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Scaled Facility Design Approach for Pool-Type Lead-Bismuth Eutectic Cooled Small Modular Reactor Utilizing Natural Circulation

Sangrok Park*, Yong-Hoon Shin, Jueun Lee and Il Soon Hwang
Nuclear Transmutation Energy Research Center of Korea (NUTRECK), Seoul National University,
1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Korea
**Corresponding author:sangrok.p@snu.ac.kr*

1. Introduction

In low carbon era, nuclear energy is the most prominent energy source of electricity. For steady eco-friendly nuclear energy supply, Generation IV reactors which are future nuclear reactor require safety, sustainability, economics and non-proliferation as four criteria [1]. Lead cooled fast reactor (LFR) is one of these reactor type and Generation IV international forum (GIF) adapted three reference LFR systems which are a small and movable systems with long life without refueling, intermediate size and huge electricity generation system for power grid [1]. NUTRECK (Nuclear Transmutation Energy Center of Korea) has been designed reactor called URANUS (Ubiquitous, Rugged, Accident-forgiving, Non-proliferating, and Ultra-lasting Sustainer) which is small modular reactor and using lead-bismuth eutectic coolant [2]. To prove natural circulation capability of URANUS and analyze design based accidents, scaling mock-up experiment facility will be constructed. In this paper, simple specifications of URANUS will be presented. Then based on this feature, scaling law and scaled facility design results are presented.

2. Approach and Scaling Law

In this chapter, test missions of pool-type mockup facility and its design approach are defined. Based on that, scaling approach methods are considered [3-5].

2.1 Test missions and scaling approach

Main purposes of this facility are verification of stead-state natural circulation with 3D flow distribution, and testing of transient natural circulation and design based accident simulation. Down scaling of four constraints are selected; length ratio, flow area ratio, total LBE content, and core outlet velocity. Based on same thermal height, other constraints are considered. To measure 3D flow, appropriate scaling approach is needed to calculate suitable flow area and keeping similarity between prototype and mockup facility.

In this work, an area-averaged scaling approach is considered [3].

2.2 Governing equations

To derive non-dimensional numbers, governing equations of conservation and energy balance are needed. Mass conservation, integral momentum conservation and fluid energy equation are considered.

$$u_i = \frac{a_0}{a_i} u_r \tag{1}$$

$$\rho \frac{d}{dt}\sum_i l_i u_i = \rho g \beta \Delta T_0 l_h - \frac{\rho}{2}\sum_i \left(\frac{l}{d} f + K\right)_i u_i^2 \tag{2}$$

$$\rho C_p \frac{\pi d_i^2 l_i}{4}\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial z}\right)_i = \pi d_i l_i h (T_s - T)_i \tag{3}$$

Heat transfer and conservation need to be considered. Equation of solid energy balance and boundary condition between fluid and solid are described as equation (4) and (5) respectively.

$$\rho_s C_{ps} \frac{\partial T}{\partial t} + k_s \nabla^2 T_s - \dot{q}_s = 0 \tag{4}$$

$$-k_s \frac{\partial T}{\partial y} = h(T_s - T) \tag{5}$$

Based on these five equations, non-dimensional numbers are derived and important scaling factors are selected.

2.3 Scaling law

Ratio between model and prototype is represented by the following equation.

$$\psi_R \equiv \frac{\psi_{\text{model}}}{\psi_{\text{prototype}}} \tag{6}$$

Fundamentally, geometrical similarity has to be satisfied.

$$A_{iR} = \frac{A_{im}}{A_{ip}} = \frac{(A_i / A_0)_m}{(A_i / A_0)_p} = 1 \tag{7}$$

$$L_{iR} = \frac{(l_i / l_0)_m}{(l_i / l_0)_p} = 1 \tag{8}$$

Dynamic similarity is derived from equation (2). This criterion is the key criterion of natural circulation similarity.

$$\mathrm{Ri}_R = \left(\frac{g\beta\Delta T_0 l_0}{u_0^{\,2}}\right)_m \Big/ \left(\frac{g\beta\Delta T_0 l_0}{u_0^{\,2}}\right)_p = 1 \quad (9)$$

$$\left(\sum_i F_i / A_i^2\right)_R = \left(\sum_i \left(\frac{l}{d} f + K\right)_i \Big/ \left(\frac{a_i}{a_0}\right)^2\right)_m \Big/ \left(\sum_i \left(\frac{l}{d} f + K\right)_i \Big/ \left(\frac{a_i}{a_0}\right)^2\right)_p = 1 \quad (10)$$

Based on energy equations, energy similarity is obtained and ratio of these criteria need to be 1.

$$Q_{s0R} = \left(\frac{\dot{q}_s l_0}{\rho_s C_{ps} u_0 \Delta T_0}\right)_m \Big/ \left(\frac{\dot{q}_s l_0}{\rho_s C_{ps} u_0 \Delta T_0}\right)_p = 1 \quad (11)$$

$$\mathrm{Ti}_{iR} = \left(\frac{\alpha_s l_0}{\delta^2 u_0}\right)_{im} \Big/ \left(\frac{\alpha_s l_0}{\delta^2 u_0}\right)_{ip} = 1 \quad (12)$$

$$\mathrm{St}_{iR} = \left(\frac{4hl_0}{\rho C_p u_0 d}\right)_{im} \Big/ \left(\frac{4hl_0}{\rho C_p u_0 d}\right)_{ip} = 1 \quad (13)$$

$$\mathrm{Bi}_R = \left(\frac{h\delta}{k_s}\right)_m \Big/ \left(\frac{h\delta}{k_s}\right)_p = 1 \quad (14)$$

3. Scaled Facility Design Results

3.1 Design specifications of URANUS

URANUS is lead-bismuth eutectic cooled small modular reactor utilizing natural circulation. Thermal power of URANUS is 100MWt (40MWe). And it can satisfy requirement of distributed electricity power grid [2, 6]. Key design parameters of URANUS are listed in Table I [2].

Table I: Design parameters of URANUS [2].

Design parameters	Description
Thermal power	100 MWt
Refueling interval	20 years
Plant design lifetime	60 years
Primary coolant	LBE
Primary heat transport system	Pool type
Primary normal cooling mode	Fully natural circulation
Steam generators	8 modules of straight shell-tube type
Secondary water/steam cycle	Rankine cycle with superheated steam
Feed water temperature	252.0 (℃)
Steam outlet temperature	356.0 (℃)
Steam flow rate	188.1 (kg/s)
Inner diameter of shell	3,741 (mm)
Wall thickness of shell	50 (mm)
Total height of inside	9,860 (mm)

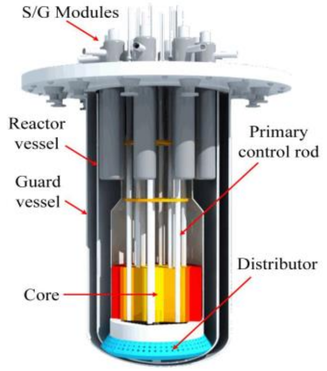

Fig 1. Sectional view of URANUS [2].

3.2 Scaling-down Design

Some constraints like electric capacity, LBE stock and budget make a limitation of mockup size. Due to these constraints, this mockup adapt hybrid-type design and design optimization is conducted. To satisfy mockup mission, key scaling factors are calculated same as prototype. In scaling facility, however, modified Stanton and Biot number are hard to be same with prototype [7]. Distortion of these numbers makes a difference, nevertheless, global phenomenon can be simulated.

3.3 Similarity validation of mockup facility

MARS-LBE code will be used for similarity validation of hand calculation [8]. For the validation of the code, an international group of experts under the auspices of OECD/NEA, called LACANES, has been performed code-to-test results and code-to-code benchmark to apply various system codes to LFR system analysis. In this program, this code shows accurate results compared with experimental results [9]. Based on the conceptual design of mockup, nodalization map for system analysis is shown in Fig 2 [10]. Further iteration of design and code will be conducted.

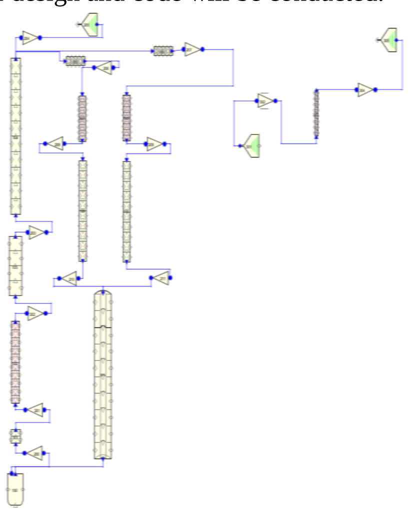

Fig 2. MARS-LBE nodalization map of mockup facility.

4. Conclusions

To validate safety feature and thermodynamics characteristic of URANUS, scaled mockup facility of URANUS is designed based on the scaling law. This mockup adapts two area scale factors, core and lower parts of mock-up are scaled for 3D flow experiment. Upper parts are scaled different size to reduce electricity power and LBE tonnage. This hybrid scaling method could distort some thermal-hydraulic parameters, however, key parameters for experiment will be matched for up-scaling. Detailed design of mock-up will be determined through iteration for design optimization.

5. Future work

Effect of some distorted scaling parts will be evaluated again and the theoretical support of this design will be provided. Through this process, specific design of mock-up parts can be determined by hand calculation and 3D CFD code validation.

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NOMENCLATURE

Roman letters

a	area [m^2]
A	area ratio
Bi	Biot number
c_p	specific heat (at constant pressure) [J/(kg K)]
d	diameter [m]
f	friction coefficient
g	gravitational acceleration [m/s^2]
h	heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
K	form loss coefficient
l	length of a component [m]
L	length ratio
$\dot{m}$	mass flow rate [kg/s]
p	pressure [Pa]
Q_s	heat source number
$\dot{q}$	heat density[W/m^3]
Re	Reynolds number
St	modified Stanton number
T	temperature [K]
Ti	time ratio number
u	velocity [m/s]

Greek letters

β	isobaric thermal expansion coefficient of a fluid [K^{-1}]
δ	conduction depth [m]
ρ	density [kg/m^3]

Subscripts

i	referring to i-th component
m	model
o	reference constant value
p	prototype
r	representative variable of a system
s	solid

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