Annals of Nuclear Energy 71 (2014) 11–22

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Thermal analysis of prismatic gas-cooled reactor core under coolant channel blockage accidents

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ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 12 March 2014
Accepted 19 March 2014
Available online 13 April 2014

Keywords:
Very high temperature gas cooled reactor
Coolant channel blockage
1-D thermal/flow analysis code
Prismatic block reactor

ABSTRACT

Limited results of studies on coolant channel blockage accidents in a prismatic-gas cooled reactor core are available, although coolant channel blockage of the fuel block in a prismatic gas-cooled reactor has been regarded as a highly important phenomenon. In this study, therefore, intensive and extensive thermal analyses were carried out to enhance the understanding and knowledge about the thermal performance of multi-hole type prismatic fuel blocks under coolant channel blockage accidents. A series of thermo-fluid calculations were performed using the CORONA code. In contrast to existing works, a full core model was used to consider an accurate coolant flow redistribution after the blockage in this work. The results of the CORONA calculations show that the single channel blockage accidents of PMR200 are not a safety concern regardless of the location. However, the maximum fuel temperature exceeds the safety limit in the case of more than ~10 channel blockage at the same region of the fuel column. It was also found that the selection of the computational domain is crucial. A full core analysis is required for accurate results in the case of severe blockage accidents.

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1. Introduction

A prismatic gas-cooled reactor is a promising reactor concept in national research programs such as the High Temperature engineering Test Reactor (HTTR) project of Japan (Ogawa and Nishihara, 2004), the Next Generation Nuclear Plant (NGNP) project of the U.S. (Idaho National Lab., 2010) and the Nuclear Hydrogen Development and Demonstration (NHDD) project of Korea (Chang et al., 2007). One of the most favorable characteristics of a prismatic gas-cooled reactor is its inherent and passive safety. To achieve the reactor safety, the heat removal capability has to be maintained to guarantee the integrity of fuel under all postulated accident scenarios.

Among the various postulated accident scenarios, the present work focuses on an accident from a blockage of the fuel block coolant channel. A fuel block coolant channel blockage may occur from debris in a prismatic core. There exists a significant uncertainty of the mechanical stress of any graphite component in a prismatic core. Moreover, the strength of the components changes with the neutron irradiation, temperature, and creep strain. The combination of these factors may result in local graphite failure, graphite spalling, and possible blockage of a fuel block coolant channel. It is also possible that flow to the coolant channels can be severely disrupted by unexpected materials, such as thermal insulation, entering the core upper plenum and blocking a wide region of coolant hole entrances. Special attention has to be paid to the fuel temperature in the case of coolant channel blockage accidents since the fuel temperature may significantly rise and exceed the design limit owing to the local loss of forced convection. The increase in the fuel temperature from a severe coolant channel blockage may result in a local failure of the fuel particle coating and release of fission products to the coolant.

Therefore, the coolant channel blockage accident is regarded as one of the important phenomena of a prismatic gas-cooled reactor. In spite of its importance, little research has been carried out around the world. It should be noted that in the report on a Phenomena Identification and Ranking Table (PIRT) published by U.S. Nuclear Regulatory Commission (2008) for the NGNP, the blockage of a fuel block coolant channel was identified as a high importance rank with a low corresponding knowledge level.

General Atomics (1992) described a coolant channel blockage accident scenario in the safety analysis document of a Modular High-Temperature Gas-Cooled Reactor (MHTGR). However, no quantitative analysis results were reported for this scenario in this document. On the other hand, Japan selected a coolant channel blockage of a fuel element as one of the design-basis accidents in the safety evaluation of the HTTR. An experimental test for a fuel

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http://dx.doi.org/10.1016/j.anucene.2014.03.022
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Nomenclatures

A	flow area (m^2)
Cp_f	fluid heat capacity
Cp_s	solid heat capacity
D_h	hydraulic diameter (m)
f	friction coefficient
g	gravity ($m\,s^{-2}$)
k_s	thermal conductivity of solid ($W\,m^{-1}\,K^{-1}$)
Nu	Nusselt number
P	pressure ($kg\,m^{-1}\,s^{-2}$)
Pr	Prandtl number
q'''_{gen}	heat source ($W\,m^{-3}$)
q'''_{conv}	heat transfer by convection ($W\,m^{-3}$)
Re	Reynolds number
T_f	fluid temperature (K)
T_s	solid temperature (K)
t	time (s^{-1})
w	z-direction velocity (m/s)
z	axial position (m)

Greek

θ	angle (degree)
ρ_f	fluid density ($kg\,m^{-3}$)
ρ_s	solid density ($kg\,m^{-3}$)

block coolant channel blockage accident was performed using a large-scale facility called a Helium Engineering Demonstration Loop (HENDEL) (Miyamoto et al., 1995). In addition, Maruyama et al. (1994) analyzed the thermo-fluid behavior of HTTR fuel blocks under a channel-blockage accident using their own codes, FLOWNET/TRUMP. A single column of pin-in-hole type fuel blocks was considered in the analysis. Although only one coolant channel blockage was assumed in HTTR, a temperature peak of 1653 °C, was predicted at the fuel compact surrounded by the blocked channel.

An analytical study on the coolant channel blockage accident of multi-hole type fuel blocks can be found in the paper of Cioni et al. (2006). They applied a Computational Fluid Dynamics (CFD) code to analyze a severe blockage of coolant channel accidents in multi-hole type fuel blocks. Seven fuel columns (i.e., single blocked fuel column surrounded by six unblocked columns) were considered for the CFD analysis. It was assumed that 23% of the helium channels (=24 channels) in a central fuel column are blocked. Their result shows a dramatic temperature rise with a peak value of 1925 °C (which is not acceptable for the TRISO particle integrity) at the fuel compact in the blocked region. They also emphasized the importance of the blockage location based on the preliminary sensitivity calculation.

As the PIRT study for the NGNP indicated a low knowledge level on coolant channel blockage accidents in a prismatic gas-cooled reactor, the two existing studies are not sufficient to understand the phenomena related with the accidents. For example, it is obvious that the consequence of the coolant channel blockage accidents depends highly on the number of coolant channels blocked as well as the location of the blockage. However, the existing studies do not provide sufficient information about such impact on the fuel temperature.

In this study, therefore, intensive and extensive thermal analyses are made to enhance the understanding and knowledge about the thermal performance of multi-hole type fuel blocks under coolant channel blockage accidents. A series of thermo-fluid calculations were carried out using the CORONA code (Tak et al., 2012), which is a specialized computer program for a prismatic core. In contrast to existing works (i.e., single column or seven column analyses), full core analyses were performed to consider an accurate coolant flow redistribution after the blockage in this work.

2. Numerical model

Fig. 1 shows the reactor core of the PMR200 (Prismatic Modular Reactor with 200 MW thermal power). Based on the design concept of a gas turbine-modular helium reactor (GT-MHR) of General Atomics (1996), PMR200 has been pre-conceptually designed by the Korea Atomic Energy Research Institute for the NHDD project (Jo et al., 2008). The annular active core consists of 66 fuel columns. Six fuel blocks are stacked to form a column in the active core. The fuel blocks used for the PMR200 are shown in Figs. 2 and 3. In the prismatic gas-cooled reactor, coated fuel particles called TRISO are bonded together with a carbonaceous matrix into rod-shaped fuel compacts, which are stacked in the fuel holes of hexagonal graphite blocks. The hexagonal graphite blocks contain 204 holes for fuel compacts as well as 108 flow channels for helium coolant. The heat generated in the fuel compacts is conducted through the graphite block and is finally cooled down by the convective heat transfer of the coolant. As shown in Figs. 2 and 3, the geometry of the solid is too complex to apply a one-dimensional approximation. However, the geometry of the coolant channels is so simple that one-dimensional approximation can be reasonable. Therefore, the CORONA code solves the three-dimensional heat transfer equation for a solid like a CFD code. For a fluid flow, however, a one-dimensional flow assumption is applied. Such a combination enables significantly reduced computational efforts with reasonable computational accuracy.

The governing equation within a solid heat transfer is:

$$\frac{\partial}{\partial t}(\rho_s Cp_s T_s) + \Delta\cdot(-k_s\nabla T_s) = q'''_{gen} \tag{1}$$

For a fluid flow, on the other hand, the following one-dimensional conservation equations for the continuity, momentum, and energy are used.

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial(\rho_f wA)}{A\partial z} = 0 \tag{2}$$

$$\frac{\partial(\rho_f w)}{\partial t} + \frac{\partial(\rho_f w^2 A)}{A\partial z} + \frac{\partial P}{\partial z} + \rho_f g\cos\theta + f\frac{\rho_f w|w|}{2D_h} = 0 \tag{3}$$

$$\frac{\partial(\rho_f Cp_f T_f - P)}{\partial t} + \frac{\partial(\rho_f wACp_f T_f)}{A\partial z} - q'''_{conv} = 0 \tag{4}$$

To combine the heat transfer between solid and fluid, the convective heat transfer correlation is adopted. Because the convective heat transfer is dominant compared to radiative heat transfer during normal operation, the convective heat transfer between the block faces is only considered in the present study. The present work uses one of the most popular correlations for a prismatic gas-cooled reactor core (McEligot et al., 2006).

$$Nu = 0.021Re^{0.8}Pr^{0.4} \tag{5}$$

For a blocked coolant channel, it was assumed that a convective heat transfer is not completely available and the heat is only transferred through conduction. The detailed mathematical formulation of the CORONA code can be found in Tak et al. (2012).

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