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Analyses of decay heat removal tests with PRACS and DRACS of a sodium loop using the NETFLOW++ code

Hiroyasu Mochizuki

Laboratory for Advanced Nuclear Energy, Institute of Innovative Research, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

HIGHLIGHTS

- Sodium experiments using PRACS and DRACS are analyzed by the plant system code.
- Heat transfers emerged during low flow rate conditions are taking into account.
- Inter-subassembly heat transfer and heat transfer in the lower plenum of IHX are considered.
- Air flow rate in the air cooler estimated using heat balance is compared to calculated result.
- Channel flow rates in different subassemblies during DRACS operation are calculated.

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ABSTRACT

The present paper describes the analyses of decay heat removal transients conducted at a sodium facility PLANDTL. The objective of the present analyses is to confirm whether the 1-D NETFLOW++ code can simulate the natural circulation induced in the PLANDTL when a decay heat removal system is operated. The facility has 7 simulated fuel assemblies, one primary heat transport system (HTS) with a primary reactor auxiliary cooling system (PRACS), a direct reactor auxiliary cooling system (DRACS) and an air cooler to remove decay heat, secondary HTS and its cooling system with an air cooler. Two representative tests among several natural circulation tests to confirm interactions between each loop and the PRACS or the DRACS are selected for the code validation experiments. Decay heat removal systems with the PRACS and the DRACS are discussed for the next generation fast breeder reactor in Japan instead of the intermediate reactor auxiliary cooling system (IRACS) provided in the “Monju” reactor. Good agreement was obtained between the test results using the PRACS and the DRACS and the calculated results when two important thermal-hydraulic models specific for low flow rate conditions are used together with common thermal-hydraulic models.

1. Introduction

The fast breeder reactor (FBR) ‘Monju’ with three loops has a reactor auxiliary cooling system with an air cooler (AC) in each secondary heat transport system (HTS). This system for decay heat removal is called the intermediate reactor auxiliary cooling system (IRACS). It was demonstrated that this system could remove decay heat without any problem in the function test at Monju (Miyakawa et al., 2005). This system cools the reactor core via piping of the secondary and primary HTSs during the turbine trip test at 40% electric power (45% thermal power) which was one of the startup tests. While, a pool-type FBR has a direct heat exchanger (DHX) of the direct reactor auxiliary cooling system (DRACS) in the reactor vessel. Although this system has piping from the DHX to an AC, this system has an advantage in terms of safety compared to the IRACS because the DHX is in the reactor pool. In this context, it has been discussed that the DRACS should be deployed other than the primary reactor auxiliary cooling system (PRACS) or the IRACS in the future Generation-IV FBR in Japan, i.e., Japan Sodium-cooled Fast Reactor (JSFR). Although the PRACS will be deployed on the primary side of the intermediate heat exchanger (IHX), the IHX is connected by a large primary piping to the reactor vessel in case of a loop-type FBR. Therefore, the function of the decay heat

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Acronyms and abbreviations: AC, air cooler; CFD, computational fluid dynamics; DHX, direct heat exchanger; DRACS, direct reactor auxiliary cooling system; FBR, fast breeder reactor; HTS, heat transport system; IHX, intermediate heat exchanger; IRACS, intermediate reactor auxiliary cooling system; JSFR, Japan Sodium-cooled Fast Reactor; PLANDTL, Plant Dynamics Test Loop; PRACS, primary reactor auxiliary cooling system; SA, subassembly.

E-mail address: mochizuki.h@lane.iir.titech.ac.jp

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Nomenclature

A_b	surface area of a pipe in between fins (m^2)
A_f	surface area of a fin (m^2)
A_o	imaginary outside surface area at the bottom of a fin (= $\pi d_o l$)(m^2)
A_T	total surface area (= $A_b + A_f$) (m^2)
B	projected tube perimeter (m)
C_V	characteristic value of valve (–)
d	pipe diameter (m)
d_e	heat transfer equivalent diameter (m)
G	mass velocity (kg/m^2 s)
g	gravitational acceleration (m/s^2)
H	fin height (m)
h	heat transfer coefficient or average heat transfer coefficient (W/m^2 K)
h_o	heat transfer coefficient defined by an imaginary surface at the bottom of a fin (W/m^2 K)
I	modified Bessel function of the first kind
K	modified Bessel function of the second kind
k	thermal conductivity (W/m K)
L	perimeter (m)
l	effective tube length (m)
N	number of tubes
Nu	Nusselt number = $h\ d_e/k$
Pr	Prandtl number = $C_p\ \mu/k$
Q	heat transfer rate (W)
Re	Reynolds number = $v\ d_e/\nu$
r	thermal resistance by fouling (m^2 K/W)
T	temperature (K)
U	over-all heat transfer coefficient (W/m^2 K)
u	non-dimensional number (–)
v	velocity (m/s)
y	half thickness of a fin (m)
ΔT_m	logarithmic mean temperature difference (K)
ζ	loss coefficient (–)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
Θ	valve opening (–)
ϕ	efficiency (–)

Subscripts

a	air
b	bottom
e	equivalent
f	fin
h	heater
i	inlet
p	primary
s	secondary
t	tube or temperature
T	total
o	outlet or outside

removal would be lost in the case of a pipe break accident. Only the DRACS has an advantage not to lose the function of the decay heat removal during a large pipe break accident. Coolability of these systems should be evaluated in the design stage in advance. Tests of thermal-hydraulic interactions between the primary, secondary HTSs and a decay heat removal system were conducted using the Plant Dynamics Test Loop (PLANDTL). This loop had 7 simulated fuel assemblies, a PRACS, a DRACS and an AC to remove decay heat, a secondary HTS and its cooling system with a main AC. Test results were reported by Momoi et al. (1996). Although this sodium loop was small compared to the real fast reactor, the test results are very precious and useful to validate the code capability.

Many kinds of decay heat removal experiments with the PRACS or the DRACS have been conducted using the PLANDTL. The DHX of the PRACS is provided at the top of an intermediate heat exchanger (IHX), and the DHX of the DRACS is provided in the upper plenum of the core as shown in Fig. 1. Due to the different positions of the DHXs for the decay heat removal systems, various interesting thermal-hydraulics could be observed compared to the case of the IRACS. Nishimura et al. (2000) investigated inter-wrapper flow caused by the cooled sodium from the DHX of the DRACS.

Up to now, the one-dimensional system code NETFLOW++ has been developed by the author (Mochizuki, 2010) in order to calculate various transients in whole plant systems that use water, heavy water or liquid metal such as sodium, lead, or lead-bismuth as coolant material, and been validated for the HTSs with water or sodium together with the turbine system. Since the above-mentioned data are applicable to validate functions of models incorporated in the NETFLOW++ code, the applicability of the code to thermal-hydraulic simulations under the natural circulation of sodium systems with various auxiliary cooling systems can be discussed in the present paper. The RELAP5-3D code (The RELAP5-3D© Code Development Team, 2012) can also be applied to a sodium system. However, a heat transfer model for finned heat transfer tubes with air cross-flow is not implemented in the RELAP5 code. Therefore, the RELAP5-3D code cannot be applied to calculate the plant transient with air cooled decay heat removers without special consideration. In order to predict the capability of the PRACS and DRACS with the air cooler, the heat transfer correlations are especially important as described in the previous study (Mochizuki and Takano, 2009). The following equations, Eqs. (1)–(10), are used in the present calculation. Heat transfer equivalent diameter d_e is used to calculate the Reynolds number and the Nusselt number. Min in Eq. (10) is an operator to select a lower value between the empirical correlations Nu_1 and Nu_2.

$$Q = U\Delta T_m A_o, \tag{1}$$

$$\Delta T_m = \frac{(T_{si}-T_{ao})-(T_{so}-T_{ai})}{\ln\left(\frac{T_{si}-T_{ao}}{T_{so}-T_{ai}}\right)}\phi_t, \tag{2}$$

$$\frac{1}{U} = \left(\frac{1}{h_T}+r_a\right)+\frac{A_T}{2\pi k_t l}\ln\left(\frac{d_o}{d_i}\right)+\left(\frac{1}{h_s}+r_s\right)\frac{A_T}{A_i}, \tag{3}$$

$$h_T = h\left(\frac{A_f\phi_f + A_b}{A_T}\right), \tag{4}$$

$$\phi_f = \frac{2}{u_b\left[1-\left(\frac{u_f}{u_b}\right)^2\right]}\left[\frac{I_1(u_b)-\beta K_1(u_b)}{I_0(u_b)+\beta K_0(u_b)}\right], \tag{5}$$

$$\beta = \frac{I_1(u_f)}{K_1(u_f)},\quad u_b = \frac{H\sqrt{h/ky}}{\frac{d_f}{d_o}-1},\quad u_f = u_b\left(\frac{d_f}{d_o}\right), \tag{6}$$

$$d_e = \frac{2(A_b+A_f)}{\pi B}, \tag{7}$$

$$Nu_1 = 9.796\times 10^{-3}\ Re^{0.9881}\ Pr^{1/3}\quad \text{for low Reynolds number}, \tag{8}$$