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Thermal-hydraulic phenomena inside hybrid heat pipe-control rod for passive heat removal

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ABSTRACT

In this study, a new type of thermosyphon, the hybrid heat pipe-control rod, was suggested as a passive decay heat removal device in nuclear facilities. A self-pressurization strategy, which is a passive pressure control mechanism, was introduced to achieve high operating pressure in the hybrid heat pipe, because most nuclear facilities are under high-pressure and high-temperature conditions. In the introduced pressurization strategy, a non-condensable gas was charged, and the steam generated, by the phase change of the working fluid during operation, was used as a pressurization source. The feasibility of the pressure control mechanism was experimentally studied using test sections containing nitrogen gas and water as non-condensable gas and working fluid, respectively. Consequently, it was confirmed that the internal pressure of the hybrid heat pipe was increased up to 19.0 bar through the self-pressurization mechanism under the conditions in which the experiments were conducted. Furthermore, the dependencies of the pressure behavior, heat transfer coefficients at the evaporator and adiabatic sections, and flooding-based maximum heat transfer rate on the working fluid fill ratio, initial pressure, and heat load were discussed. The evaporation heat transfer coefficient was independent of the fill ratio and initial pressure, while the condensation heat transfer was inversely proportional to the amount of non-condensable gas charged inside the test section. The maximum heat transfer rate increased as the operating pressure increased, owing to the reduction of entrainment rate. Based on the experimental results, new models on condensation heat transfer and flooding limit were proposed, considering the effects of the non-condensable gas and different cross-sectional areas along the evaporator and adiabatic sections of the hybrid heat pipe.

1. Introduction

The nuclear accidents that occurred at the Chernobyl, Three-Mile Island, and Fukushima nuclear power plants were caused by complex reasons such as human error, failure of safety systems, and unpredictable natural disasters. To mitigate the progression of the accident and prevent severe accidents, there are various types of safety systems in nuclear power plants to protect humans and the environment from radiation hazards. The current decay heat removal systems installed in commercial nuclear power plants are designed to supply additional coolant to the reactor pressure vessel or feed water to the steam generators using the pump or pressure difference between the coolant reservoir and target system. However, potential inability of depressurization of the reactor coolant system during a station blackout (SBO) could result in failure of the safety system operations [1]. SBO is one of the key contributors to the core damage frequency (CDF) of reactors. Although various passive safety systems have been developed to cope with SBO conditions, the systems consist of many valves and pipelines, which have possibilities of single or and common cause failures, thus contributing to the malfunction of the systems. The driving force in passive safety systems (natural force) is lower than that in active safety systems (pump) in an equal system scale. Therefore, the passive safety system is commonly larger in size. High uncertainties and lack of operating experience create reliability issues in passive safety systems. These issues of passive safety systems have delayed their integration in nuclear facilities, despite their advantages in terms of probabilistic risk reduction and, more importantly, human error reduction.

The hybrid heat pipe was developed as a new conceptual passive decay heat removal system that has a different working principle from that of the existing safety systems and involves a diversity of safety features [2]. The hybrid heat pipe is a new type of thermosyphon heat pipe combining the functions of control rod and heat pipe. The control rods drop to the core using gravity and

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Nomenclature

A	area [m^2]
Bo	bond number [–]
C	correlation coefficient [–]
C_{pl}	liquid specific heat [J/K]
d	diameter [m]
g	gravity [m/s^2]
h	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat [kJ/kg]
I	current [A]
j	superficial velocity [m/s]
K	Kutateladze number [–]
k	thermal conductivity [W/m K]
l	length [m]
m	correlation coefficient [–]
$\dot{m}$	mass flow rate [kg/s]
M	molecular mass [g/mol]
P	pressure [Pa]
PINCs	passive in-core cooling system
Pr	Prandtl number [–]
PWR	pressurized water reactor
Q	heat, power [W]
q''	heat flux [kW/m^2]
r	radius [m]
Re	Reynolds number [–]
SMR	small modular reactor
T	temperature [°C]
$\bar{T}$	average temperature [°C]
V	voltage [V]

Greek symbols

ρ	density [kg/m^3]
σ	surface tension [N/m]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2/s]

Subscript

adia	adiabatic
atm	atmosphere
b	bubble
c	condenser
cool	coolant
cs	cross-sectional
cw	condenser wall
e	evaporator
ew	evaporator wall
f	film
h	heated
in	inlet of water jacket
k	Kutateladze
l	liquid
max	maximum
out	outlet of water jacket
sat	saturation
v	vapor
w	Wallis

shutdown the reactor by neutron absorption. The thermosyphon heat pipe is gravity-driven wickless heat pipe which uses the phase changes (evaporation and condensation) and natural convection of the working fluid at high and low temperature interfaces. With this combination of thermosyphon and control rod functions, the hybrid heat pipe can simultaneously achieve reactor shutdown and decay heat removal in accident conditions [3] (see Fig.1).

The environment wherein the hybrid heat pipe will be applied, a nuclear facility, is under high-temperature and high-pressure conditions. For operation in a high-temperature and high-pressure environment, the hybrid heat pipe must achieve high internal pressure. Thus, a self-pressurization strategy using a non-condensable gas and accumulation of steam was established, as shown in Fig. 2, whereas the operating conditions of the

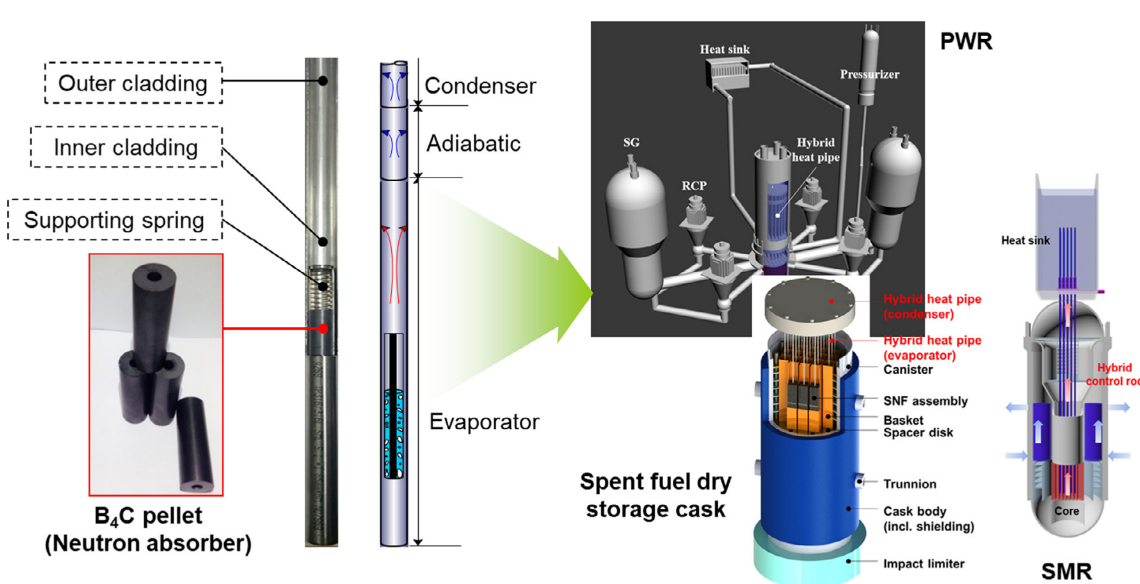

Fig. 1. Concepts of hybrid heat pipe and passive in-core cooling system [1].