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Scaling analyses for the open flashing-driven natural circulation system

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ABSTRACT

Transient simulating and scaling analyses are carried out to reproduce the transient operating behaviors of the prototypical big-scale open natural circulation system, which is designed for the Passive Containment Cooling System (PCCS). Firstly, a transient numerical code to simulate the operating behaviors of the open natural circulation system is developed and validated. Than, an effective and simplified 1:1 height scaling analyses based on the steady-state flow are conducted to model the operating behaviors of the prototypical open natural circulation system. The scaling process consists of heat transfer scaling of the heat exchanger and the pressure resistance scaling of the riser and downcomer sections, the purpose of which is to keep the driven force and pressure resistance of the model same with those of the prototype by changing the dimensions of the pipes. When choosing the geometrical parameters of the heat transfer tubes, the Reynolds number of fluid inside the heat transfer tube has a great influence on the modeling results. Thus, the flow regime inside the tube in the model system should be the same as that in the prototype system when choosing the geometrical parameters of heat transfer tube. The dimensions of the riser and downcomer section are scaled separately to keep the pressure resistances of them in the model same with those in the prototype respectively. From the comparison results of the model and prototype it can be found that the scaling open natural circulation system can reproduce the transient operating behaviors of the prototype very well and the scaling method in this study can be used for the engineering applications.

1. Introduction

The containment is the last obstacle to prevent the radioactive substances releasing into the environment. In order to maintain the integrality of the containment after the severe accidents or the design basis accidents, such as the loss of coolant (LOCA) and main steam line break (MSLB), effective measures should be taken to remove the high energy inside the containment. Recently, a number of investigations relating to the promising passive containment cooling systems which are safer and more reliable than the traditional security systems which rely on the external interventions have been conducted. Several conceptual passive containment cooling systems (Seong-Wook Lee et al., 1997) have been proposed for the large-scale dry double-wall concrete containment, which is promoted by the European Utilities Requirements (EUR) concerning the costs and experiences of the construction and operation. In this investigation, an innovative concept of passive containment cooling system based on the internal evaporator (IEO) concept Byun et al. (2000) raised is proposed in this paper. Generally, this type of security system has a very large geometry and a big scale because of the large amount of energy released into the containment after the severe or design basis accidents. The 1:1 experimental investigation of the transient operating behaviors in laboratories is almost impossible in most situations. In order to solve this problem, reasonable and effective scaling method should be developed to establish a model system with the reduced power and dimensions to reproduce the operating behaviors of the prototype.

At present, nearly all of the scaling methods and scaling criteria are derived from the basic conservation equations. Ishii and Kataoka (1984) derived the scaling criteria for a natural circulation system under the single-phase and two-phase flow conditions based on the one-dimensional assumption. The geometrical similarity groups, friction number, Richardson number, characteristic time constant ratio, Biot number, and heat source number were obtained for the scaling of single-phase flow. They pointed out that the phase change number, subcooling number, drift-flux number and the friction number are very important for the two-phase scaling analysis based on the perturbation analysis of one-dimensional drift-flux model. Vijayan and Austregesilo (1994) used the power-to-volume scaling laws to model the primary system of nuclear power plants. Three rectangular loops with different diameters were obtained based on the scaling laws to simulate the

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Nomenclature

General symbols

M	mass flow rate in main pipes ($kg\ s^{-1}$)
Q	heat transfer of the heat exchanger (kW)
H	height (m)
L	length (m)
D	diameter (m)
N	number of heat transfer tubes
A	cross section area (m^2)
P	pressure (MPa)
i	specific enthalpy ($kJ\ kg^{-1}$)
t	time (s)
z	axial position (m)
q	linear heating rate ($W\ m^{-1}$)
u	velocity ($m\ s^{-1}$)
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
x	mass quality
T	temperature (°C)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
A_t	heat transfer area (m^2)
V	volume (m^3)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
f	frictional factor
a	scaling heat transfer ratio
v	specific volume ($m^3\ kg^{-1}$)
k	total heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
X_v	volume fraction

Greek letters

ρ	mass density ($kg\ m^{-3}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
α	vapor void fraction
β	vapor volume fraction
ξ	local resistance coefficient

Superscript and subscripts

+	parameters in scaling model
max	maximum
exp	experimental
up	the riser section
dn	the downcomer section
he	heat exchanger/heat transfer tube
in	inside the heat transfer tube
out	outside the heat transfer tube
fri	frictional
gra	gravitational
loc	local
acc	acceleration
g	saturated vapor
f	saturated liquid
∞	inside the containment
l	liquid
0	initial time in the rest
l0	liquid parameters in the initial rest state
wo	the outer surface of the heat transfer tube
wi	the internal surface of the heat transfer tube
w	tube wall
a	air
e	outlet of pipeline
i	inlet of pipeline
m	mixture of liquid and steam
t	water tank
d	driven force

single-phase natural circulation system. They found that the power-to-volume scaling principles can describe the steady-state flow very well but cannot reproduce the stability behavior in the loops with small diameters. Through the theoretical investigation they concluded that the transient and stability behavior can be simulated only when the diameter ratio between the prototype and model is also simulated. However, the scaling criteria they derived neglected the flow resistance and heat source similarity. Yadigaroglu and Zeller (1994) used a step-by-step facility design procedure to define suitable scaling criteria for a refrigerant-113 (R-113) experiment to simulate the dynamics and stability of flashing-induced natural circulation reactor system. They achieved almost perfect simulation mainly by reducing the height of the facility according to the liquid density ratio and scaling for similar void fraction distributions in the prototype and the model. The scaling analysis is fluid-to-fluid scaling, which may display different characteristics of heat transfer and flow resistances. JinHo Song (2008) used the normalized flow rate to present the steady performance of a typical natural circulation loop. Normalized flow rate was derived as the function of heat input, density ratio, and pressure loss coefficient to obtain an optimal geometric configuration under the constraints of a fixed fluid volume and an installation volume. They predicted that the gravity dominated regime and the friction dominated regime depend on the heat input and the scaling criterion in terms of the ratio of the length scale and the ratio of heat input can be utilized for the design of scaled model. Comparing with other scaling methods, this scaling analysis cannot present the detail operating phenomenon of two-phase flow and whether the model system can reproduce the behaviors of the prototype was not definite. Donghua et al. (2010) performed the scaling analysis to construct an integrated scaled test facility to investigate the reactor natural circulation system and verify the system thermal-hydraulic code. Based on the conservation equations, a set of non-dimensional equations independently for the single-phase and two-phase flow were derived and the scaling criteria respectively for these two flow regimes were obtained. They also suggested the property similarities for different practical applications according to these criteria. However, scaling models with detail dimensions are not given in their investigations and the accuracy of the scaling methods for different situations cannot be evaluated intuitively. Li et al. (2013) conducted the scaling analyses for several existing passive cooling systems with air natural circulation. Different appurtenances were concerned for different designs with special purposes. They proved that the flow regime is the most critical parameter for initial test condition definition, with which the system height can be selected and the test time scale ratio can be defined. They also pointed out that the time scale, facility height, hydraulic diameter, wall thickness and the heat transfer area ratio were the most important parameters for the scaling designs. Yan and Wen (2014) performed the scaling analysis for the ocean motions in single-phase natural circulation system, which was used in the design of floating reactor natural circulation system. The selection and optimization of scaling criteria are also analyzed for both single ocean motion and compound ocean motions. They considered that the length scale, oscillating period and experimental power should be taken into account to obtain a reasonable experimental period.

The investigations mentioned above provide many scaling criteria and simulating methods to design the experimental model facility. However, in the practical application, the geometrical dimensions of one part or the entire of system, such as length, diameter and height, may be restricted, and the scaling criteria number proposed cannot be