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Experimental research on the thermal hydraulic characteristics of sodium boiling in an annulus

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ABSTRACT

Thermal hydraulic characteristics of sodium boiling are significant in the safety analysis for the sodium cooled fast reactor, one of the Generation IV reactors. However, the knowledge on the mechanism of sodium boiling is quite limited. In this study, boiling experiments on sodium flowing through an annulus are performed. The annulus is of 1000 mm length, 8 mm inner diameter and 12 mm outer diameter. The heat flux varies from 80 to 500 kW/m^2, with inlet subcooling from 63 to 285 °C, inlet flow velocity from 0.02 to 0.5 m/s and system pressure from 3.67 to 103 kPa. The boiling phenomena, two phase friction pressure drop and boiling heat transfer coefficient are investigated. Correlations for the two-phase friction multiplier factor ϕ_l^2 and boiling heat transfer coefficient are proposed, respectively. Predicted results show good agreement with the experimental data.

1. Introduction

Sodium cooled fast reactor (SFR) is one of the Generation IV reactors with the most mature technology and the best application prospect in the short term and is considered as the prime candidate for the large scale implementation of breeder reactor technology in the medium-term future by several countries. As noted by Farmer [1], Hennies [2], Waltar and Padilla [3], Waltar and Reynolds [4] and Maschek and Struwe [5], boiling may appear during some postulated accidents such as the unprotected loss of flow, loss of piping integrity, loss of heat sink, anticipated transient without scram and subassembly blockage. Boiling may lead to dry-out, so far as to the melting of material, and also the void distribution in the core of SFR which is one of the principal parameters that dominates the reactivity feedback during hypothetical transients. The study on the phenomena and thermal hydraulic characteristics of sodium boiling is significant in the safety analysis for the SFR.

1.1. Boiling process

Compared with water or organic liquids, liquid metals show a divergent picture of boiling patterns due to the difference in thermal and fluid dynamic properties which makes the two-phase flow specific correlations used for 'ordinary' liquids cannot be applied in liquid metals immediately [6].

Some experiments have been carried out to study the boiling phenomena of sodium and other liquid metals. For example, three types of boiling were observed by Schleisiek [7] including stable pulsating boiling with low heat flux, unstable pulsating boiling even dry-out with high heat flux and quasi-stationary two-phase flow by throttling before the test section. In Takahashi et al. [8] experiments, quasi-steady state boiling was frequently observed as well as violently pulsating boiling with alternate ejection and fallback of liquid into test section, and slug type boiling was also sometimes observed. Three boiling processes observed by Fujiie et al. [9] were local boiling preceding bulk boiling, local boiling immediately before bulk boiling and bulk boiling occurred without local boiling, respectively. Single-phase flow, presence of one or several bubbles, slug flow, dry-out were indicated in the experiments of Kottowski et al. [10] with flow run-down conditions. Xiao et al. [11] divided the boiling process in his experiment into 6 regions including single-phase region, transition region from single phase to subcooling boiling, unsteady subcooling boiling region, steady subcooling boiling region, saturation boiling region and liquid-deficient region.

1.2. Two-phase pressure drop

It has been observed in many experiments that friction pressure drop of two-phase flow can be much larger than that of corresponding single-phase flow for a given mass flow. Classically, a multiplier factor ϕ_l^2 is used to account for the two-phase effects while the single-phase friction factor as in the two-phase flow is

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Nomenclature

f	friction factor
G	mass flux density, kg/(m^2 s)
h	heater transfer coefficient, specific enthalpy, W/(m^2 K), J/kg
h_f, i_f	specific enthalpy of saturated liquid, J/kg
h_{fg}	latent heat of evaporation, J/kg
I	current, A
l	effective heating length of the heater pin, m
L	length, mm
n	Blasius exponent, number
p	pressure, Pa, kPa, MPa
ΔP	pressure drop, Pa
RSD	relative standard deviation
ΔT	temperature difference, °C
q	heat flux, W/m^2
r	radius, m
t	time, s
T	temperature, °C
u	velocity, m/s
U	voltage, V
x	quality
X_{LM}	Martinelli parameter
z	axial distance between the point and the outlet, m
α	void fraction
λ	heat conductivity, W/(m K)
ε	dimensionless location
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
η	heat efficiency
ϕ_l^2	two phase friction multiplier

Subscripts

Acc	acceleration
ave	average
cal	calculated
exp	experimental
f	fluid
g	gas
Grav	gravitation
i	number of thermocouple, inside
in	inner
inlet	inlet of the test section
l	liquid
m	measured
max	maximum
min	minimum
o	outside
out	outer
sat	saturated
spl	single phase
tot	total
TP	two phase
w	wall
z	point z

assumed. Different correlations for the two-phase friction multiplier factor ϕ_l^2 have been proposed by scholars based on their own experimental data.

Lockhart and Martinelli's [12] experiment was performed in horizontal pipes with air–water at pressure near to atmospheric. A correlation between ϕ_l^2 and X_{LM} for turbulent flow was obtained based on the data. The Lockhart–Martinelli parameter X_{LM} can be written as [13]

$$X_{LM} = \left(\frac{1-x_{ave}}{x_{ave}}\right)^{\frac{2-n}{2}} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{\frac{n}{2}} \tag{1.a}$$

where "n" is the Blasius exponent. For turbulent flow of sodium, "$n = 0.2$" is usually employed (e.g. Chenu et al. [14]).

As a result, in this paper the parameter X_{LM} was defined as

$$X_{LM} = \left(\frac{1-x_{ave}}{x_{ave}}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \tag{1.b}$$

A set of data based on sodium boiling in an annular test section (6.35 mm inner and 12.7 mm outer diameter) was published by Lurie and Noyes [15]. The liquid *Re* number was in the range of 6000–34,000 and pressure from 0.1 to 0.7 bar. Lottes and Flinn [16] proposed that the frictional effect is primarily due to drag of the liquid phase along the wall for small values of quality. They suggested that, the friction multiplier can be calculated by the vapor volume fraction, independent of pressure and flow rate. The model has been used in the SABENA by Ninokata and Deguchi [17] to predict the sodium two-phase pressure drop. In order to compare the model with others in this study, the correlation has been transformed as a function of X_{LM}, using the correlation for the void fraction obtained by Nguyen [18]. Kottowski and Savatteri [19] performed experiments for quasi steady-state sodium boiling in circular tube and a least-square fit correlation was obtained from the measurement data. On the base of measurements in a sodium loop with an induction heated circular test section of 9 mm inner diameter and 200 mm heated length, a correlation for the two-phase friction multiplier was derived by Kaiser et al. [20]. A set of data were measured by Kaiser et al. [21] in the sodium boiling loop NSK, Karlsruhe, with a 7-pin bundle test section. The friction pressure drop was calculated by an iterative procedure as only the total pressure drop could be measured. Another correlation from the data above was carried out. The correlation proposed by Chen and Kalish [22] based on potassium data is also taken into account in this study.

Correlations mentioned above for the two-phase friction multiplier factor ϕ_l^2 are listed in Table 1. The results calculated by different models are quite different.

1.3. Boiling heat transfer

It has been pointed out that, an annular (and then disperse-annular) mode arises in channels even with low sodium vapor quality since boiling of liquid metals usually take place at low pressure. A liquid film flows along the heating wall and the vapor containing droplets of liquid form the flow core in this mode of flow [23]. In this case, because of the high thermal conductivity of liquid metal and small thickness of the liquid film, the wall superheat will be insufficient for nucleation of bubbles in the wall. The heat from the heating wall is firstly transferred by thermal conductivity through the liquid film and then by evaporation of liquid from the interface [24]. As a result, the boiling heat transfer coefficient is affected by the heat flux and system pressure instead of the mass velocity or the sodium vapor quality. The effective heat transfer coefficients can achieve hundreds of kW/m^2 [25]. Experimental data under different conditions and several correlations for the boiling heater transfer coefficient have been announced by different scholars.