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Research Paper

Hydraulic resistance of in-tube cooling supercritical water accompanying out-tube pool boiling

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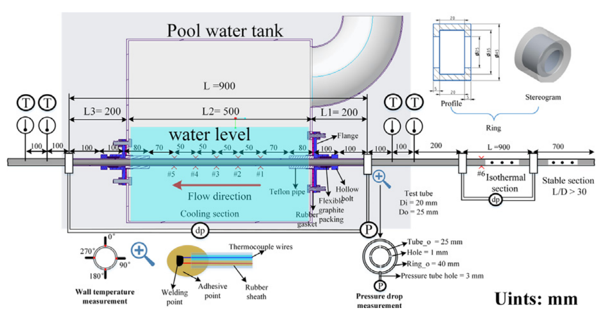
HIGHLIGHTS

- Studied hydraulic resistance of in-tube cooling SCW with out-tube pool boiling.
- Existed a steep "pit" for friction factor of adiabatic flow near PC region.
- Observed a noticeable "Λ-shaped" profile of the cooling frictional pressure drop.
- Introduced deceleration-factor into the cooling friction factor correlation.

GRAPHICAL ABSTRACT



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ABSTRACT

The experiment was conducted by immersing a smooth horizontal tube in a pool tank to simulate the flow condition of Passive Residual Heat Removal System (PRHRS) in a SuperCritical Water-cooled Reactor (SCWR). Hydraulic resistance and friction factor of in-tube cooling supercritical water accompanying out-tube pool boiling were investigated in this study with test pressure ranging from 23 to 28 MPa and mass flux ranging from 600 to 1000 $kg \cdot m^{-2} \cdot s^{-1}$. The influence of pressure and mass flux on pressure drop in adiabatic and cooling flows was analyzed. This paper also discussed the effect of deceleration in the cooling flow and assessed various friction-factor correlations by employing the experimental data. Results showed that the friction factor of the adiabatic flow exists a steep "pit" approaching to pseudocritical region. A noticeable "Λ-shaped" profile was observed in the vicinity of the pseudocritical temperature, due to deceleration-effect of frictional pressure drop in the cooling flow. The deceleration factor of supercritical cooling flow led to the axial fluid element shrinkage and radial bulk fluid velocity parabolic distribution. Taking into account the effect of deceleration-factor, a modified correlation was proposed for in-tube cooling supercritical water accompanying out-tube pool boiling, of which the average error and root mean square error are −2.51% and 15.28% respectively.

1. Introduction

The SuperCritical Water-cooled Reactor (SCWR) is one of the six advanced nuclear-reactor concepts being developed by Generation IV [1]. A SCWR power plant presents significant advantages such as high thermal efficiency, low capital investment, simplified loop and nuclear nonproliferation, which is recognized as one of the promising water-cooled nuclear systems for the future [2,3]. The Fukushima Nuclear Accident [4] in March 2011 aroused security concerns of nuclear industries all over the world. How to ensure the inherent safety of nuclear reactors after extreme external events has become an issue to address. Especially, the passive residual heat removal system (PRHRS) of a

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Nomenclature

C_p	specific heat, kJ·kg^{-1}·K^{-1}
d_{in}	inside diameter, m
G	mass flux, kg·m^{-2}·s^{-1}
H	enthalpy, kJ·kg^{-1}
ΔH	enthalpy increment, kJ·kg^{-1}
L	cooling length, m
P	pressure, MPa
ΔP	pressure drop, kPa
ΔP_{fr}	frictional pressure drop, kPa
ΔP_{ac}	acceleration pressure drop, kPa
Pr	Prantl number
q	heat flux, kW·m^{-2}
Re	Reynolds number
T	temperature, °C
v	specific volume, m^3·kg^{-1}
$\bar{v}$	integral means specific volume, m^3·kg^{-1}

Greek symbols

β	thermal expansion coefficient, K^{-1}
μ	dynamic viscosity, Pa·s
ρ	density, kg·m^{-3}
ε_{fr}	friction factor

Subscripts

b	bulk
cal	calculated
exp	experimental
int, i	inlet, inner
out. o	outlet, outer
w, wi, wo	wall temperature, inner wall temperature, outer wall temperature

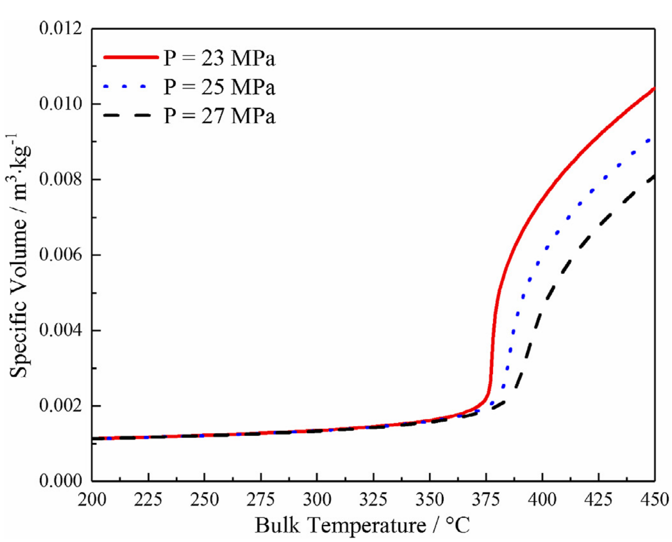
Abbreviations

PRHRS	passive residual heat removal system
SCWR	super critical water-cooled reactor
PC	pseudocritical

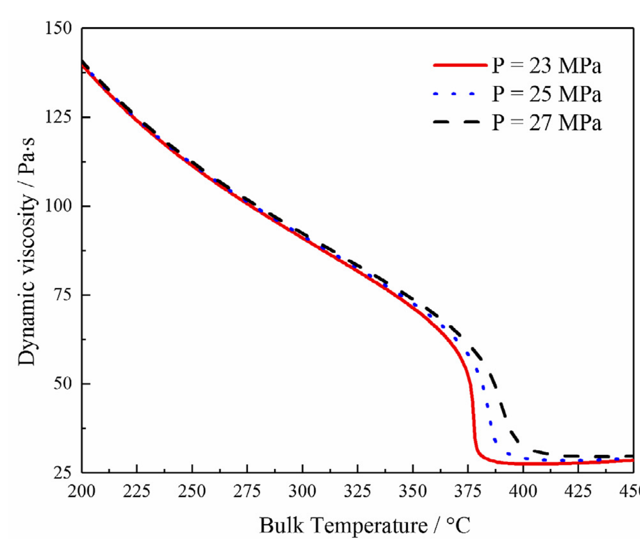
station blackout accident has drawn more and more attention [5]. At present, the two-phase passive cooling system has been adopted in the generation III advanced nuclear reactor to improve the safety [5–8]. As for improving inherent safety of the SCWR, the PRHRS is a good choice [9,10]. Some advanced SCWR designs incorporate a system to remove decay heat passively through the natural circulation loop. This is accomplished by submerging a heat exchanger in a tank of water to cool the supercritical water of reactor core.

Supercritical fluid is taken as the working medium through the PRHRS. Beyond the pseudocritical (PC) region, the fluid does not undergo phase transition which is similar to single-phase fluid. However, near the PC region, it should be noteworthy that the thermophysical properties of supercritical fluid present steep and drastic variations (as seen in Fig. 1). These drastic variations lead to non-uniform flow features in the channel. The issue is more complicated in a PRHRS of SCWR, wherein the supercritical fluid is in-tube cooled accompanying out-tube pool boiling. The flowing condition of in-tube cooling and out-tube pool boiling may expedite the cooling process and affect the hydraulic resistance, which needs to be further studied.

Many experimental studies have been carried out in the hydraulic resistance of supercritical fluid [11–13]. It is found that the friction factor is related to the Reynolds number and thermal physical property ratio [14–19]. Kondrat'ev [16] conducted hydraulic resistance experiments in a horizontal heated tube within a wide range of flow condition. He found that the acceleration factor could lead to a “V-shaped” profile displayed by the friction factor of supercritical fluid within the PC region. Wang [3] conducted experiments to investigate the hydraulic resistance and friction factor of supercritical fluid in an annular channel. In his experiment, a local hump in the friction factor was observed in annular channel in the PC region, which becomes stronger with the decrease of mass flux or pressure. Zhang [20] explained the reason why concave curves and convex curves were appeared in the variation trend of the frictional coefficient along with the fluid enthalpy in the PC region. He believed that it was resulted from measurement



(a) Specific volume VS bulk temperature



(b) Dynamic viscosity VS bulk temperature

Fig. 1. Thermal physical property changes with bulk temperature at the different pressure.