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Numerical Investigation of Pipe Diameter Influence on Turbulent Behavior in Molten Salt Natural Circulation Systems

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1. Introduction

Molten salts are promising high-temperature heat transfer media for advanced nuclear reactors and thermal energy storage systems. In natural circulation loops (NCLs), flow is driven by buoyancy without mechanical pumps, making geometric effects critical for stability. As system scales increase, pipe diameter may significantly influence turbulence onset and flow behavior. This study investigates diameter-induced turbulence in molten salt NCLs using transient CFD simulations with the SST (URANS) model. Turbulence intensity is quantified through eddy viscosity ratio.

2. Methods and Results

In this section, the numerical methods and modeling approaches used to simulate the molten salt natural circulation loop are described. The computational model includes the geometric configuration of the loop, thermophysical properties of the molten salt, boundary condition implementation, and turbulence modeling using the SST (URANS) approach. The present study extends previous modeling work on natural circulation loops reported in [2], where the governing equations, numerical implementation, and validation strategy were comprehensively established. The current investigation adopts the validated numerical framework from Simamora et al. [2] and further develops it to examine the influence of pipe diameter on turbulent behavior. Detailed descriptions of the numerical formulation, verification process, and validation methodology are documented in [2].

2.1 Benchmark Experiment

The present numerical model is validated against the Molten-Salt Natural Circulation Loop (MSNCL) experiment reported by Srivastava et al. [1]. The Inconel 625 loop has a rectangular geometry (2 m height, 1.4 m width) with 15 mm NB SCH 80 piping (13.88 mm inner diameter, 3.73 mm thickness, 38 mm bend radius). Molten salt is melted in a pressurized tank and circulated by buoyancy induced through electrical heating and air cooling. Temperature measurements at heater and cooler inlets/outlets are used for validation. The study focuses on the vertical-heater–horizontal-cooler configuration, referencing detailed operational procedures from [1]. The numerical work then extended to different diameter such as 1”, and 2” to see the diameter effect on the natural circulation behavior.

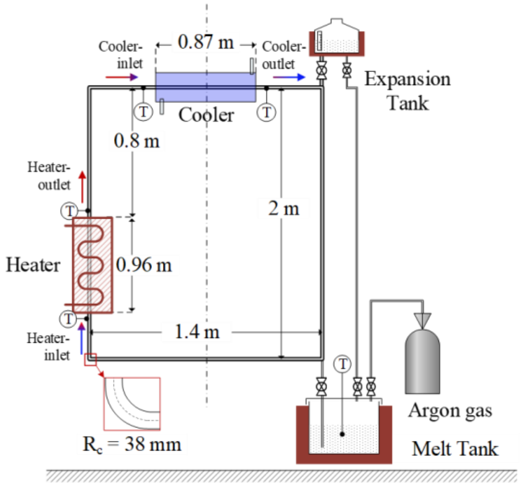

Fig. 1 Simplified schematics of MSNCL experiment [2]

2.2 Numerical Model of Transition – SST

The modeling approach for natural circulation in this study applies the Transition-SST turbulence model within a transient CFD framework. Equations (1)–(3) represent the momentum-related transport equations in the Transition SST framework. Equation (1) describes the transport of turbulent kinetic energy, including transient, convective, production, dissipation, and diffusive terms. Equation (2) governs the transport of the specific dissipation rate, which controls the turbulence scale through corresponding production, dissipation, and diffusion mechanisms. Equation (3) is the intermittency transport equation, enabling prediction of laminar-to-turbulent transition by modeling transition onset and suppression effects. Equation (4) is the energy equation, which accounts for transient and convective heat transfer, with thermal diffusion modeled using the effective thermal conductivity to incorporate both molecular and turbulent heat transport.

$$\frac{\partial(\rho k_{TKE})}{\partial t}+\frac{\partial(\boldsymbol{u}_j)}{\partial x_j}=P_k-Y_k+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k_{TKE}}{\partial x_j}\right] \qquad \text{Eq. (1)}$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho\boldsymbol{u}_j\omega)}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\beta_t\rho\omega^2+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial\omega}{\partial x_j}\right] \qquad \text{Eq. (2)}$$

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho\boldsymbol{u}_j\gamma)}{\partial x_j}=P_\gamma-E_\gamma+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial\gamma}{\partial x_j}\right] \qquad \text{Eq. (3)}$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+\boldsymbol{u}\frac{\partial T}{\partial x}+\boldsymbol{v}\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{eff}\frac{\partial T}{\partial y}\right) \qquad \text{Eq. (4)}$$

2.3 Results and Validation

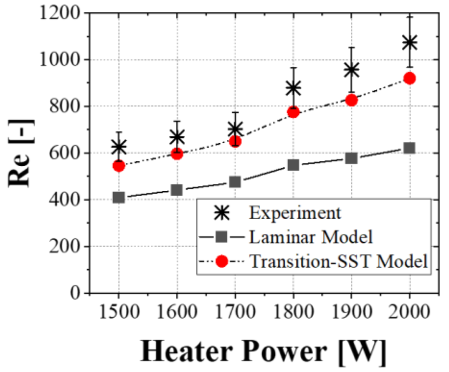

Fig. 2. Results of benchmark studies with Laminar and Transition – SST.

Figure 2 presents the benchmark validation of the numerical model against experimental data prior to extending the analysis to different pipe diameters. The comparison includes predictions from both the laminar and Transition-SST models. The laminar model consistently underpredicts the Reynolds number, particularly as flow intensity increases, indicating its limitation in capturing developing instabilities. In contrast, the Transition-SST model shows significantly improved agreement with the experimental results, accurately reflecting the increasing turbulence effects. This validation confirms that transition modeling is necessary for reliable simulation of molten salt natural circulation and justifies the use of the Transition-SST model for subsequent diameter variation studies. More detailed information on the validation process can be found in [2].

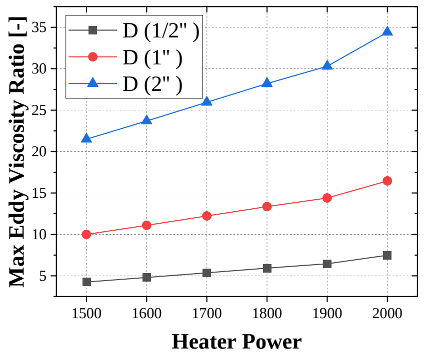

Fig. 3. Diameter-effect on eddy viscosity ratio.

Figure 3 presents the variation of the maximum eddy viscosity ratio for different pipe diameters. The results indicate that larger diameters exhibit higher peak eddy viscosity ratios, suggesting stronger localized turbulence intensity. This behavior is not directly reflected by the Reynolds number, which remains within the nominally laminar range (Re ≈ 400–1000). Therefore, the observed turbulence activity cannot be explained solely by global Reynolds number criteria.

As reported by Reis et al., [3] this phenomenon is associated with thermally developing flow especially near the heater wall where strong temperature gradients induce localized acceleration. In larger diameters, the radial temperature gradient becomes more influential, enhancing the underdeveloped thermal region. The fluid near the heated wall accelerates more rapidly due to buoyancy, while the core region remains thermally developing and rises more slowly. This radial imbalance promotes localized instabilities that are difficult to capture using a purely laminar model, thereby emphasizing the necessity of the Transition-SST approach for accurately resolving such effects.

3. Conclusions

Based on the present results, pipe diameter significantly influences the local turbulent behavior in molten salt natural circulation systems. Although the global Reynolds number remains within the nominally laminar range (Re ≈ 400–1000), the maximum eddy viscosity ratio indicates the presence of localized turbulence. These results suggest that under strong thermal gradients, localized instability mechanisms may arise even when the global Reynolds number remains within the nominal laminar regime. Strong radial temperature gradients accelerate the near-wall fluid, while the core region remains thermally underdeveloped, creating velocity imbalance and localized instabilities. To further validate the observed influence of pipe diameter on the natural circulation loop system, dedicated experimental investigations are proposed as part of future work.

ACKNOWLEDGEMENT

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