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Experimental and analytical studies on heat transfer in a scaled intermediate heat exchanger with water

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ABSTRACT

The present paper describes an experimental and analytical study in terms of the temperature distribution and heat transfer of an intermediate heat exchanger (IHX). An experimental apparatus of IHX with the primary heat transport system and the secondary heat transport system is made, and forced and natural circulation experiments are conducted using the apparatus. Temperature distributions inside the shell are measured using the fixed thermocouples as well as traversable thermocouples. The Nusselt numbers are investigated based on the measured temperature distributions. One-dimensional and three-dimensional computations are conducted under the forced circulation and natural circulation conditions in order to simulate the experimental results. One-dimensional computation is conducted during the transient cooling down process using a plant system code for the heat transport systems of primary and secondary loops. For the three-dimensional computations, a quasi-steady state condition is analyzed. Good agreement is obtained between the one-dimensional computational results and the experimental results for both flow patterns. The precise temperature distribution inside the shell is computed by the three-dimensional CFD code. Based on the calculated temperature distribution, the heat transfer coefficients are evaluated and converted into the Nu numbers, and are compared with the experimental results. As a result of the 3D computation, the Nu number levels off to a constant value as the Reynolds number decreases to the laminar flow condition.

1. Introduction

The present paper describes an experimental and analytical study in terms of the temperature distribution and heat transfer of an intermediate heat exchanger (IHX). The IHX of a fast breeder reactor is important equipment which transfers heat from the core to the secondary heat transport system. Until now, several IHXs for sodium facilities were fabricated and Table 1 shows the comparison of dimensions of the IHXs in different facilities. The 50 MW Steam Generator Facility (50 MW SG) was built to investigate the heat transfer characteristics of the evaporator and super-heater for the 'Monju' reactor. A cross-sectional view of the IHX for the 50 MW SG is illustrated in Fig. 1. The primary sodium enters into the shell through the nozzle provided on the side of the IHX, halfway up the IHX, and flows up toward six windows provided on the inner shroud at 60 degree intervals. The primary sodium flows down exchanging heat with heat transfer tubes and flows out of the nozzle provided at the bottom. Five baffle plates except two plates at the ends are provided inside the shell in order to hold the heat transfer tubes. Small holes for the primary sodium are provided beside the hole for the heat transfer tube on the baffle plate. The secondary sodium is provided from the top of the IHX, and flows down to the bottom of the IHX using the center shroud. The sodium changes direction and enters into the heat transfer tubes. The secondary sodium receives heat from the primary side. Therefore, heat transfer of the IHX in the present study is realized under countercurrent flow.

When the heat transfer experiment was conducted at the 50 MW SG in the 1980s, it was found out that the heat transfer coefficient of the IHX in low flow rate conditions was very low compared to earlier studies such as Seban and Shimazaki (1951), Lyon (1951) and Lubarsky and Kaufman (1955). This result was reported by Nakai et al. (1986) at first, and Mochizuki and Takano (2009) correlated the heat transfer coefficients under the low flow rate condition assuming that the same non-dimensional correlation based on the thermal hydraulic equivalent diameter would be applied on the primary and the secondary sides of the IHX. Mochizuki (2010a) tried to explain this phenomenon by the heat conduction in flow direction. However, he found out that the heat conduction in flow direction has almost no effect on the

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Nomenclature

A	flow area (m^2)
Cp	specific heat capacity (J/kg K)
D_H	heat transfer equivalent diameter (m)
G	flow rate (kg/s)
Gr	Grashof number (–)
d	diameter of the heat transfer tube (m)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2K)
K	overall heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
l	effective heated length (m)
Nu	Nusselt number (=hD_H/k)
n	number of heat transfer tubes
Pr	Prandtl number (–)
q	heat transfer rate (W)
R	thermal resistance (1/W)
Ra	Rayleigh number (–)
Re	Reynolds number (–)
T	temperature (K)
ΔT	temperature difference (K)
z	number of horizontal position across z axis (–)
β	coefficient of volumetric expansion (1/K)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity (m^2/s)

Subscripts

b	bulk
c	coolant
i	inside or inlet
o	outside or outlet
t	heat transfer tube
ti	tube inside
to	tube outside
w	tube wall
1	primary
2	secondary (tube side)

degradation. Therefore, an apparatus with an IHX was made in order to investigate flow patterns and temperature distributions inside the shell and tubes under various flow conditions. A series of the experiments are conducted by cooling down the secondary loop after the establishment of the isothermal initial conditions for both loops. However, Mochizuki (2015) finally have solved this problem using a 1D system code NETFLOW++. The degraded heat transfer coefficient under low flow rate conditions is a superficial phenomenon caused by the local heat transfer in the lower plenum and the lower part of the heat transfer tubes. It is clarified that the practical heat transfer coefficient can be expressed by the Seban and Shimazaki (1951) correlation. Nevertheless, the importance of the above mentioned experiment does not change. Because a future fast breeder reactor (FBR) in Japan so called Japan Sodium-cooled Fast Reactor (JSFR) will implement a direct reactor auxiliary cooling system (DRACS) in the reactor vessel and a primary reactor auxiliary cooling system (PRACS) in the upper region of the IHX, and the heat transfer characteristics should be evaluated precisely using a 3-dimensional computational fluid dynamics (CFD) code. In order to apply the CFD code for the evaluation of the real plant, the calculation method of the heat transfer should be verified.

In the present study, the velocity distribution and the temperature distribution in the IHX is computed precisely using a CFD code in order to apply the computation method to the sodium cooled IHX. Up to now, there are several studies which compute the thermal hydraulics in IHX such as studies by Gajapathy et al. (2008), Ohyama et al. (2009). However, they computed the thermal hydraulics only on the primary side. The important thing in the present computation is to evaluate the thermal–hydraulics on the primary side together with the secondary side simultaneously, because both sides are affecting each other under the natural circulation condition.

The local heat transfer coefficient is also evaluated by the calculated temperature distribution and compared with the experimental results. This sort of computation is impossible using the one-dimensional system code but possible using the three-dimensional CFD code. This method will contribute to evaluate thermal–hydraulics of the sodium–sodium IHX with more than 3000 heat transfer tubes of the fast breeder reactor.

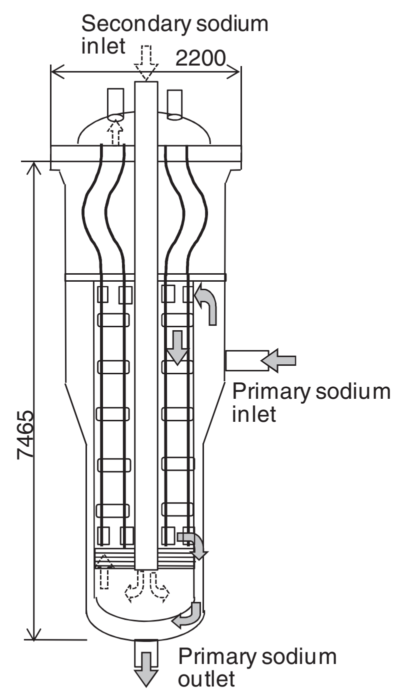

Fig. 1. Outline of IHX at the 50 MW SG Facility.

Table 1
Specifications of intermediate heat exchangers.

Items	50 MW SG	Monju	Joyo
Capacity (MW)	50	238	70
Number of heat transfer tubes	2044	3294	2088
Outer diameter of heat transfer tube (m)	0.0159	0.0217	0.0190
Thickness of heat transfer tube (m)	0.0012	0.0012	0.0010
Effective heat transfer length (m)	3.90	4.86	2.93
Flow rate in secondary side (kg/s)	222	1038	329
Outer diameter of outer shroud (m)	1.560	2.184	1.872
Thickness of outer shroud (m)	0.0240	0.025	0.016
Outer diameter of inner shroud (m)	0.457	0.746	0.532
Inner diameter of inner shroud (m)	0.0143	0.020	0.0115
Flow rate in primary side (kg/s)	263	1422	370
Total length (m)	Approx. 9	Approx. 12	Approx. 8.3