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Code validation of a scaled-down DRACS model in RELAP5/SCDAPSIM/MOD 4.0

Hsun-Chia Lin [a,b], Qiuping Lv [a,c], Shanbin Shi [a,b], Xiaodong Sun [a,b,*], Richard Christensen [a,d], Graydon Yoder [e]

[a] Nuclear Engineering Program, Department of Mechanical and Aerospace Engineering, The Ohio State University, 201 W 19th Avenue, Columbus, OH 43210, USA
[b] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, 2355 Bonisteel Blvd, Ann Arbor, MI 48109, USA
[c] Argonne National Laboratory, 9700 Cass Ave, Lemont, IL 60439, USA
[d] Department of Nuclear Engineering, University of Idaho,1776 Science Center Drive, Idaho Falls, ID 83402, USA
[e] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

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ABSTRACT

Direct Reactor Auxiliary Cooling System (DRACS) is a passive safety system proposed for Fluoride-salt-cooled High-temperature Reactors (FHRs). Benchmark study of decay heat removal capability of DRACS by natural circulation is critical for FHR safety analysis. Two scaled-down test facilities, a low-temperature DRACS test facility (LTDF) and a high-temperature DRACS test facility (HTDF), were designed following a scaling analysis and constructed to investigate thermal performance and heat removal capability of the DRACS. The LTDF uses water as a surrogate coolant for both the primary and DRACS loops. Two transient scenarios were carried out in the LTDF, namely, DRACS startup and primary coolant pump trip. In both of the scenarios, the experimental results demonstrate sufficient heat removal capabilities of the DRACS with natural circulations established in the system. These two scenarios were simulated using RELAP5/SCDASIM/MOD4.0 code and the code simulation results show good agreement with the LTDF experimental data. For the HTDF, molten salts FLiNaK and KF-ZrF_4 are used respectively as the primary coolant and DRACS coolant. Thermodynamic and transport properties of FLiNaK and KF-ZrF_4 were implemented into RELAP5/SCDAPSIM/MOD 4.0. Simulations of transient scenarios in the HTDF were also performed and the code results will be compared with the HTDF experimental data once available.

1. Introduction

Fluoride-salt-cooled High-temperature Reactor (FHR) is one of the advanced reactors that combines improved technologies including low-pressure fluoride salt coolant, coated tristructural-isotropic (TRISO) particle fuel, Brayton power cycle, and passive safety systems. These features provide advantages including increased thermal efficiency, low operation pressure, high core power density, and high safety characteristics (Forsberg, 2005; Bardet et al., 2008). One of the major safety systems proposed for FHRs, Direct Reactor Auxiliary Cooling System (DRACS), is capable of removing decay heat passively. The DRACS was originally developed for Experimental Breeder Reactor II (EBR-II) (Roglans et al., 1993) and has been widely adopted in pool-type reactors, e.g., Sodium Fast Reactors (SFRs) and FHRs (Zhang et al., 2009; Forsberg et al., 2003). In the DRACS, three natural circulation/convection loops are coupled through two heat exchangers, namely, the DRACS Heat Exchanger (DHX) and Natural Draft Heat Exchanger (NDHX), which enable decay heat removal from the reactor core to the ambient air. The performance of decay heat removal in such a system is significantly affected by the designs of both the DHX and NDHX. Fluidic diode that is utilized as a passive flow controller is another key component in the DRACS. The functionality of the fluidic diode limits parasitic heat loss into the DRACS during reactor normal operation, while it ensures a sufficient decay heat removal capability when the reactor is shutdown during accidents.

To support the FHR development and licensing, it is critical to investigate, both experimentally and numerically, the DRACS thermal performance and scalability for developing an optimum DRACS design and ensuring reactor safety under accident conditions (Holcomb et al., 2009). The primary objectives of this study are to perform a code validation of RELAP5/SCDAPSIM/MOD 4.0 on the DRACS thermal performance and to analyze the establishment of natural circulation flows in the DRACS. RELAP5/SCDAPSIM/MOD 4.0 was chosen for this study over other system analysis codes

* Corresponding author at: Department of Nuclear Engineering and Radiological Sciences, University of Michigan, 2355 Bonisteel Blvd, Ann Arbor, MI 48109, USA.
E-mail addresses: hsunlin@umich.edu (H.-C. Lin), xdsun@umich.edu (X. Sun).

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primarily due to its flexibility of implementing thermophysical properties of various molten salts, and heat transfer and friction factor correlations for salts (Allison et al., 2016). The authors at The Ohio State University (OSU) and University of Michigan (UM) have access to the source code. Based on a prototypic DRACS design for a 20-MWth test FHR, two scaled-down DRACS test facilities were designed following a detailed scaling analysis to study the thermal performance of the DRACS, including the natural circulation/convection flow during transients, and heat exchanger testing for FHR applications (Lv et al., 2015a,b; Lv et al., 2016a,b; Chen et al., 2015; Chen et al., 2016). A low-temperature DRACS test facility (LTDF) that uses water as a surrogate to molten salts and a high-temperature DRACS test facility (HTDF) that uses molten salts, namely, FLiNaK and KF-ZrF_4, as the primary and DRACS coolant salts, were constructed at OSU. An extensive test matrix was developed for the LTDF and experiments were carried out accordingly. The experimental results confirmed the establishment of natural circulation flows and sufficient capability of removing the decay heat in the LTDF (Lv et al., 2016a,b). In addition, a computer code written in MATLAB was developed for analyzing the thermal performance of the HTDF. The simulation results by the MATLAB code showed good agreement with the HTDF design values (Lv et al., 2015a).

To perform numerical analyses for FHRs using a system-level analysis code, Davis (2005) implemented the thermophysical properties of four molten salts, namely, FLiBe, FLiNaK, $NaBF_4$-NaF, and NaF-ZrF_4, into the RELAP5-3D/ATHENA code. The implemented salt properties, including the salt thermodynamic and transport properties as a function of temperature were obtained from Williams (2006). Two more molten salts, KF-ZrF_4 and KCL-$MgCl_2$, were also studied by Anderson and Sabharwall (2012) for system code implementation. In this study, we chose RELAP5/SCDAPSIM/MOD 4.0 as the system-level analysis tool to develop accurate numerical models for both the LTDF and HTDF. Necessary implementation of heat transfer correlations for the DHX and NDHX, and molten salt thermophysical properties for the HTDF was carried out. Heat losses were considered in both of the RELAP5 LTDF and HTDF models.

2. Experimental facilities

2.1. Low-temperature DRACS facility

The LTDF was built, following a detailed scaling study, to investigate the passive decay heat removal performance by natural circulation/convection (Fig. 1) (Lv et al., 2015b; Lv et al., 2016a,b). Pressurized (10 bar) distilled water is used as a surrogate to molten salt in the primary loop and distilled water near the atmospheric pressure is used as the working fluid in the DRACS loop (i.e., the "secondary" loop in the LTDF). Three electric cartridge heaters, each rated at 2 kW, are used to simulate the core heating in the primary loop. These 1.0-m long heater rods with stainless steel 304 (SS304) sheath are vertically oriented and arranged in a triangular pattern. The water in the primary loop is pressurized to eliminate any potential of water boiling on the heater rod sheath surface. A pump is installed in the primary loop to drive the flow prior to a transient that would lead to the shutdown of the reactor and the initiation of the natural circulation flow in the primary loop. In addition, a fluidic diode simulator is used in the LTDF, in which two ball valves provide two distinctively different flow resistances in the two opposite flow directions (i.e., very large flow resistance in the upward flow direction but significantly smaller flow resistance in the downward direction). Two heat exchangers in the LTDF, namely, the DHX and NDHX, transfer heat from the primary coolant, i.e., pressurized water to the ambient air. Their design parameters are summarized in Table 1 (Lv et al., 2016a,b).

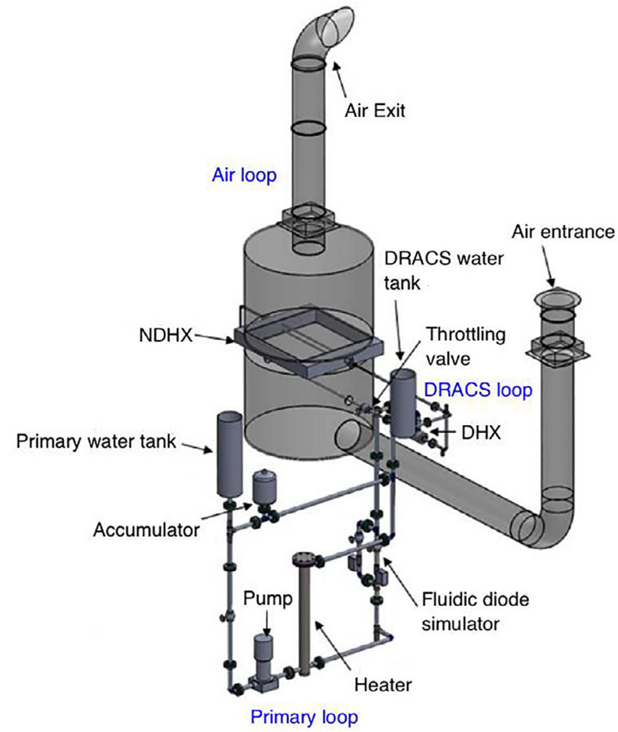

Fig. 1. Three-dimensional layout of the LTDF (Lv et al., 2016a,b).

Table 1
Design parameters of the DHX and NDHX in the LTDF (Lv et al., 2016a,b).

Item	Specification	Value
DHX	Heat exchanger type	Shell-and-tube
	Tube outer diameter (mm)	9.525
	Tube thickness (mm)	1.118
	Tube Number	80
	Pitch to diameter ratio	1.208
	Tube length (m)	0.3556
	Shell inner diameter (m)	0.127
	Baffles number and baffle cut	4 and 25.8%
	Material	SS316
NDHX	Heat exchanger type	Finned tube bundle
	Tube outer diameter (mm)	15.875
	Tube thickness (mm)	0.889
	Tube Number	52 (in 2 rows, 26 per row)
	Pitch to diameter ratio	2.4
	Tube length (m)	0.9906
	Fin height (mm)	12.065
	Fin thickness (mm)	0.254
	Fin spacing (mm)	2.54
	Material	Copper tube + Aluminum fin

In the LTDF, T-type thermocouples, ultrasonic flow meters, and a thermal mass flow meter are used to measure the fluid temperatures, water flow rates (for both the primary and DRACS loops), and air flow rate, respectively. The measurement uncertainties (including both the systematic uncertainties associated with the instruments and the random uncertainties associated with the measured data) of the fluid temperatures, primary water, DRACS water and air mass flow rates are estimated as ±0.5 °C, ±0.0089 kg/s, ± 0.0033 kg/s, and ± 0.01 kg/s respectively, with a 95% confidence level (Lv et al., 2016a,b).

2.2. High-temperature DRACS facility

The overall structure of the HTDF is similar to the LTDF, but the coolants in the primary and DRACS loops are FLiNaK and KF-ZrF_4, respectively (see Fig. 2). Seven electric cartridge heaters are used