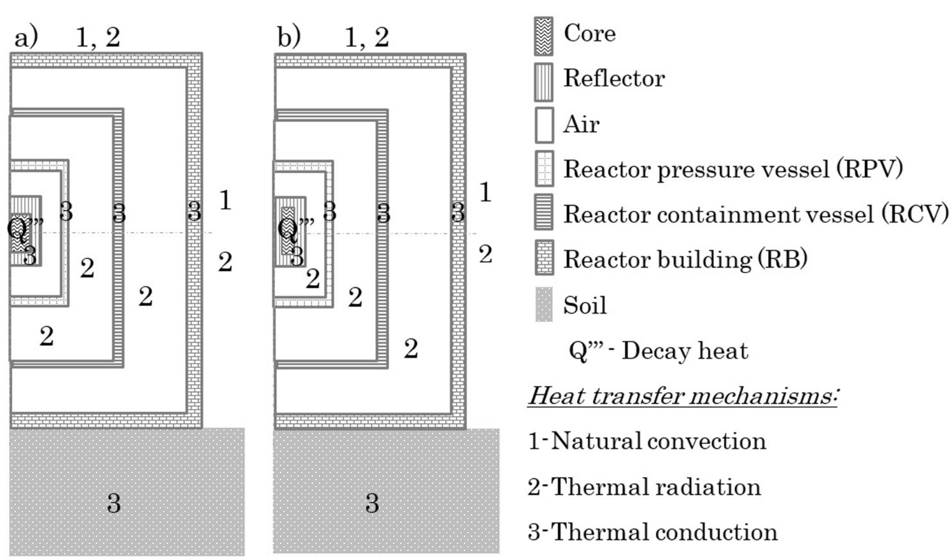

Fig. 1. Basic compartments of a reactor with decay heat transfer mechanisms. a) Solid cylinder core, b) Annular cylinder core.