HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

WATER-LBE FLOW SIMILARITY LAWS AND THEIR NUMERICAL EXPERIMENTS

Chen X.-N.*[1], Chen Z.[1,2] and Chen H.[2]

[1]Institute for Nuclear and Energy Technologies (IKET),
Karlsruhe Institute of Technology (KIT),
D-76344 Eggenstein-Leopoldshafen, Germany
E-mail: xue-nong.chen@kit.edu

[2]School of Nuclear Science and Technology (SNST),
University of Science and Technology of China (USTC),
Hefei, Anhui, 230027 China

ABSTRACT

This paper studies theoretically and numerically flow similarity laws between water and lead-bismuth eutectic (LBE) liquid. It is associated practically with the problem how to use water to simulate experimentally natural convections in an LBE cooled reactor. It is revealed that Reynolds, Richardson and thermal power similarity laws can hold not only globally (in a sense of the global parameters) but also locally. The water model scale, power and other factors are determined by choosing the inlet and outlet temperatures, so that the local Reynolds numbers at these two points in the water experiment are equal to the corresponding LBE ones. Several cases are shown by the variation of the inlet temperature. There are two particular cases: (i) Froude numbers are equal additionally; (ii) the model scale is one to one. For the case of the model scale 1:1, the similarity solution is presented in detail. Numerical experiments of reactor flows of both water and LBE are carried out. They show that the theoretical similarity predictions can have deviations of 5% in Reynolds number and 10% in Richardson number. The reason for it is that flow patterns in the upper coolant plenum are different due to the much lower LBE Prandtl number than waters one.

NOMENCLATURE

A	[m^2]	Flow area
c_p	[J/kg]	Specific heat capacity
D_H	[m]	Hydraulic diameter
Gr	[-]	Grashof number
g	[m/s^2]	Acceleration due to gravity
H	[m]	Heat exchanger height
L_w	[m]	Flow area associated wet perimeter
$\dot{m}$	[kg/s]	Mass flow rate
P	[W]	Power
p	[Pa]	Pressure
Re	[-]	Reynolds number
Ri	[-]	Richardson number
T	[K, °C]	Temperature
u	[m/s]	Velocity

Special characters

λ	[-]	Scale ratio of water to LBE
μ	[kg/m/s]	Dynamical viscosity
ν	[m^2/s]	Kinematical viscosity
ρ	[kg/m^3]	Density

Subscripts

in	Core inlet
LBE	Lead-Bismuth-Eutectic
out	Core outlet
water	Volumetric effective expression

INTRODUCTION

Heavy metal liquids, e.g. liquids of lead or lead-bismuth eutectic (LBE), are considered world-widely to be used as coolant for future fast reactors, especially for accelerator driven systems (ADS). Their natural convection ability has been recognized and applied to cool passively the reactor in operational and accident conditions [1,2]. Its flow distribution in the active core and the reactor pool is a crucial issue for the design of such a kind of reactor. The small-scale loop experiment cannot solve this problem. The experiments with heavy metal liquids in a large scale are very expensive and demand a high technology, mainly because of their high material costs, especially for LBE, their high melting points and corrosion problems. Unfortunately such experiments are still necessary for studying flow distribution in natural and forced convection states.

In this paper, additionally to previously discovered Reynolds and Richardson similarity laws [3], Froude similarity law is found to be valid as well for certain model scale. It has been proved theoretically that all these characteristic numbers can be equal for water and LBE at the same time! This makes it possible to use water to simulate the whole LBE reactor flow experimentally.

The similarity laws should be validated at best by experiments. At the moment we don't have possibility to carry out both water and LBE experiments. Therefore, the numerical validation is reasonable and feasible approach. A numerical method to simulate multi-channel reactor flow based on a CFD code has been developed. In this paper we would like to apply this calculation method to do numerical experiments to prove the similarity laws and to show how to interpret the water results to the LBE ones. The numerical results show that there are only slight differences between water and LBE natural convection flows. The reason for that is the heat transfer processes are different in the upper coolant plenum due to different Prandtl numbers, which has a macroscopic effect on the flow pattern and correspondingly the pressure distribution at the core outlet.

FLOW SIMILARITY LAWS BETWEEN WATER AND LBE

Natural Convection Problem and Its Modelling

We consider a nuclear fission reactor that produces a certain amount of thermal power and is cooled by liquid lead or LBE, see Figure 1. The coolant is heated up, as it goes through the reactor core, and takes the heat with it away from the core and is cooled down, as it goes through the heat exchanger and gives the heat to the so-called secondary circuit. The density difference between hot and cold sides leads to a static pressure difference, which is a driving force (a kind of buoyancy) that makes the coolant be circulated by itself, even if there is no pump. This is the so-called natural convection, which can be used to cool the reactor under operational or accident conditions [1,2,3].

The natural convection is actually a balance (equilibrium) between two effects, namely the pressure drop mainly due to viscous friction and the driving pressure due to the difference of density between hot and cold sides. Therefore two principal non-dimensional parameters, Reynolds number and Richardson number, come into play. The problem can be formulated and solved in an integral equation model, as given in the next.

As already described in [3], the transient integral model can be formulated. For the sake of simplicity we consider now only the steady state.

The mass conservation gives that the mass flow rate is constant in a flow channel,

$$\dot{m} = \rho u A = const. \tag{1}$$

where u is the mean flow velocity. Since different channel has different mass flow rate, we may consider an average channel for set-up similarity laws and extend their results approximately to other channels.

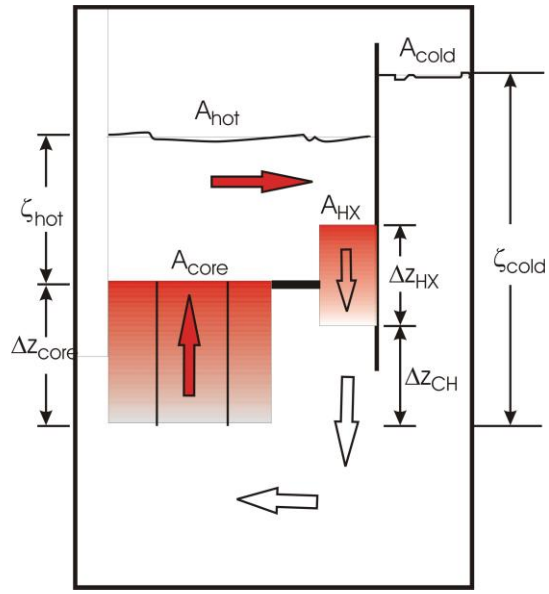

Figure 1 Schematic of theoretical modeling of an LBE cooled reactor

The momentum conservation gives the pressure balance, i.e. the dynamic pressure drop Δp_d is equal to the static buoyancy pressure, as

$$\Delta p_d = \Delta\rho\, g\, H \tag{2}$$

where H is the effective height between the levels of core and heat exchanger mean temperatures, $\Delta\rho$ the density change between cold and hot sides and g the gravity acceleration

The energy conservation leads to an equation for obtaining the temperature as,

$$\dot{m} c_p(T)\frac{dT}{dx} = \frac{dP}{dx} \quad \Rightarrow \quad \int_{T_{in}}^{T_{out}} c_p(T)\,dT = \frac{P}{\dot{m}} \tag{3}$$

where P is the channel power, T_{in} and T_{out} the core inlet and outlet temperatures, respectively

In order to obtain the similarity laws we have to non-dimensionalize our formulation. Because the mass flow rate is constant, it can be used as a basic quantity for the non-dimensionalization. The coolant velocity is expressed as

$$u = \frac{\dot{m}}{\rho A} \ . \tag{4}$$

As usual the pressure equation (2) is divided by $\bar{\rho}\bar{u}^2$, where $\bar{\rho}$ and $\bar{u}$ are the average coolant density and velocity in the core. Thus, its right-hand side becomes the Richardson number, i.e.

$$Ri = \frac{\Delta\rho}{\bar{\rho}}\frac{gH}{\bar{u}^2} \ . \tag{5}$$

The left-hand side of (2) can be evaluated as usual by various correlations of pressure losses [4] as

$$\frac{\Delta p_d}{\bar{\rho}\bar{u}^2} = \frac{1}{\bar{\rho}\bar{u}^2}\left\{\sum_i \left[f(Re_{D_H}) \frac{L}{D_H}\frac{1}{2}\rho u^2 \right]_i + \sum_j \left[K\frac{1}{2}\rho u^2 \right]_j \right\}, \tag{6}$$

where index i indicates a certain flow section and index j a certain position where the flow area changes significantly, Re_{D_H} is the local Reynolds number defined as

$$Re_{D_H} = \frac{u\,D_H}{\nu}. \tag{7}$$

and D_H the hydraulic diameter defined as

$$D_H = \frac{4A}{L_W}, \tag{8}$$

where A is the flow area and L_w the associated wet perimeter.

The power in the energy equation can be normalized as, (3) divided by $\bar{c}_p \Delta T$,

$$\frac{1}{\bar{c}_p \Delta T}\int_{T_{in}}^{T_{out}} c_p(T)\,dT = \frac{P}{\dot{m}\bar{c}_p \Delta T}, \tag{9}$$

where $\bar{c}_p$ is the average coolant heat capacity, $\Delta T = T_{out} - T_{in}$, T_{in} and T_{out} are the core inlet and outlet temperatures. Since the average coolant heat capacity can be defined as

$$\bar{c}_p = \frac{1}{\Delta T}\int_{T_{in}}^{T_{out}} c_p(T)\,dT, \tag{10}$$

the dimensionless power becomes unity, i.e.,

$$\frac{P}{\dot{m}\bar{c}_p \Delta T} = 1. \tag{11}$$

Approach to Similarity Laws

The geometrical similarity is a basis for the physical similarity. Assume that the water experiment facility is similar to the LBE one with a model scale factor λ defined as

$$\lambda = \frac{L_{\text{water}}}{L_{\text{LBE}}}. \tag{12}$$

where L_{water} and L_{LBE} are typical lengths in the water and LBE experiments, respectively. It seems at the moment that it can be chosen arbitrarily for a global parameter similarity. Later on we will see that it will be determined for a more accurate local similarity.

The physical similarity will be achieved (guaranteed) by establishing the equality between LBE and water experiments in the three non-dimensional numbers, i.e. Reynolds number, Richardson number and the non-dimensional power number. We call processes of equating these three numbers as Reynolds similarity law, Richardson similarity law and power similarity law. These three similarity laws can be satisfied by suitably choosing water experiment parameters. Since we use water to simulate an LBE experiment, we may call the LBE experiment the original (target) experiment and the water one the model experiment.

Starting point is that the LBE experiment parameters are fixed according to a certain design, such as the core thermal power, the coolant inlet and outlet temperatures and the coolant mean velocity. For instance the temperature range in the LBE experiment is determined mainly due to corrosion limits of materials, e.g. from 270 °C to 430 °C. First of all we fix certain model scale λ. By Reynolds similarity law, where we may first consider its mean value defined as,

$$\bar{R}e_{D_H} = \frac{\bar{u}\,\bar{D}_H}{\bar{\nu}}. \tag{13}$$

We can determine the coolant average velocity in the water experiment, if the average kinematical viscosity is known, which depends on the choice of temperature range. Then, by Richardson similarity law (5), in which the part $gH/\bar{u}^2$ is associated with the coolant velocity as discussed before, we obtain $\Delta\rho/\bar{\rho}$ for the water experiment. Consequently we can determine the temperature range for the water experiment. Notice that we still have the possibility of choosing parameter T_{in}, which is very important for the further discussion on the local similarity. Finally by the power similarity law (11), we determine the power for the water experiment.

Up to this step we realized the global similarity between LBE and water experiments. Naturally the question is arising here, how about the local similarity. This is particularly important for the local Reynolds similarity, because the viscous friction depends on the local Reynolds number. We notice that the viscosity and density of LBE and water have similar trends with temperature variation. Therefore we might choose a suitable value of T_{in} in the water experiment, so that the variation of the viscosity is also in similarity, i.e. *Re* numbers are same in the both experiments. This can be realized as well and will be discussed in detail in the next subsection.

Since the density change is linear with temperature in the considered similarity temperature ranges, the global Richardson similarity will cover the local Richardson similarity, meaning the local similarity concerning $\Delta\rho/\bar{\rho}$ has already been guaranteed by the global similarity.

The local power similarity will be approximated, since c_p varies very slightly with temperature, where $\Delta c_p/\bar{c}_p$ is just a few percentage.

Thermo-physical Properties and Local Similarity

The density of LBE liquid depends almost solely on temperature. Its density variation with pressure can be totally neglected, not only because it is very small, but also the cover gas pressure in the LBE system is just about 1 bar or less. An empirical formula for it has been given in [5], as repeated here as,

$$\rho_{\text{LBE}}[\text{kg/m}^3] = 11096 - 1.3236T[\text{K}]. \quad (14)$$

The dynamical viscosity of LBE liquid has been given in [5] as well, as repeated here as

$$\mu_{\text{LBE}}[\text{Pa s}] = 4.94 \times 10^{-4} \exp\left[\frac{754.1}{T[\text{K}]}\right]. \quad (15)$$

The kinematical viscosity of LBE liquid can be calculated by using (14) and (15) in the following formula,

$$\nu_{\text{LBE}} = \frac{\mu_{\text{LBE}}}{\rho_{\text{LBE}}}. \quad (16)$$

The heat capacity of LBE liquid is repeated here as well [5] as

$$c_{\text{p,LBE}}[\text{J/(kg K)}] = 159.0 - 0.0272T + 7.12 \times 10^{-6}T^2. \quad (17)$$

where temperature is in Kelvin.

There are a lot of open sources for obtaining water thermo-physical properties. We just use the website of U.S. National Institute of Standards and Technology (NIST) [6] for obtaining data. Except the boiling point of water, the thermo-physical properties change very slightly with pressure. For the sake of simplicity, we might assume they are independent of pressure. Since the water density change with temperature is not linear, we may need a larger temperature range for searching our similarity solution. Therefore we consider in this paper the temperature range from 0 to 200 °C at pressure of 16 bar. We have following fitting functions

$$\rho_{\text{water}}[\text{kg/m}^3] = 1001.0934 - 0.0796868T - 0.00375086T^2 + 3.615219 \times 10^{-6}T^3, \quad (18)$$

$$\mu_{\text{water}}[\text{Pa s}] = \frac{0.001779}{1 + 0.03368T + 0.0002210T^2}, \quad (19)$$

$$c_{\text{p, water}}[\text{J/(kg °C)}] = 4204.87 - 0.961226T + 7.85734 \times 10^{-3}T^2 + 2.0525 \times 10^{-5}T, \quad (20)$$

where temperature is in °C.

The local Richardson and Reynolds similarities demand the local Richardson and Reynolds numbers defined in (5) and (7) to be equal in the both experiments. Since the mass flow rate is constant through the flow channel, it is more accurate to discuss two numbers in a form based on the mass flow rate as

$$Ri = \frac{\Delta\rho\,\bar{\rho}}{\dot{m}^2} gH\bar{A}^2, \quad Re_{D_H} = \frac{\dot{m}}{\mu}\frac{D_H}{A} \quad (21)$$

We eliminate the scale factor λ by multiplying $\left(Re_{D_H}\, A/D_H\right)^5$ and $Ri/(H\bar{A}^2)$ to get a new dimensionless number, i.e.

$$\left(Re_{D_H}\, A/D_H\right)^5 Ri/(H\bar{A}^2) = \frac{\dot{m}^3}{\mu^5}\Delta\rho\,\bar{\rho}\, g. \quad (22)$$

By the similarity requirement it implies

$$\left(\frac{\dot{m}^3}{\mu^5}\Delta\rho\,\bar{\rho}\right)_{\text{water}} = \left(\frac{\dot{m}^3}{\mu^5}\Delta\rho\,\bar{\rho}\right)_{\text{LBE}}. \quad (23)$$

This equation includes only the flow and thermo-physical properties without the scale factor λ. Thus, we first make the similarity of the local dynamical viscosity change. This can be approached by suitably choosing T_{in} and T_{out} in the water experiment so that

$$\frac{\mu(T_{\text{in}})_{\text{water}}}{\mu(T_{\text{in}})_{\text{LBE}}} = \frac{\mu(T_{\text{out}})_{\text{water}}}{\mu(T_{\text{out}})_{\text{LBE}}} = \frac{\mu_{\text{water}}}{\mu_{\text{LBE}}}. \quad (24)$$

Then we calculate

$$\frac{\left(\Delta\rho\,\bar{\rho}\right)_{\text{water}}}{\left(\Delta\rho\,\bar{\rho}\right)_{\text{LBE}}}. \quad (25)$$

where

$$\Delta\rho = \rho(T_{out}) - \rho(T_{in}),$$

$$\bar{\rho} = \left[\rho(T_{out}) + \rho(T_{in})\right]/2. \quad (26)$$

By (23) we obtain

$$\frac{\dot{m}_{\text{water}}}{\dot{m}_{\text{LBE}}} = \left[\left(\frac{\mu_{\text{water}}}{\mu_{\text{LBE}}}\right)^5 \Big/ \frac{\left(\Delta\rho\,\bar{\rho}\right)_{\text{water}}}{\left(\Delta\rho\,\bar{\rho}\right)_{\text{LBE}}}\right]^{\frac{1}{3}}. \quad (27)$$

Returning to the Reynolds similarity law (21), we obtain the model scale factor as

$$\lambda = \frac{L_{\text{water}}}{L_{\text{LBE}}} = \frac{\dot{m}_{\text{water}}}{\dot{m}_{\text{LBE}}} \Big/ \frac{\mu_{\text{water}}}{\mu_{\text{LBE}}}. \quad (28)$$

The power similarity gives

$$\frac{P_{\text{water}}}{P_{\text{LBE}}} = \frac{\Delta T_{\text{water}}}{\Delta T_{\text{LBE}}}\frac{\bar{c}_{\text{p, water}}}{\bar{c}_{\text{p,LBE}}}\frac{\dot{m}_{\text{water}}}{\dot{m}_{\text{LBE}}}. \quad (29)$$

So now we have completed the local similarity laws, i.e. Reynolds, Richardson and energy similarity laws hold not only globally but also locally. It is amazing and very useful for using water to simulate LBE circulations.

Similarity Examples

For the sake of simplicity we fix the temperature range in the LBE experiment for the whole discussion in this section as $T_{\text{in, LBE}}$ = 270 °C (543 K) and $T_{\text{out, LBE}}$ = 430 °C (703 K). The power and the mass flow rate, which are associated with each other as given in (3), are actually parameters that are searched and determined in the natural convection experiments upon a certain reactor design. Therefore they are not fixed here.

Inlet Temperature Variation in Water Experiments

We choose several inlet temperatures as input data and go through the local similarity laws described before. The results are shown in Table 1. With the increase of inlet temperature the model scale factor decreases, the model power factor decreases as well and the model velocity factor increases only slightly. Since the temperature range is below 100 °C, e.g. in Case 1, it can be carried out at atmospheric pressure, but its size scale and power is more than doubled in the water model experiment. Case 4 shows a particular situation, where the model is one-to-one to the real one and the heat power is reduced by a factor of 0.661. The model scale and the power can be even reduced by choosing a higher inlet temperature, as shown in Cases 5 and 6. If we want to even reduce the model size, we can still go on to increase the inlet temperature. This means higher pressure is needed for avoiding that the temperature reaches the boiling point. This is definitively feasible with today's water technology.

Table 1. Results of Model Experiments by Variation of Inlet Temperature

Case	**1**	**2**	**3**	**4**	**5**	**6**
T_{inlet},°C	60	88.56	100	118.45	130	140
T_{outlet}, °C	81.8	115.53	129.0	150.7	164.3	176.1
ΔT, °C	21.8	26.97	29.0	32.28	34.3	36.1
Model scale factor	2.166	1.4166	1.229	1.000	0.891	0.811
Model power factor	2.006	1.0911	0.888	0.661	0.559	0.490
Model velocity factor	1.1419	1.1901	1.206	1.225	1.236	1.246

By calculation of examples of inlet temperature variation we found in this paper that the Froude similitude law can hold as well, which was not expected before doing calculations. In Case 2 the inlet temperature is so chosen, so that the model scale factor is equal to the square of the model velocity factor, i.e. the Froude numbers in both water and LBE cases are equal. In other cases the Froude law does not hold. Therefore, for the transient simulation where free surface motions have influence, Case 2 is recommended for applying.

Theoretical Results of 1:1 Scale Water Experiment

As a particular example we choose Case 4, where the model geometric scale is identical to the original LBE one, for presenting our similarity results. We assume that the linear power rate is constant along the core height. Therefore the temperature distribution along the core height can be solved easily by integrating (3). Since the heat capacities of water and LBE are almost constant, the temperature distributions are almost linear along the core height and they are overlapped, as shown in Figure 2. The maximal discrepancy of $\Delta T/\Delta T_{\max} = (T - T_{in})/(T_{out} - T_{in})$ between water and LBE is about 0.005.

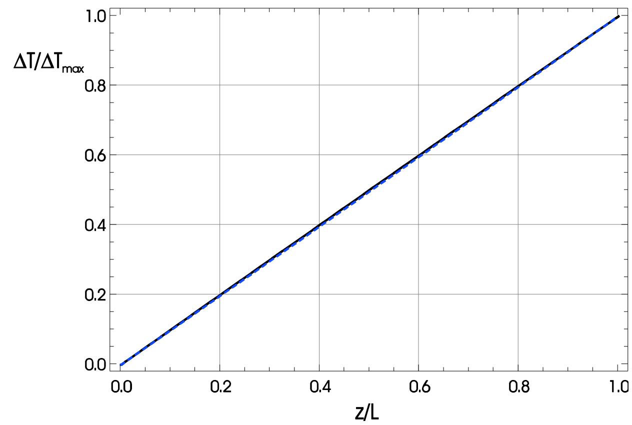

Figure 2 Relative temperature distributions for water and LBE Experiments

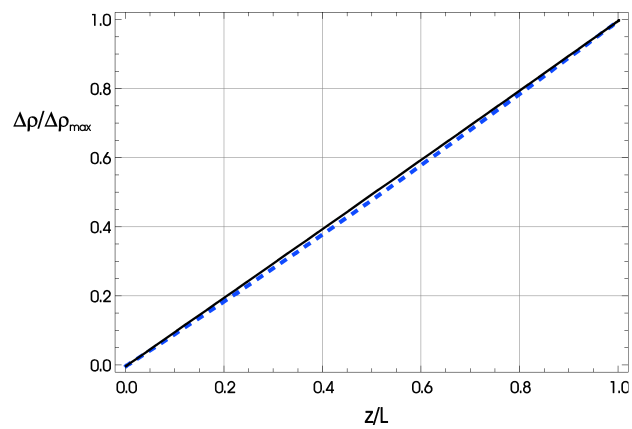

Figure 3 Relative density change distributions for water (lower dashed one) and LBE (upper solid one) experiments

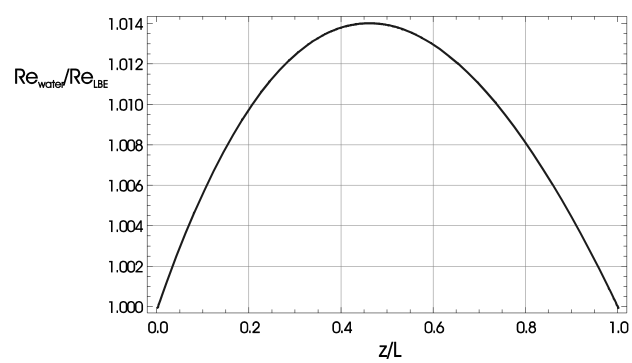

Figure 4 Reynolds number ratio of water/LBE

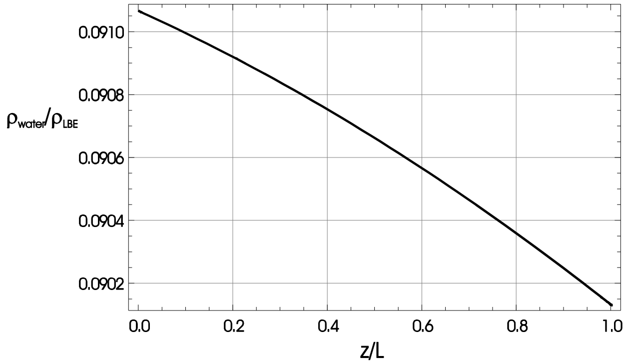

Figure 5 Local density ratio of water/LBE

The comparison of relative density changes are shown in Figure 3. Their difference is zero at the two ends of reactor and their maximal difference about 0.02 taking place at the core mid-plane. This implies that the local Richardson similarity holds as well as the global one.

The local Reynolds number ratio Re_{water}/Re_{LBE} is shown in Figure 4. As we chose the inlet and outlet temperatures in the water experiment, we made this ratio equal to one at the core inlet and outlet. The maximal deviation of Reynolds number is only 1.4% occurring at the core mid-plane. Therefore the Reynolds similarity law has been guaranteed very well locally everywhere in the reactor. This is very important for experimental pressure drop simulations.

The local density ratio is shown in Figure 5. It has been required that this ratio is equal at the two reactor ends. Nevertheless the deviation of this ratio from its average value is only about 0.5 %. This implies that the velocity deviation from its average value has the same amount. Therefore the similarity laws hold very well for every variable.

NUMERICAL EXPERIMENTS

Numerical experiments are carried out for a very preliminary design of LBE cooled reactor [7] with the CFD code FLUENT. The reactor core is divided by five active sub-assembly (SA) rings and is simulated by the porous medium model with certain pressure drop correlation. The power density distribution is adapted from a neutronic calculated result. Since in this paper only the steady state is investigated, the thermal power is directly deposited in the coolant in the active core. Therefore the fuel pin-coolant heat transfer process in the active core region will not be simulated.

The thermal physical properties such as density, viscosity, heat capacity and thermal conductivity are inputted as functions of temperature for both water with (18), (19), (20) and LBE with (14), (15), (17) correspondingly. Case 4 is chosen, where the water experiment scale is 1:1 to the LBE one. The LBE reactor power is 20.55 MW and the average inlet and outlet temperatures are 543 and 703 K. Correspondingly the water reactor power is 20.55*0.661 = 13.58 MW and its average inlet and outlet temperatures are obtained as 391 and 423 K. The flow distribution has not been adjusted to be uniform on purpose. This means all orifice coefficients in flow channels are equal. The heat exchanger height is 2 m for both water and LBE experiments.

Figure 6 shows the numerical results of the velocity distribution at the core outlet for both water and LBE cases. Figure 7 shows calculated velocity ratio of water to LBE in comparison with the theoretical value. The theoretical prediction has an about 3% deviation.

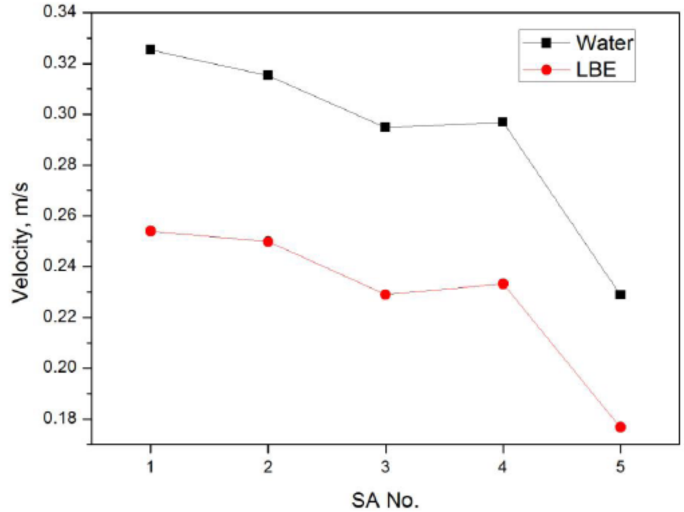

Figure 6 Calculated velocity distributions of water and LBE at the core outlet

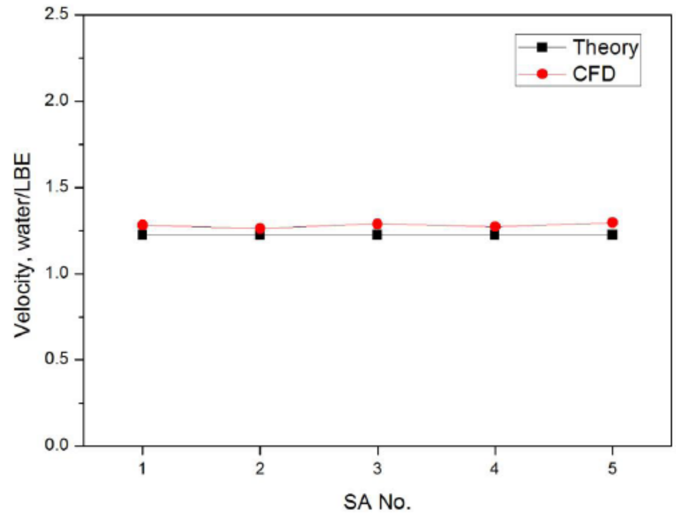

Figure 7 Calculated velocity ratio of water to LBE at the core outlet in comparison with the theoretical value

Figure 8 shows calculated local Reynolds numbers at the core outlet for both water and LBE cases. They have 5% difference in both cases, although their shapes are quite similar. Figure 9 shows calculated local Richardson numbers at the core outlet for both water and LBE cases. The difference in Richardson numbers becomes larger, about 10%. The reason was analysed in the following.

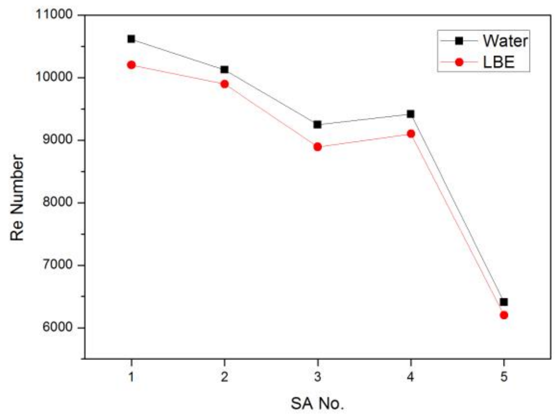

Figure 8 Calculated local Reynolds numbers of water and LBE at the core outlet

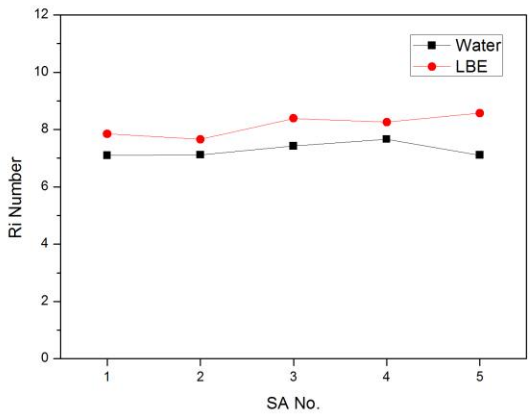

Figure 9 Calculated local Richardson numbers of water and LBE at the core outlet

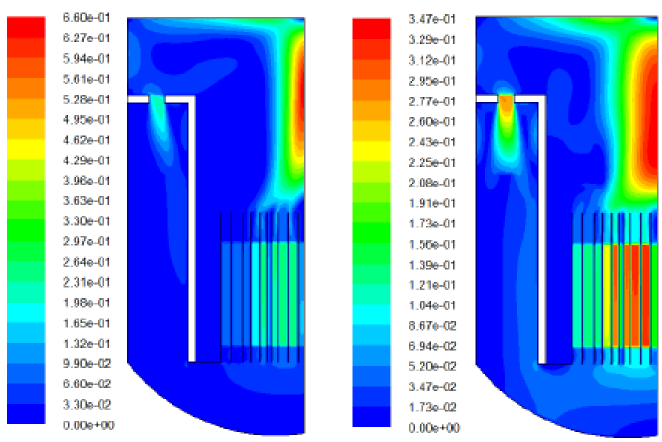

Figure 10 Calculated velocity fields of LBE (left) and water (right)

It has been shown by the numerical experiments that the flow rate distributions in the core region are quite similar between water and LBE. However the flow patterns are quite different in the upper coolant plenum, where the thermal boundary layers (density layers) appear differently because of very different thermal conductivities (Prandtl numbers), where the waters Prandtl number is about 100 times higher than the LBE's. To confirm this effect, we did additional calculations by increasing the water thermal conductivity artificially, so that the water Prandtl numbers is equal to the LBE one. Really, as expected, the difference between water and LBE flows in the upper coolant plenum disappears in the new calculated results. This confirms that the reason for the difference is due to the different Prandlt numbers of water and LBE.

CONCLUSION

This paper studies similarity laws between water and LBE liquid under natural convention conditions. It demonstrates that the large scale of water experimental simulation is appropriate for the LBE natural convention flow. The similarity laws of Reynolds, Richardson, Froude and power hold concurrently and moreover not only globally but also locally, i.e. every variable is well locally in similarity. Although the current study is orientated in the natural convection steady state, it can be extended to forced convection unsteady states in a straightforward manner.

Numerical results confirm that the similarity laws can work quite well in the core flow region. But due to very different thermal conductivities of water and LBE, the upper plenum flows are quite different. This affects the outlet pressure quite significantly. For the very preliminary LBE cooled reactor design, the water simulation could have 5% error and 10% error in Reynolds number and Richardson number, respectively. The CFD method could be useful to correct the error in water simulation results.

REFERENCES

[1] De Bruyn, D., Ait Abderrahim, H., Baeten, P., and Fernandez, R., MYRRHA: the Multi-purpose hYbrid Research Reactor for High-tech Applications, *Performance & Flexibility: the Power of Innovation (ICAPP'11)*, Nice, France, 2011, pp. 472-478

[2] Wallenius, J., and Suvdantsetseq, E., ELECTRA: European Lead Cooled Training Reactor, *GLOBAL 2011*, Makuhari, Japan, 2011, pp. 300

[3] Chen, X.-N., On LBE natural convection and its water experimental simulation, *Progress in Nuclear Energy*, 2014, accepted and proofed for publishing

[4] Waltar, A.E., and Reynolds, A.B., *Fast Breeder Reactors*, Pergamon Press, New York, Oxford, Toronto, Sydney, Paris, Frankfurt, 1981

[5] OECD/NEA Nuclear Science Committee, Working Party on Scientific Issues of the Fuel Cycle, Working Group on Lead-Bismuth Eutectic, *Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-Hydraulics and Technologies*, OECD/NEA, Nuclear Energy Agency 2007

[6] US National Institute of Standards and Technology (NIST), http://webbook.nist.gov/chemistry/fluid/, Gaithersburg, MD, USA, 2012

[7] Chen, Z., Zhou, P.C., Chen, G. M., and Chen, H. L., Studies of core flow distribution for small modular natural circulation lead or lead-alloy cooled fast reactors, *Annals of Nuclear Energy*, accepted for publishing