Validation of the 1-D Thermal Stratification Model in Gallium Environment

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INTRODUCTION

Understanding the thermal fluid phenomena in different components of the nuclear reactor systems is crucial for reactor safety analysis. The study of thermal stratification in liquid-metal-cooled reactors (LMRs), among the others, is especially indispensable due to its large impact.

Thermal stratification could occur in an LMR in various conditions, including the down-power transients or the Protected Loss of Flow (PLOF) accidents, where cooler coolant flows out of the core to the upper plenum, or the Unprotected Loss of Flow (ULOF) accidents, where hotter coolant flows from the core to the upper plenum. Thermal stratified layers could be formed in the upper plenum of an LMR under the scenarios mentioned above and introduce uncertainties to the core safety. The stratified layers are unstable and could cause temperature oscillations with fairly large amplitude [1], which further result in neutronic and thermal-hydraulic instabilities. The stratified layers with a large temperature gradient could also damage both the reactor vessel and the in-vessel components through thermal fatigue crack growth. More importantly, the formation of the stratified layers could impede the establishment of natural circulation during accidental scenarios, which endangers the passive safety of LMRs.

Various approaches with different fidelities have been investigated to provide predictions of this phenomenon to prevent its occurrence or to mitigate the damage caused. System-level codes require minimal time for the predictions, but can only provide approximated solutions for simple cases because of the highly simplified models employed. The CFD methodologies, on the other hand, provides high-fidelity calculations, but at high computational expenses. In our precious work [2, 3], we developed an integrated 1-D system-level model with improved fidelity for the prediction of the thermal stratification phenomenon in the pool-type sodium-cooled reactors (SFRs). The experimental data used for the development and validation of the 1-D thermal stratification model was acquired in the Thermal Stratification Experimental Facility (TSTF) [4] built at the University of Wisconsin-Madison, using sodium as the working fluid.

In this paper we will investigate the applicability of the 1-D model, developed using the experimental data acquired in a sodium environment, to the gallium environment. In this study, the experimental data used for the model validation was acquired in the Gallium Thermal-hydraulic Experiment (GaTE) [5] built at Kansas State University, using gallium as the working fluid.

EXPERIEMENTAL DESIGN

The Thermal Stratification Experimental Facility

The Thermal Stratification Experimental Facility (TSTF) was designed and built at the University of Wisconsin-Madison to provide high-quality experimental data for the development of the 1-D stratification model. Its test section consisted of cylindrical tank with a height of about 150 cm and a diameter of about 32 cm. During the experiments, the tank was initially filled with hotter sodium, and cooler sodium was injected from the bottom of the tank through three inlets with a diameter of about 1.3 cm. The three inlets were isometrically located around the centerline of the tank. A diagram of the TSTF is shown in Figure 1.

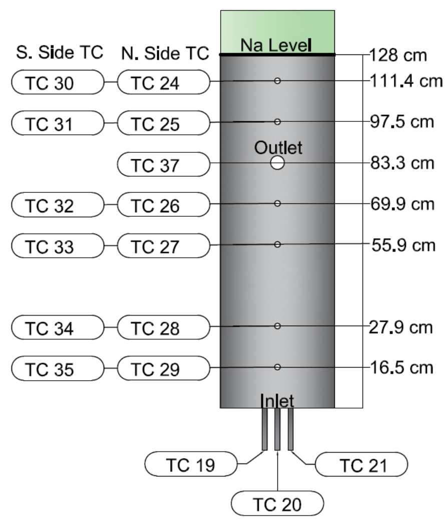

Figure 1. The test section of the TSTF (Credit of [3]).

The temperature measurement was made through thermocouples, located at 2.45 cm from the tank wall at six different axial levels. The outlet was located at 83.3 cm from the inlets. The temperature measurement from the thermocouples located at 16.5 cm, 27.9 cm, 55.9 cm, and 69.9 cm was used for the development of the 1-D thermal stratification model because this model can only be used to predict the temperature profile before the outlet.

The Gallium Thermal-hydraulic Experiment

The Gallium Thermal-hydraulic Experiment (GaTE) was designed and built at the Kansas State University to provide high-quality experimental data for the validation of the 1-D stratification model. Its test section consisted of cylindrical tank with a height of about 40 cm and a diameter of about 15 cm. During the experiments, the tank was initially filled with hotter gallium, and cooler gallium was injected from the bottom of the tank through a center inlet with a diameter of about 5.3 cm. A diagram of the GaTE is shown in Figure 2.

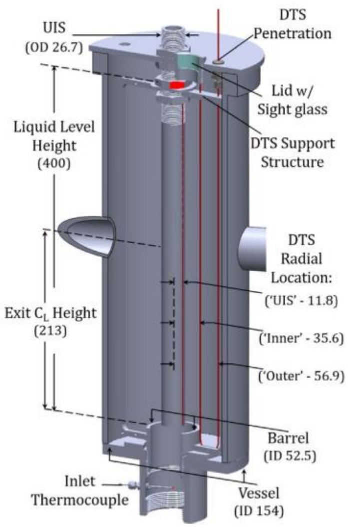

Figure 2. The test section of the GaTE (Credit of [5]), the unit for the length shown is mm.

The temperature measurement was made throughout the height of the test section by using distributed temperature sensors. Two arrays of sensors, located at 3.6 cm (T1) and 5.7 cm (T2) from the centerline were used for the temperature measurement of the fluid, while the last array of the sensors was embedded within the Upper Internal Structure (UIS). The outlet was located at 21.3 cm from the inlets, and the temperature measurement from T1 and T2 located at 10 cm and 20 cm was used for the validation of the 1-D thermal stratification model because this model can only be used to predict the temperature profile of the fluid before the outlet.

1-D SYSTEM LEVEL MODEL

The governing equation

Following the work of Peterson [6], Eq. (1) was developed in our previous studies [2, 3]:

$$\rho_{amb} c_{p,amb} \frac{\partial T_{amb}}{\partial t} + \rho_{amb} c_{p,amb} \frac{Q_{jet}}{A_{amb}} \frac{\partial T_{amb}}{\partial z} - \frac{\partial}{\partial z}\left(k_{amb} \frac{\partial T_{amb}}{\partial z}\right) = \frac{c_{p,jet}\rho_{jet}}{A_{amb}} Q'_{jet}\left(T_{jet} - T_{amb}\right) \quad (1)$$

where the mass density, heat capacity, surface area, temperature, and thermal conductivity of the ambient fluid were respectively represented by $\rho_{amb}, c_{p,amb}, A_{amb}, T_{amb}$, and k_{amb}. The mass density, heat capacity, volumetric flow rate, temperature, and the linear volumetric dispersion rate of impinging jet were respectively represented by $\rho_{jet}, c_{p,jet}, Q_{jet}, T_{jet}$ and Q'_{jet}. The only two terms that needed additional closure relations were k_{amb} and Q'_{jet} in Eq. (1), and the temperature profile of the ambient fluid could be obtained by numerically solving this equation.

Modeling of k_{amb}

k_{amb} is equal to the static thermal conductivity of the ambient fluid, k_s, when the ambient fluid is not disturbed by the impinging jets. This only happens when the velocity of the impinging jets is close to zero. When the velocity of the impinging jets becomes larger, turbulence will be created in the ambient fluid, and its conductivity will be enhanced. In one concurrent research [7], we performed an inverse uncertainty quantification (inverse UQ) study and established an empirical correlation between k_{amb} and k_s based on the non-dimensional numbers Re_τ and Ri:

$$k_{amb} = a\left(\frac{Re_\tau}{Ri}\right)^b \cdot k_s \quad (2)$$

Here Re_τ and Ri are respectively the turbulence Reynolds number of the impinging jet and the Richardson number of the ambient fluid, whose definition are given in [3]. The inverse UQ study was performed based on the experimental data acquired in the TSTF, and the empirical combinations of a and b were determined in different ranges of $\frac{Re_\tau}{Ri}$, as summarized in Table 1. The procedure of obtaining these parameters are elaborated in Ref. 7 and will not be repeated here. Due to the lack of experimental data, the boundaries of each $\frac{Re_\tau}{Ri}$ range remain to be confirmed, but are sufficient for the purpose of the current study. This correlation is expected to have reasonable performance in the gallium environment thanks to the non-dimensional numbers used in terms of its establishment.

Table 1. k_{sf}/k_c ratio in different $\frac{Re_\tau}{Ri}$ ranges.

$\frac{Re_\tau}{Ri}$	k_{amb}
$\frac{Re_\tau}{Ri} < 0.01$	k_s
$0.01 \le \frac{Re_\tau}{Ri} < 1$	$7.8\left(\frac{Re_\tau}{Ri}\right)^{0.035} k_s$
$1 \le \frac{Re_\tau}{Ri}$	$7.8\left(\frac{Re_\tau}{Ri}\right)^{0.32} k_s$

Modeling of Q'_{jet}

In this study we adopted an extreme simplification on Q'_{jet} by assuming meaning it to have a uniform profile within the jet length L_{jet}:

$$Q'_{jet} = Q_{jet}/L_{jet} \quad (3)$$

where L_{jet} can be estimated as:

$$L_{jet} = \int_{t=0}^{t(v=0)} (v_0 - (C\frac{v^2 \rho_{amb}}{\rho_{jet}} + \frac{\rho_{jet} - \rho_{amb}}{\rho_{jet}})dt)dt \quad (4)$$

Here v_0 is the initial jet velocity, and the C is a constant which was determined in [3] through data-driven methods, by using the experimental data from the TSTF. Because the model for L_{jet} was not established using non-dimensional numbers, it is not expected to provide good predictions in the GaTE environment when the enclosure geometries and the fluid properties are different. However, the error caused by the use of this jet model will not be significant when the impinging jet velocity is small.

RESULTS

Six sets of experimental data from the GaTE were used to investigate the applicability of the 1-D model. In all the six experiments, the initial temperature in the test section was 100 °C and the impinging jet had a temperature of 50 °C. The jet velocity and the resultant $\frac{Re_\tau}{Ri}$ of each test are summarized in Table 2.

Table 2. Test conditions of the GaTE experiments.

Test #	jet velocity (mm/s)	Re_τ/Ri
1	2.39	0.003
2	10	0.02
3	20	0.05
4	40	0.14
5	60	0.29
6	80	0.51

The comparison between the 1-D model predictions with the experimental data set #1 is shown in Figure 3. Because of the small jet velocity, $k_{amb} = k_s$ was used for the calculation.

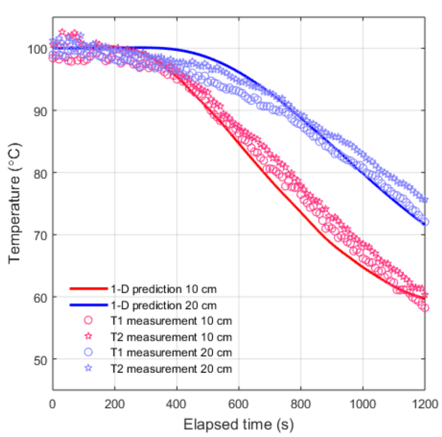

Figure 3. Comparison between the 1-D prediction and the experimental data for test #1.

The good agreement observed in 1-D prediction and experimental data of test #1 proved the 1-D model to be physically reasonable. The comparisons between the 1-D model predictions with the experimental data acquired in tests #2-6 are shown in Figure 4 to Figure 8, respectively. The outstanding agreements between 1-D predictions and experimental data in tests #2-4 demonstrated the viability of the empirical correlation of k_{amb}, obtained from the sodium experiment, to be used in the gallium environment. Because of the increase in jet velocity from test #2 to #6, the jet length increased. The impact of k_{amb} on the predicted temperature profile decreased because the ambient fluid was cooled directly by the jet through convection rather than by cooler ambient fluid through conduction. The fact that the 1-D model did not work as well in tests #5-6 as in tests #2-4 revealed the insufficiency of the jet model used. Establishing a more accurate and physical model for the impinging jet dispersion rate will be the focus of our future work.

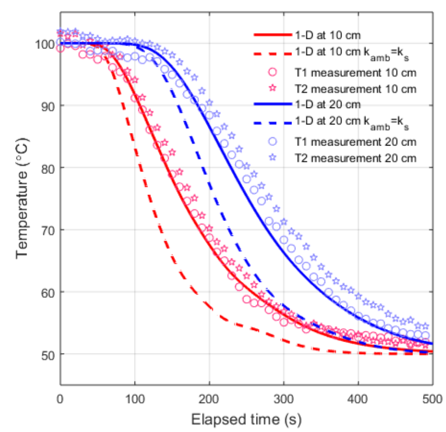

Figure 4. Comparison between the 1-D prediction and the experimental data for test #2.

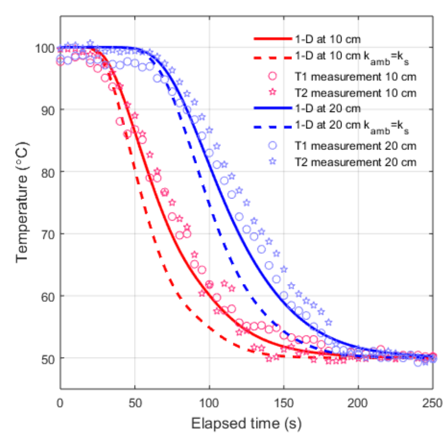

Figure 5. Comparison between the 1-D prediction and the experimental data for test #3.

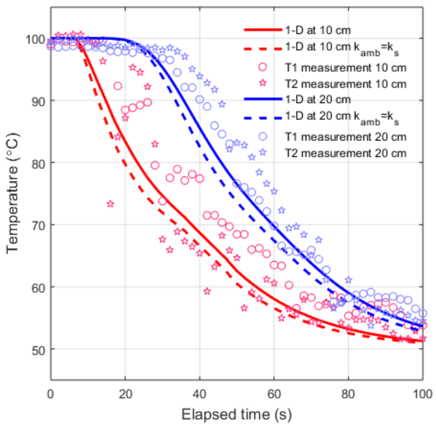

Figure 6. Comparison between the 1-D prediction and the experimental data for test #4.

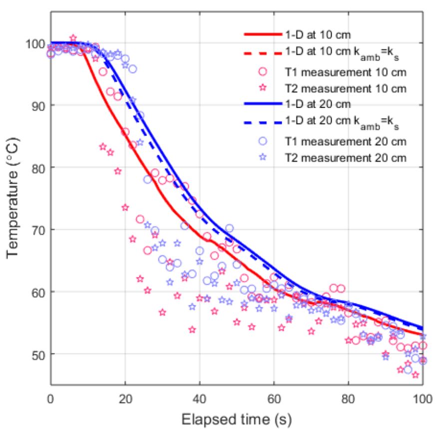

Figure 7. Comparison between the 1-D prediction and the experimental data for test #5.

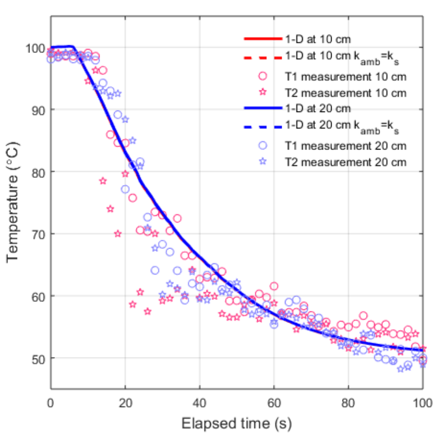

Figure 8. Comparison between the 1-D prediction and the experimental data for test #6.

CONCLUSIONS

In this paper, we examined the applicability of 1-D thermal stratification model, developed using the experimental data acquired in a sodium environment, to the gallium environment. The sodium experimental data was acquired in TSTF built at the University of Wisconsin-Madison, while the gallium experimental data was acquired in GaTE established at Kansas State University.

The comparison between the 1-D prediction and the experimental data demonstrated that the improved correlation of k_{amb}, trained with the sodium data, had reasonable performance in the gallium environment thanks to the non-dimensional numbers used in terms of its establishment. The model for L_{jet}, on the other hand, did not work as well in a new environment where the enclosure geometries and the fluid properties are different. A more accurate and physical model based on non-dimensional numbers for the impinging jet dispersion rate will be the focus of our future work.

In this work, the Re_{τ}/Ri was only calculated at the beginning of the problem and assumed to be identical at all axial levels. For a better performance, in future work we will calculate these non-dimensional numbers at each node, and have them updated throughout the calculation.

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