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Preliminary experiment design of graphite dust emission measurement under accident conditions for HTGR

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HIGHLIGHTS

- A theoretical analysis is used to predict the total graphite dust release for an AVR LOCA.
- Similarity criteria must be satisfied between the experiment and the actual HTGR system.
- Model experiments should be conducted to predict the graphite dust resuspension rate.

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ABSTRACT

The graphite dust movement behavior is significant for the safety analyses of high-temperature gas cooled reactor (HTGR). The graphite dust release for accident conditions is an important source term for HTGR safety analyses. Depressurization release tests are not practical in HTGR because of a radioactivity release to the environment. Thus, a theoretical analysis and similarity principles were used to design a group of modeling experiments. Modeling experiments for fan start-up and depressurization process and actual experiments of helium circulator start-up in an HTGR were used to predict the rate of graphite dust resuspension and the graphite dust concentration, which can be used to predict the graphite dust release during accidents. The modeling experiments are easy to realize and the helium circulator start-up test does not harm the reactor system or the environment, so this experiment program is easily achieved. The revised Rock'n'Roll model was then used to calculate the AVR reactor release. The calculation results indicate that the total graphite dust releases during a LOCA will be about 0.65 g in AVR.

1. Introduction

High-temperature gas cooled reactors using graphite as the structure material and helium as the coolant have the inherent safety features and are being extensively considered as a Generation IV advanced reactor (U.S. DOE, 2002). There is far more graphite in the reactor core than fuel and control rod material (Luo et al., 2010; Yu and Yu, 2010). However, contact with the fuel elements and wear of the graphite components results in graphite dust during normal reactor operation. The graphite dust can affect the reactor operation (Moormann, 2008; Humrickhouse, 2011) with large particles deposited on the bottom of the reactor vessel influencing the fuel elements motion, while small particles flowing with the helium gas in the primary loop of the reactor and depositing on the primary loop surfaces and in dead flow zones, would make maintenance and repair difficult (Lind et al., 2010). Graphite dust will also be deposited on the steam generator surfaces would reduce the heat transfer efficiency. Moreover, the graphite dust is radioactive in HTGR. During an HTGR loss of coolant accident (LOCA), the helium gas and graphite dust mixture would leak through the break at a high speed, which would carry the radioactive graphite dust particles into the environment. Therefore, the graphite dust movement in the helium gas during an HTGR accident is important because the graphite dust release during a depressurization accident is an important part of the source term in the HTGR safety analyses.

The movement of graphite dust in the primary loop of the HTGR includes dust generation, diffusion, deposition and resuspension. Some previous research has concentrated on some specific aspects such as dust generation and analysis of the dust diameters (Cogliati and Ougouag, 2008; Cogliati et al., 2011; Luo et al., 2004, 2005; Boddu et al., 2011; Hiruta et al., 2013; Rostamian et al., 2012;

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Nomenclature

a	length between two contact points (m)
F(t)	aerodynamic force acting on the particle (N)
F_L	lift force acting on the particle (N)
F_D	drag force acting on the particle (N)
$f_{res,d}$	dust resuspension fraction of during a LOCA (%)
$f_{res,s}$	dust resuspension fraction during the fan start up modeling experiment (%)
$f_{res,d}$	dust resuspension fraction during the depressurization modeling experiment (%)
M_{tot}	total dust release during a LOCA (kg)
M_{dep}	mass of deposited dust that can be resuspended during a LOCA (kg)
N^b_{dust}	mass concentration of dust in the primary loop during a LOCA (kg/m^3)
N_{dust}	mass concentration of dust in the primary loop for normal operating conditions (kg/m^3)
N^s_{dust}	mass concentration of dust during the actual helium circulator start-up experiment in HTGR (kg/m^3)
r	particle radius (m)
u^*	friction velocity (m/s)
u_m	mean velocity of fluid (m/s)
V_{tot}	total volume of helium in the primary loop (m^3)
V_{He}	volume of leaking helium (m^3)
p	resuspension rate constant

Greek letters

ρ	density (kg/m^3)
ν	kinematic viscosity (m^2/s)

Subscript

exp	experimental conditions
HTGR	HTGR conditions

Rostamian et al., 2013; Troy et al., 2012; Troy et al., 2015; Shen et al., 2015, 2016) or the movement including deposition, diffusion, coagulation and resuspension (Peng et al., 2013b, 2014, 2016; Giang and Sudarshan, 2015; Gutti and Loyalka, 2009; Barth et al., 2013; Simones and Loyalka, 2015; Kissane et al., 2012; Jayaraju et al., 2016).

During a depressurization accident, the graphite dust deposited on the surfaces of the primary loop is resuspended by the rapidly changing flow field and again mixed with the helium gas. However, there are few studies of the graphite dust motion during a depressurization accident.

The graphite dust release in the HTR-MODULE during a LOCA was predicted by the SIEMENS/Interatom Corporation (INTERATOM, 1988). An enveloping predicted result of 1 kg of graphite dust was assumed to leak from the reactor. However, it did not provide the theoretical or calculation basis for the prediction.

A graphite dust release experiment for LOCA conditions was planned by Juelich (Fachinger et al., 2008; Verfondern et al., 2012; Gottaut and Krüger, 1990) when the AVR reactor was about to be retired but not carried out ultimately. Instead, fan-speed start-up experiments in the helium circulator were conducted. The graphite dust deposited in the AVR reactor primary loop was kicked up by the accelerated helium gas with the graphite dust concentration in the helium gas in primary loop reaching 1000–2000 μg/m^3. The experiments showed that the graphite dust deposited on the primary loop surfaces had fairly strong transferability. The changing flow conditions easily resuspended the dust deposit into the helium because of the changing flow shear stresses.

Sawa et al. (1992) analyzed the graphite dust movement during a depressurization accident to verify the assumption that the dust resuspension rate is proportional to the flow shear rate. The experiments showed that the shear ratio was not sufficient to describe the dust behavior and the linear model did not accurately describe the graphite dust movement during a depressurization accident but that more parameters should be included in the model.

Peng et al. (2013a) experimentally studied the resuspension of graphite dust during depressurization. The research showed that the resuspension fraction increased with increasing initial pressure with good agreement with the predictions of the revised Rock'n'-Roll model by Biasi et al. (2001).

In summary, previous studies of the graphite dust movement in the HTGR have concentrated mainly on the dust generation, particle characteristics, deposition, diffusion and resuspension for normal conditions. However, there is little research on the graphite dust movement during a depressurization accident, especially to predict the total graphite dust release. Nuclear reactors are quite complex, so LOCA experiments cannot be conducted on actual reactors; therefore, accurate modeling experiments are needed. A theoretical analysis and experimental models are established here to predict the total graphite dust release for an HTGR accident conditions and the revised Rock'n'Roll model by Biasi et al. (2001) is then used to calculate the AVR reactor release.

2. Problem description

2.1. The graphite dust distribution in the HTGR

The graphite dust in the HTGR primary loop mainly consist of dust deposited on the primary loop surface and dust flowing in the helium gas.

2.1.1. Dust deposited on the primary loop surfaces

During operation, fine graphite dust from the fuel elements and graphite components deposits on the surfaces of many components in the primary loop because of gravity, Brown diffusion, turbulent diffusion and thermophoresis deposition. The total amount of deposit dust increases with time and the adhesive force between the dust and the components also increases. According to Fachinger et al. (2008), some of the deposit dust adheres firmly to the components as shown in Fig. 1 and is nearly impossible to resuspend for any conditions. However, there is also some dust with weaken adhesive forces that can be resuspended during a LOCA due to the rapid velocity changes of the helium flow in the primary loop because of sharp fall in the pressure.

AVR reactor had 50–60 kg dust at the end of the reactor life. Moormann (2008) estimated the dust generation rate from the AVR data due to abrasion to be about 5 kg/yr. Thus, the rate in a pebble-bed HTGR with a similar structure would be about 0.1 kg/MWt·yr. On-line measurement on AVR reactor showed that the graphite dust concentration in the primary loop was only 5 μg/m^3 (Verfondern et al., 2012), which indicates that the total amount of dust flowing in the helium in primary loop is quite small with most of the dust deposited on the primary loop surfaces.

When a LOCA happens, the flow shear forces change dramatically due to the changes in helium's flow field, so some of the dust deposited on the components would be resuspended and again