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Investigation of NACOK air ingress experiment using different system analysis codes

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ABSTRACT

Air ingress into to the core after the primary circuit depressurization due to large breaks of the pressure boundary is considered as one of the severe hypothetical accidents for the high temperature gas-cooled reactor (HTR). If the air source and the natural convection cannot be impeded, the continuous graphite oxidation reaction along with the formation of burnable gas mixtures resulting in the corrosion of the fuel elements and the reflectors might damage the reactor structure integrity and endanger the reactor safety. In order to study the effects of air flow driven by natural convection as well as to investigate the corrosion of graphite, the NACOK (Naturzug im Core mit Korrosion) facility was built at Jülich Research Center in Germany. A complete 2A-rupture of the coaxial duct in the HTR primary system, as well as the chimney effect caused by breaks in both upper and lower parts of the pressure boundary was simulated in the test facility. Several series of experiments and the related code validations (TINTE, DIREKT, THERMIX/REACT, etc.) have been performed on this facility since the 1990s. In this paper, the latest NACOK air ingress experiment, carried out on October 23, 2008 to simulate the chimney effect, was preliminarily analyzed at NRG with the SPECTRA code, as well as at INET, Tsinghua University of China with the TINTE code. The calculating results of air flow rate of natural convection, time-dependent graphite corrosion, and temperature distribution are compared with the NACOK test results. The preliminary code-to-experiment and code-to-code validation successfully proves the code capability to simulate and predict the air-ingress accident. In addition, more research work, including parameter sensitivity analysis, modeling refinement, code amelioration, etc., should be performed to improve the simulation accuracy in the future.

1. Introduction

Air ingress accident, which will result in graphite oxidation reaction of fuel elements and reflectors so as to weaken the structural strength, damage the graphite structure integrity of the core bottom, impact retention capacity of coated particle and produce the flammable gas mixtures, is considered as one of the severe hypothetical accidents for the high temperature gas-cooled reactor (HTR).

The heterogeneous chemical reactions between graphite and oxygen include:

Complete oxidation

$$C + O_2 \rightarrow CO_2 \quad \Delta H = -394\,\text{kJ/mol}$$

Incomplete oxidation

$$2C + O_2 \rightarrow 2CO \quad \Delta H = -222\,\text{kJ/mol}$$

Boudouard reaction

$$C + CO_2 \leftrightarrow 2CO \quad \Delta H = 171\,\text{kJ/mol}$$

The main homogenous reaction referring to the air ingress accident is:

$$2CO + O_2 \rightarrow 2CO_2 \quad \Delta H = -564\,\text{kJ/mol}$$

With low steam content in the gas mixture, the effect of the following reactions can be almost ignored:

Water gas reaction

$$H_2O + C \Leftrightarrow H_2 + CO \quad \Delta H = 131\,\text{kJ/mol}$$

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Water shift reaction

$$H_2O + CO \Leftrightarrow H_2 + CO_2 \quad \Delta H = -41.6\,\text{kJ/mol}$$

The mass transfer and diffusion play important role in the reaction rate between the gas and the porous graphite. Accordingly, the chemical reaction could be divided into the following three types:

I. *CR* (*chemical regime*) *at low temperature*
The reaction rate is very slow, the gas transfer process in the graphite can be neglected and the reaction takes place in total graphite homogeneously.

II. *IPDR* (*in-pore diffusion controlled regime*) *at middle temperature*
The gas transport process cannot be neglected. The porous diffusion and chemical reaction both determine the gas convection rate.

III. *BLDR* (*boundary layer diffusion controlled regime*) *at high temperature*
The chemical reaction takes place at the graphite boundary and the boundary layer diffusion determine the corrosion rate.

The temperature range for above three reaction types are approximately as follows:

CR: <500 °C
IPDR: 500–900 °C
BLDR: >900 °C

The graphite/gas reaction characteristics are described as shown in Fig. 1 (Moormann et al., 1982).

The NACOK (Naturzug im Core mit Korrosion) facility was built at Jülich Research Center in Germany to study the oxidation behavior of graphite blocks with air flow driven by natural convection (chimney effect) in the event of a complete rupture of the coaxial duct or a tube break in the HTR primary system.

This paper presents a preliminary analysis performed to investigate the NACOK air ingress experiment carried out on October 23, 2008 (Nissen et al., 2008), which simulates the chimney effect and studies the corrosion of graphite blocks with two different geometries and types. A detailed simulation model of this NACOK facility was developed at NRG with the SPECTRA code and at INET, Tsinghua University of China, with the TINTE code. The calculations were performed to validate those codes for the HTR air ingress scenarios.

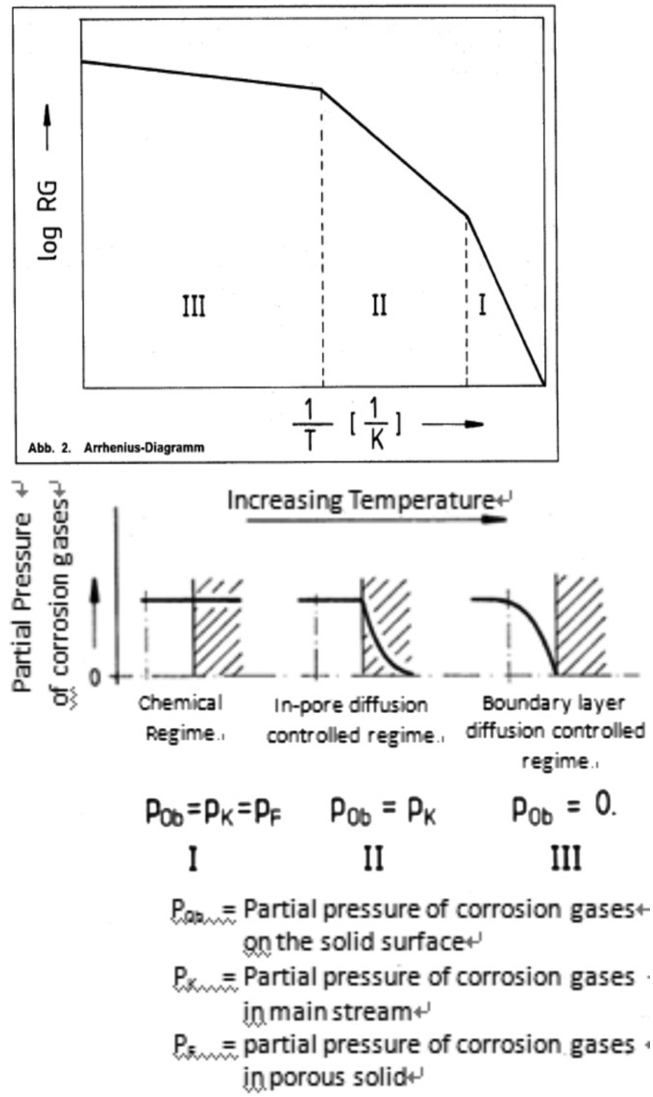

Fig. 1. Graphite/gas reaction characteristics.

2. NACOK facility

The overall experimental arrangement of the NACOK facility is shown in Fig. 2 (Nissen et al., 2008). The inner diameter of the horizontal inlet tube is 0.125 m. During the open chimney test, the return tube is unavailable, and the air can flow out from the top of the experimental channel. The experimental channel, with a cross section of 30 cm × 30 cm and a height of more than 8 m, can be heated up to 1200 °C by electric heaters with a maximum power of about 150 kW.

To provide an appropriate pressure drop, a packed bed of 0.3 m high, filled with small (10 mm) ceramic spheres, is placed in the upper part of the main channel. In the lower part of the main channel, three levels of graphite blocks are installed, as shown in Fig. 3 (dimensions are given in mm).

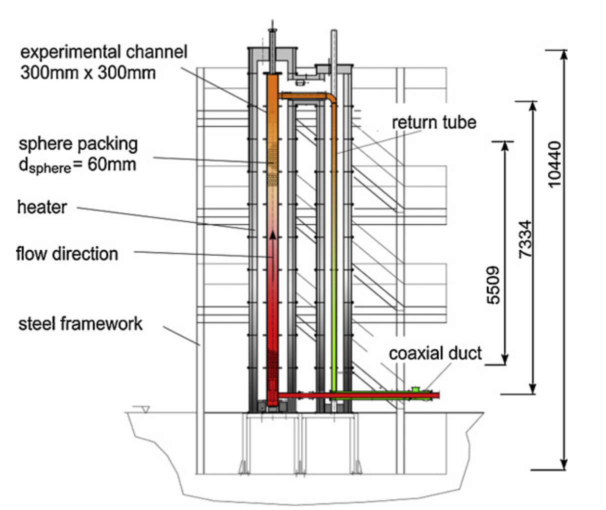

Fig. 2. NACOK test facility.

Each graphite block is 0.3 m high. To study the influence of geometry and material type on the reaction rate, two geometries