Thermal Stratification Modeling for Sodium-Cooled Fast Reactors: A Status Update

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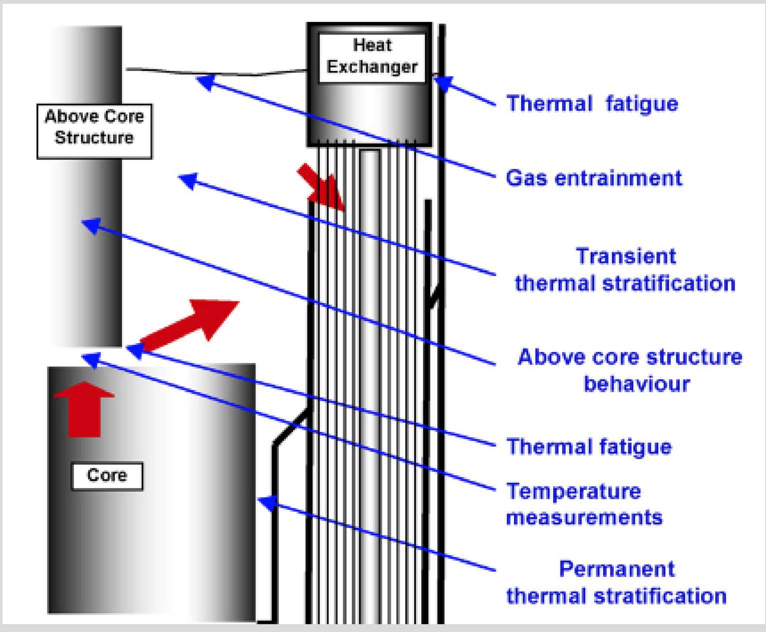
Introduction to Thermal Stratification

Thermal hydraulic behavior in the upper plenum of pool-type sodium-cooled fast reactors (SFRs) is a major concern as many design challenges are concentrated in this region. As SFR designs aim for licensing and commercialization, it is important to accurately analyze and predict the thermal-hydraulic behavior in this region during accident scenarios, specifically thermal stratification.

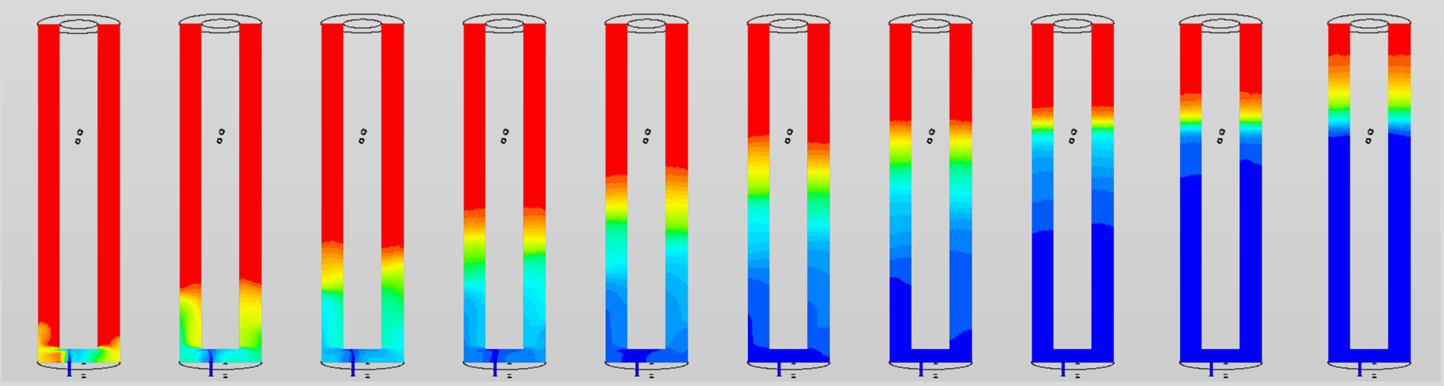


Thermal hydraulic challenges identified in the upper plenum of SFRs (Tenchine).

Thermal stratification is a three dimensional thermal hydraulic phenomenon that can have a large influence on the behavior of a reactor during a transient – possibly affecting the start of natural circulation and decay heat removal in pool-type SFRs. The phenomenon this project is examining occurs in a large pool when the fluid entering is colder than the fluid contained in the pool and the momentum of the flow is not large enough to overcome the negative buoyant force. A difference in fluid density results in denser cold fluid flowing in the lower region of the outlet plenum while the large upper volume of the outlet plenum remains hot. Thermal stratification can also occur in the reverse situation of warmer fluid entering the outlet plenum, also creating density differences. These two cases can be observed in a protected loss of flow (PLOF) and unprotected loss of flow (ULOF) scenarios respectively.

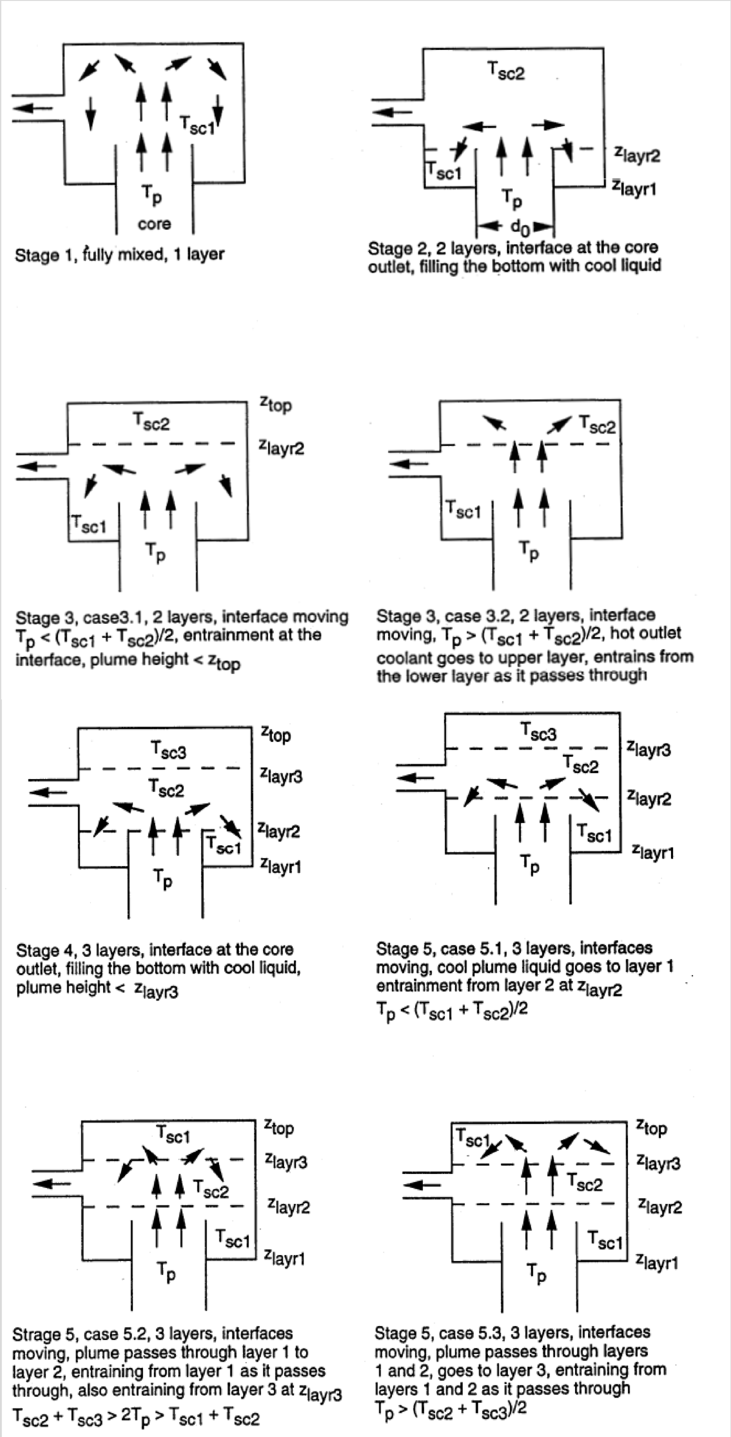
Current Modeling Practices

Thermal stratification models specifically are a major source of uncertainty in most system codes for all types of power plants. Most system codes, including SAS4A/SASSYS-1, a system level code developed by Argonne National Laboratory (Argonne), use coarse meshes that cannot capture the complexities of the stratification phenomena. Other 2-D and 3-D methods, such as computational fluid dynamics (CFD) models, can analyze simple configurations with higher fidelity but at a large computational expense. Finding a modeling solution that is both accurate and computationally efficient has proven difficult over the last several decades.



Thermal stratification in a protected loss of scenario (Baglietto et al. 2017)

SAS4A/SASSYS-1 Stratified Volume Model



Stratified volume stages from SAS4A/SASSYS-1 User's Manual (Fanning).

The SAS4A/SASSYS-1 computer code is a system level code developed by Argonne for thermal, hydraulic, and neutronic analysis for power and flow transients in liquid-metal-cooled fast reactors. It was originally developed in the 1960s and has continuously undergone further development. The stratified volume model currently used in the thermal hydraulics solver PRIMAR-4 of SAS4A/SASSYS-1 stems from the older model developed by Howard and Lorenz. The newer model is now able to handle up transients as well as down transients, and horizontal discharges.

- $\frac{Q}{V_j d_j^2} = \frac{\pi}{4} a(Ri)^{-b}$
- $\frac{\varepsilon}{V_j}\left(\frac{D}{d_j}\right)^2 = a(Ri)^{-b}$
- $w_{ent} = .2\pi\rho_{plume} V_j d_j F_f^{-1.1}$
- $z_0 = \frac{r_0}{.111}$
- $z_m = 1.0484 Fr_0^{0.785}$

Other Modeling Approaches

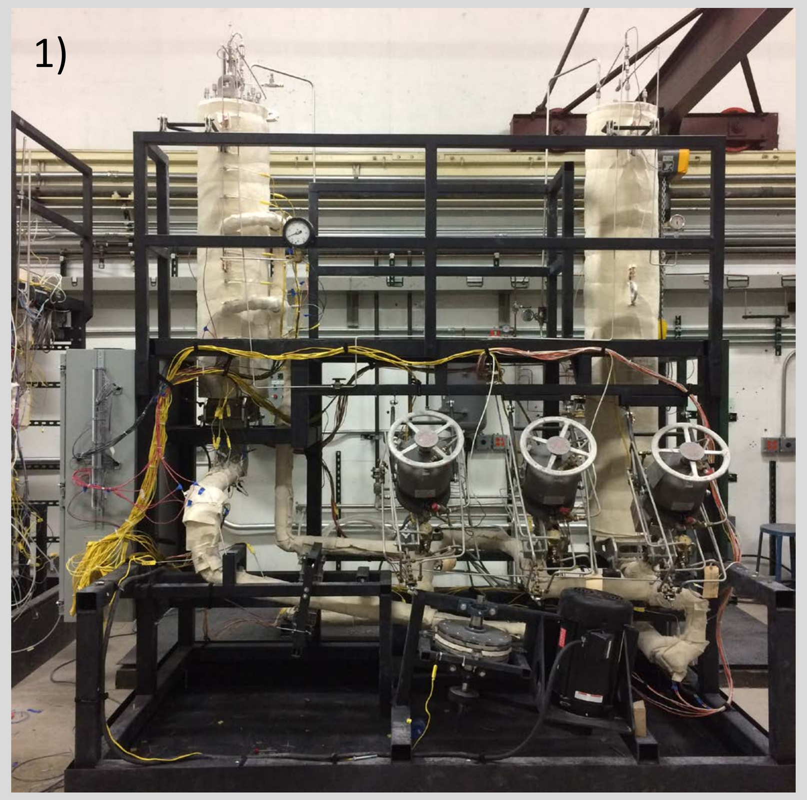
There is a large number of system level codes previously or currently being developed in many countries to predict safety analysis for all types of reactor designs. While not all of these codes have stratified layer models, the ones that do are for the most part inadequate for similar reasons as SAS4A/SASSYS-1. Some codes that have adapted different modeling strategies include CONTAIN, which incorporates a "hybrid flow solver" or GOTHIC which uses network of volumes connected by flow paths. The Japanese code Super-COPD uses a one-dimensional approach and has proven to be effective but still not as accurate at 3D solutions. Berkeley's in house code BMIX++ also uses a 1D approach but struggles with transient situations.

Coupling system level codes with CFD has also been attempted. This involves using CFD to model regions of 3D interest and leave the rest of the reactor loop to be modeled by the system code. While this method has cut down computational time, its computational expense is too large to be used for licensing and design applications.

Future Work

An improved stratified volume model will be developed through this project. This new model will be informed by new experimental data being collected by the UW-Madison collaborators, and by the associated CFD models analyzed by MIT collaborators. Currently a 0D or 1D model is in the process of being further developed. In the future reduced order modeling (ROM) techniques will be used and aided through the use of machine learning.

1)



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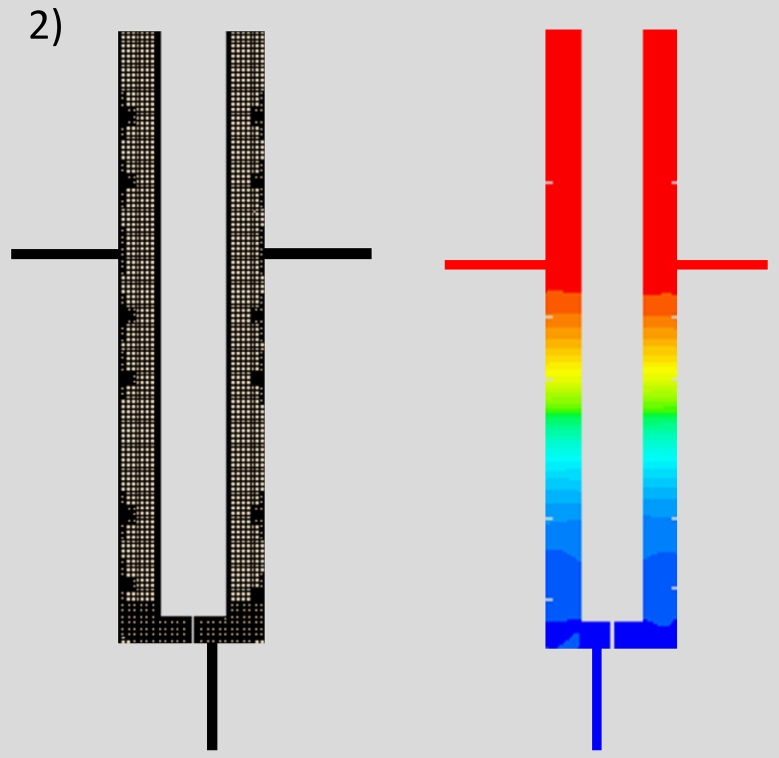

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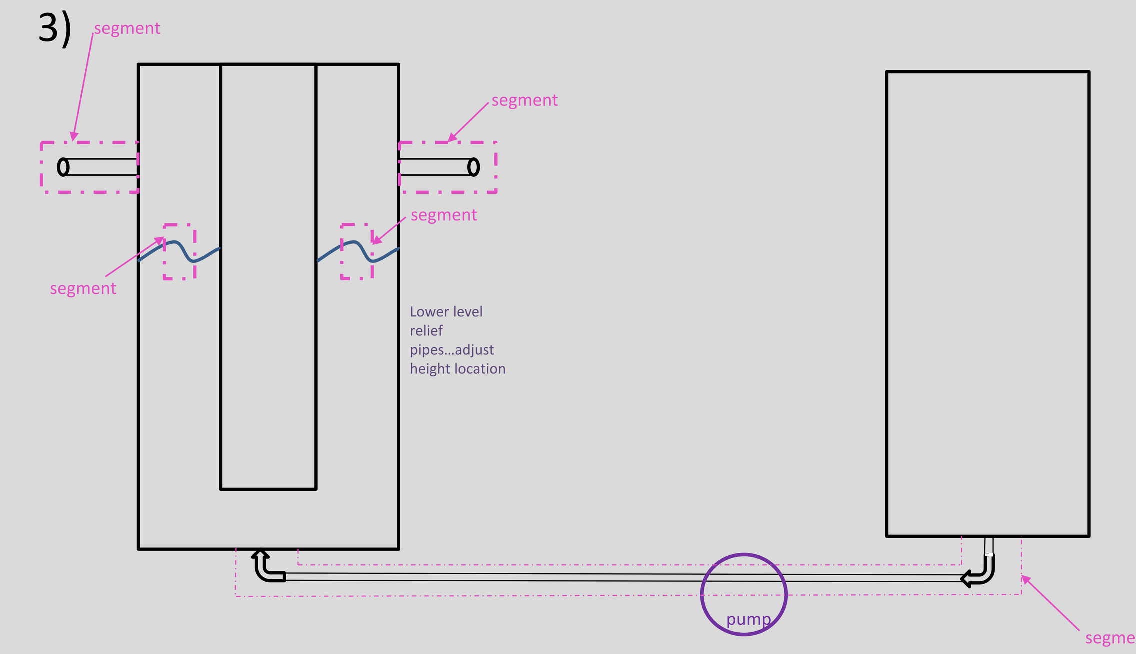

Collaborative efforts among schools include a sodium loop (1) at UW-Madison. The loop was designed with the help of CFD calculations from MIT (2), and constructed at UW-Madison facilities. A simplified model is being developed out of VCU (3). Results from the experiment along with CFD advancements will be compared to the model developed for SAS4A/SASSYS-1.

Acknowledgements

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