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Numerical Study on Unsteady Flow Phenomena Behavior with LES Simulation for High Temperature Test Facility's Lower Plenum

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1. Introduction

The development of Very High Temperature Reactors (VHTR) as Generation IV reactors is driven by their primary objective to supply high-temperature heat for diverse industrial applications such as hydrogen production, petrochemicals, and metallurgy. Furthermore, VHTR demonstrates its versatility by efficiently generating electricity with high thermal efficiency, utilizing either a gas turbine or a steam cycle. Recognized as one of the six reactor technologies endorsed by the Generation IV International Forum (GIF) for the next generation of nuclear energy, VHTR distinguishes itself through characteristics like a higher outlet temperature, lower power density, and passive decay heat removal, contributing to heightened safety and reliability.

Utilizing helium as the primary coolant, VHTR can achieve elevated temperatures suited for various applications. The lower plenum, positioned below the core, serves as the domain where the hot coolant converges before exiting the reactor. Within this lower plenum, a significant technical challenge arises from the turbulent mixing of the coolant, posing the risk of local hot spots on support columns and disrupting the uniformity of the outlet temperature.

To gain a deeper understanding of this issue, computational fluid dynamics (CFD) simulations are employed to model the flow and mixing behavior in the lower plenum. These simulations prove instrumental in optimizing the design and operation of the VHTR lower plenum, ensuring both safety and efficiency. [1]

In the pursuit of comprehensive thermal-hydraulics validation, the benchmark leverages Oregon State University's (OSU) High Temperature Test Facility (HTTF). [2] HTTF, as an extended integral effects experiment, is designed to investigate the transient behavior of high-temperature gas-cooled reactors, featuring prismatic fuel and reflector blocks resembling a quarter-scale model of General Atomics' MHTGR. Various tests, including depressurized conduction cooling (DCC) and pressurized conduction cooling (PCC) transients, were conducted at HTTF to generate high-quality measurement data. [3]

The dataset derived from these experiments serves as a valuable resource for validating thermal-hydraulics codes employed in gas-cooled reactor simulations. This facility is benchmarked around world and the goal of the benchmark is to facilitate solutions through system code, CFD code, or a combination of both system code and CFD model. The benchmark's primary goal is to enhance the accuracy and reliability of these codes by facilitating comparisons between different thermal-hydraulic models and evaluating their performance against experimental measurements obtained at HTTF.

In this Study, we conducted focuses on the CFD simulation of helium gas mixing within the lower plenum of a HTTF.

2. Numerical Methodology

2.1 Analysis Model

A schematic diagram of the HTTF overall configuration and lower plenum is shown in Figure 1. The experimental apparatus was designed to explore the thermal behavior of materials subjected to elevated temperatures and pressures. Utilizing helium as the cooling gas, it is introduced into the lower plenum for experimentation, subsequently directed to the T-junction via an exit duct. The incoming cooling gas is segregated into five groups, each entering the lower plenum with different temperatures and mass flow rates. Following the experimentation in the lower plenum, the helium is discharged from the system through the exit duct, completing the experimental cycle. The configuration and flow path of the cooling gas are visually represented in the provided diagram, elucidating the operational details of the experimental device.

This system serves as a versatile platform for acquiring experimental data under diverse conditions,

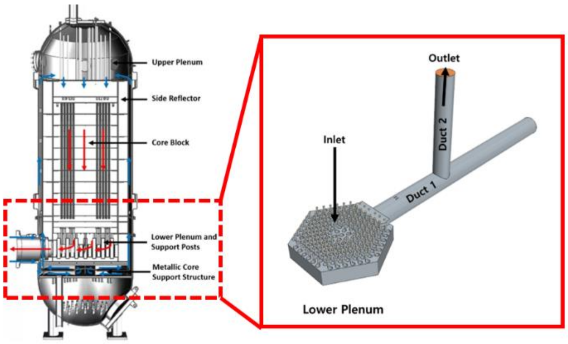

Fig. 1. Schematic of overall HTTF and lower plenum.

thereby advancing our understanding of heat transfer phenomena.

2.2 Numerical Physics and Governing Equations

The turbulent flow in numerical analyses can be categorized into three main techniques: DNS (Direct Numerical Simulation), LES (Large-Eddy Simulation), and RANS (Reynolds-Averaged Navier-Stokes). DNS is utilized to precisely depict the entire turbulent flow field, considering various scales of vortices. LES involves the direct simulation of larger coherent turbulent structures using the computational grid, complemented by modeling smaller turbulent structures through subgrid scale (SGS) models [4]. RANS models employ time-averaging techniques to eliminate unsteadiness, approximating them with engineering models [5]. In this study, for capturing the turbulent behavior in the HTTF, LES models were employed using in the commercial software STAR-CCM+.

The LES WALE (Wall-Adapting Local-Eddy Viscosity) subgrid scale model presents a contemporary approach to subgrid scale modeling, incorporating a novel formulation for the velocity gradient tensor. This model addresses certain limitations observed in previous models by introducing a new framework for subgrid scale modeling. Unlike the universally undefined model coefficient Cw in the Smagorinsky subgrid scale model, the WALE model does not have a universally defined coefficient, which may be perceived as a drawback [6]. However, a notable advantage of the WALE model is its exemption from the requirement of near-wall damping, as it inherently ensures accurate scaling near the walls. The distinctive feature of the WALE model lies in its refined velocity gradient tensor formulation, contributing to its enhanced accuracy in representing turbulent flows. Furthermore, its practicality and reliability are underscored by the absence of the need for wall damping and its intrinsic ability to provide accurate scaling near walls. The WALE subgrid scale model formulates the subgrid scale viscosity through a mixing length type formula as follows:

$$\mu_t = \rho \Delta^2 S_w \ (1)$$

The deformation parameter S_w is defined as:

$$S_w = \frac{S_d{:}S_d^{3/2}}{S_d{:}S_d^{5/4} + S{:}S^{5/2}} \ (2)$$

The tensor S_d is defined as:

$$S_d = \frac{1}{2}\left[\nabla v \cdot \nabla v + (\nabla v \cdot \nabla v)^T\right] - \frac{1}{3} tr(\nabla v \cdot \nabla v) I \ \ (53$$

Where I is the identity tensor.

2.3 Fast Fourier Transform analysis

The Fast Fourier Transform (FFT) is an algorithm designed for the rapid computation of the Discrete Fourier Transform (DFT) by leveraging periodicity and symmetry properties. Employing FFT allows for the efficient conversion of a signal into the digital frequency domain. In this study, FFT analysis was executed to scrutinize potential hazards related to thermal striping arising from the intricate jet mixing behavior or occurrences of hot striking within the system.[7]

2.4 Boundary conditions

The boundary conditions for the HTTF are presented in Table 1. Inlet conditions are classified into five groups, each characterized by distinct flow rates. Exit conditions are defined as pressure outlets, ensuring that the exit mass flow rate aligns with the total inlet mass flow rate to the experimental setup. Adiabatic conditions are applied to the inlet walls, rake, and adiabatic walls, while the remaining walls are held at constant temperatures. For the computational fluid analysis, a no-slip condition was imposed on all walls. The computational fluid analysis grid created using STAR-CCM+ consists of approximately 80 million hexahedral cells. Solver settings for the turbulence models used in the analysis are summarized in Table 2.

Table 1: Boundary Condition

	Name	Mass flow rate [kg/s]	Total Temperature [K]
Inlet	Inlet 1	1.30E-3	562.22
	Inlet 2	9.83E-3	561.84
	Inlet 3	1.48E-2	541.34
	Inlet 4	1.54E-2	512.03
	Inlet 5	4.67E3	471.64
Outlet	Name	Gauge Pressure [Pa]	Static temperature [K]
	outlet	110486.05	504.25
Wall	Name	Condition	Temperature
	Duct Wall 1	No-slip	416.17
	Duct Wall 2		309.32
	Lower plenum side		435.71
	Lower plenum Bottom		476.88
	Lower Plenum Top		565.68
	Column Walls		518.26
	Extruded Inlet Wall		Adiabatic
	Rake		Adiabatic

Table 2: LES model solver setup for HTTF lower plenum

Simulation type	3D, Implicit-unsteady
Turbulence model	LES
SGS model	WALE
Convection scheme	Bounded-central
Time step size [s]	1.0E-3
Temporal discretization	Second-order
Inner loop iteration	10

3. Results

The location of the thermocouple for measuring the temperature of the lower plenum is shown in Figure 2. As shown in the figure, the temperature is measured at 25% and 75% of the total height of the lower plenum at a total of 16 positions. [8]

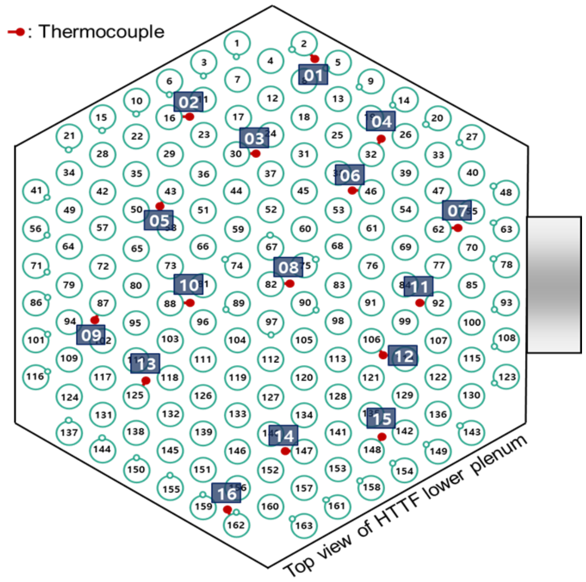

Fig. 2. Thermocouple location in lower plenum

The temperature data measured from the 25%height thermocouple is shown in Figure 3, and the temperature data measured from the 75%height thermocouple is shown in Figure 4.

In the course of a 10-second duration, temperature data was recorded at discrete measurement points at 0.001 s intervals. A discernible trend emerged, with the temperature fluctuation level at the position 75%height notably exceeding that recorded at 25%height. This discrepancy in fluctuation levels suggests a spatial variability in the thermal dynamics within the system. Furthermore, the lower plenum side wall, characterized by a lower temperature range, exhibited the most pronounced temperature fluctuations. This observation underscores the significance of localized thermal conditions, particularly along the lower plenum side wall, contributing valuable insights into the intricate thermal behavior of the system.

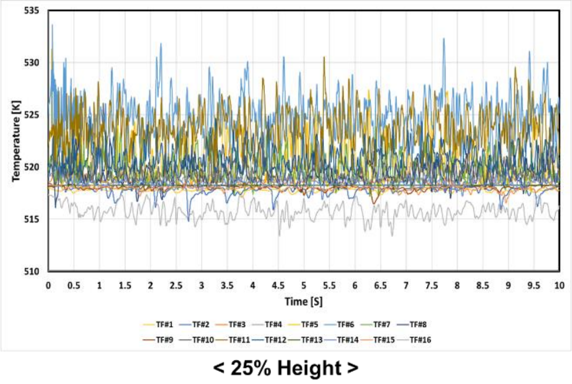

Fig. 3. Simulated Temperature data on each measurement thermocouples of lower plenum 25%height

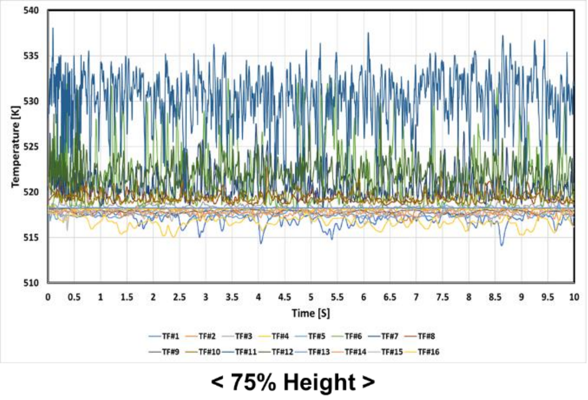

Fig. 4. Simulated Temperature data on each measurement thermocouples of lower plenum 75%height.

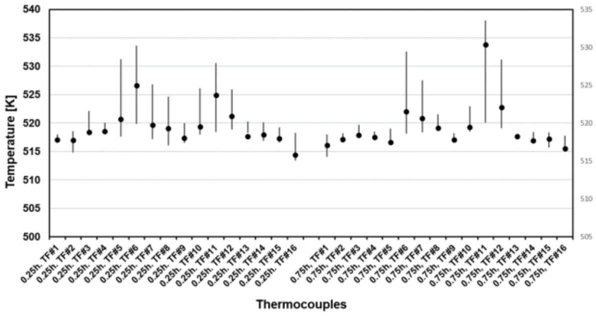

Fig. 5. Simulated mean variables and variances at thermocouples of lower plenum

A graph summarizing the simulated mean variables and variances for the thermocouples in the lower plenum is shown in Figure 5. The graphical representation serves to elucidate the meticulously calculated average temperature and temperature variation characteristics for all Thermocouple at distinct vertical positions—specifically, at 25% and 75% heights. An examination of the graph brings to light a noteworthy observation the region proximal to TF#5, 6, 7, 11, and 12 manifests itself as an area marked by conspicuous temperature fluctuations and suboptimal helium gas mixing dynamics.

This analysis discerns a specific spatial domain within the experimental system where the thermal dynamics and gas distribution deviate significantly from anticipated norms. Such observations, rooted in a comprehensive analysis of the presented data, furnish invaluable insights into the nuanced performance characteristics of the experimental setup, paving the way for targeted refinement and optimization in subsequent investigations.

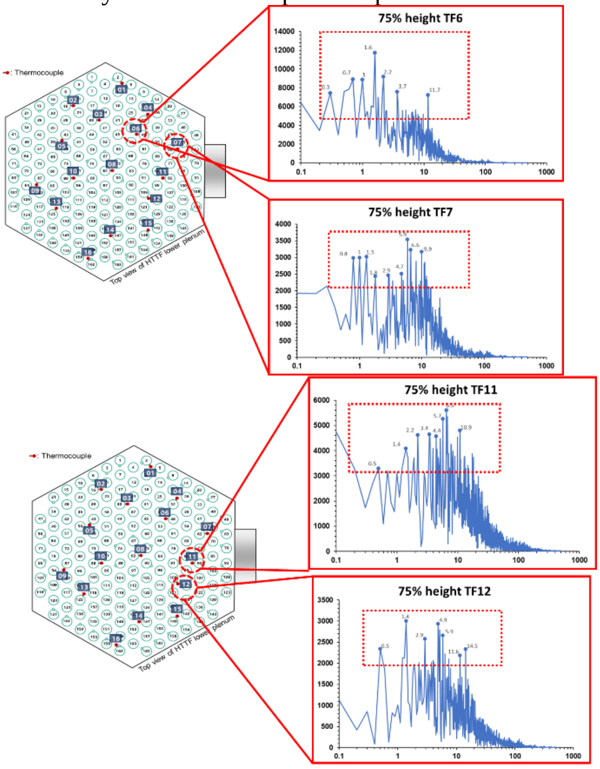

Fig. 6. FFT Analysis of Temperature Data on 25%h

The summary of the FFT analysis of the temperature data at 25% height is shown in Figure 6, and the summary of the FFT analysis of the temperature data at 75% height is shown in Figure 7. Through FFT analysis, it is discerned that the predominant distribution of peak temperature frequencies occurs within the range of 1 to 10 Hz. The temporal characteristics of temperature fluctuations in the lower plenum are illuminated by the vital insights offered through this frequency distribution. Furthermore, the predictive capability of material strength through FFT analysis offers profound insights, emerging as a pivotal indicator intricately linked to the temporal characteristics.

4. Conclusions

In conclusion, this study presents a comprehensive analysis of the thermo-hydraulic behavior of the High-Temperature Test Facility (HTTF) lower plenum through a high-fidelity computational fluid dynamics (CFD) approach, employing Large Eddy Simulation (LES) models. The LES simulation provides valuable quantitative insights into the unsteadiness within the HTTF lower plenum, allowing for a thorough examination of the system dynamics.

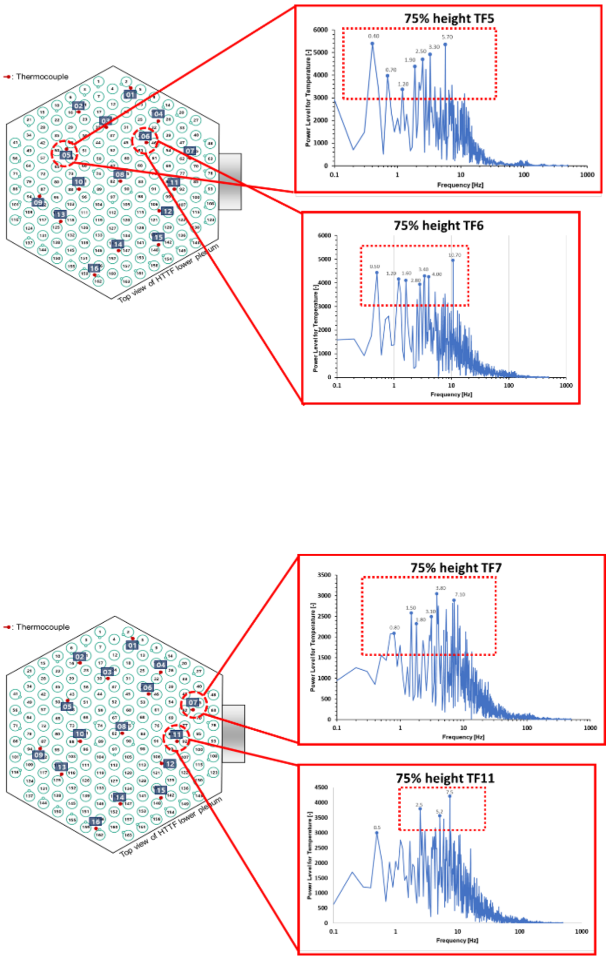

Fig. 7. FFT Analysis of Temperature Data on 75%h

The investigation reveals that the fluctuation levels at 0.75%height of the lower plenum are significantly higher compared to those at 0.25%height, indicating that the primary factor influencing fluctuation levels is the inlet flow characterized by elevated temperatures. Notably, the most substantial temperature fluctuations occur on the lower plenum side wall, exhibiting a distinct pattern within a lower temperature range.

The Fast Fourier Transform (FFT) analysis reveals that peak temperature frequencies are predominantly distributed within the range of 1 to 10 Hz. This frequency distribution provides crucial information about the temporal characteristics of temperature fluctuations in the lower plenum.

In summary, the high-fidelity CFD analysis using LES models enhances our understanding of the thermo-hydraulic behavior in the HTTF lower plenum, shedding light on the factors influencing temperature fluctuations. These insights contribute to the broader goal of improving the safety and efficiency of nuclear reactor systems through advanced simulation and analysis techniques.

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