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Innovative flow-resistance performance in the single-phase natural circulation loop and relevant experiment verification

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ABSTRACT

In consideration of the effects of the local resistance and the frictional resistance in the natural circulation loop, the analytical relation between the natural circulation mass flow rate G and the heating power Q can be express as $G \sim Q^m, m = f(\mathrm{Re}, R_n)$, where the R_n is the ratio of the local pressure loss coefficient and the friction coefficient. The relation of flow-resistance to the natural circulation mass flow rate can be expressed as $\Delta p_f \sim G^r, r = f(t, m)$. These correlations is tested with experimental data from the experimental facility of HRTL-200 II and showed reasonable agreement.

1. Introduction

In order to improve the safety and economics of new nuclear power plant designs, the principle of natural circulation is widely used in recent years. The natural circulation arises because of the fluid density difference between the heat source (core) and the elevated heat sink (heat exchanger). Fig. 1 presents a schematic that illustrates the salient features in the natural circulation reactor. The natural circulation flow rate of PWR is related to the geometrical structure and resistance characteristics, the heating power of the reactor core and the operation characteristics of the secondary loop. The heat transport capability and natural circulation flow rate are positively correlated. It is important to study the relationship between natural circulation flow, power, and flow resistance for design and performance evaluation of natural circulation loops.

By formula derivation, Zvirin [1] and Ishii [2] found that the natural circulation mass flow rate is the power function of the heat power: $G \sim Q^{1/3}$, where the G is the natural circulation mass flow rate and Q is the heating power. However, in Yang's experiment [3], the pressure of the natural circulation loop is 0.3 MPa–11 MPa and the power index is 0.469 to 0.414, and in Jang's experiment [4], $G \sim Q^{0.47768}$ where the pressure is about 2.0 MPa. All these experiments results show the power index does not equal to 1/3.

Yang [5] proposed that $G \sim Q^{\frac{1}{1+c}}$ and the total resistance in the natural circulation loop is $\left(\frac{fl}{D} + K\right)\frac{1}{2}\rho U^c$, where the power index c is a variable parameter which depends on the flow regime. However, power index c has no physical meaning and the dimensional of the total resistance $\left(\frac{fl}{D} + K\right)\frac{1}{2}\rho U^c$ is not MLT^{-2} ($\mathrm{kg \cdot m \cdot s^{-2}}$).

Vijajan [6,7] proposed an expression $\mathrm{Re}_{ss} = C[Gr/N_G]^r$ for steady state flow in uniform or non-uniform diameter single-phase natural circulation loops, where the constants C and r depend on the regime of the flow (laminar or turbulent). Re_{ss} contains the information of G and Gr number contains Q. In Vijajan's approach, the local pressure loss coefficient is absorbed into total resistance coefficient by using equivalent length. But this method has its limitation: the effect of the local resistance and the frictional resistance on the natural circulation mass flow rate can't be analyzed in detail. According to Vijajan's approach, Swapnalee [8] proposed a generalized equation for the steady state flow in single-phase natural circulation loops. The generalized equation is based on 1-D theory by assuming the loop to be partly in laminar and partly in transition or turbulent flow. The derived dimensionless flow equation is applicable for any loop obeying multiple friction laws.

Recently, Tan [9] studied the single-phase natural circulation flow and heat transfer under the rolling motion condition, experimentally and theoretically; Huang [10] developed the homogenous model with SINDA/FLUINT under different condition of heat loads. For the stability of the natural circulation, non-linear stability analysis and the experimental approach were used to seek the unstable

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Nomenclature

A	cross-sectional area of flow
a	constant coefficient in the friction coefficient
b	power index in the friction coefficient
c	power index
c_p	constant pressure specific heat
D	hydraulic diameter
f	friction coefficient
g	acceleration of gravity
G	natural circulation mass flow rate
k	resistance coefficient in the inlet of the heating source
K	local pressure loss coefficient
l	length
m	flow rate-heating power characteristic number
n	fitted function constant coefficient
N	section number or substitution parameter
p_t	total pressure
Q	heating power
Q_l	equivalent heat power of the local resistance
Q_f	equivalent heat power of the frictional resistance
r	flow-resistance characteristic number
R_n	ratio of resistance coefficient
R_f	ratio of resistance term
Re	Reynolds number
s	fitted function coefficient or natural coordinate parameter
s_0	power index
t	temperature rise-heating power characteristic number
U	velocity
Greek symbols	
β	thermal expansion coefficient
ε	relative deviation or variation
μ	dynamic viscosity
ρ	density
ΔH	height difference between the hot core and the cold core
ΔT	difference temperature
Δp_d	driving force
Δp_f	total flow resistance
$\Delta p_{c\text{-}in}$	local resistance in the inlet of heat source
Δp_c	frictional resistance in the heat source
Δp_h	frictional resistance in the heat sink
Δp_{other}	other part of the resistance
Subscripts	
A, B, C, D, E, F	sign of each section
i	number of each section
l	local resistance
f	frictional resistance
q	heating power
R	rated condition
0	reference value/initial/primary

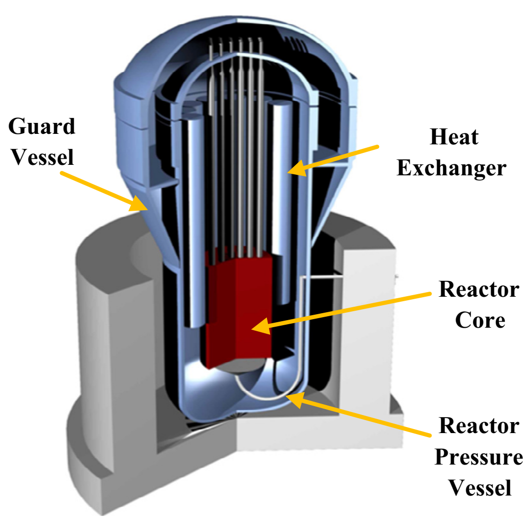

Fig. 1. Schematic diagram of the nature circulation reactor.

convection regime and the nonlinear dynamics of the flow [11–13]. All these researches are based on the flow-resistance performance of the natural circulation by using the previous approaches, and no modified aspects are presented.

In summary, most of the previous research on the flow resistance characteristics of the natural circulation loop are focused on the relation between the variable power index of Q and flow regime. The flow resistance is simplified. In this study, the roles of the local resistance and the frictional resistance in the natural circulation loop are analyzed respectively, and the relations between the natural circulation flow rate and the heating power, and the flow resistance are proposed. These relations are tested by experimental data from the HRTL-200 II test facility and literatures, and the correctness of these relations is proved.

2. Theoretical model of the innovative flow-resistance performance

2.1. Relation between the natural circulation mass flow rate and the heating power $G \sim Q$

By simultaneously solving a set of the mass, momentum, and energy convection equations, the steady solution of the natural circulation loop can be achieved. The basic assumptions include:

1. The flow was one-dimensional along the loop axis, therefore fluid properties were uniform at every cross-section.
2. The Boussinesq approximation was applicable.
3. The fluid was incompressible.
4. Heat loss and viscous dissipation in the natural circulation loop are all neglected.

In the steady state of the natural circulation, a set of the mass, momentum, and energy convection equations are simultaneously solved.

$$G = \text{const} \tag{1}$$

$$\rho_0 g\beta\Delta H\Delta T = \sum_{i=1}^{N}\left(\frac{fl}{D}+K\right)_i \frac{G^2}{2\rho_0 A_i^2} \tag{2}$$

$$Q = Gc_p\Delta T \tag{3}$$

Substituting Eq. (3) into Eq. (2), we obtain: