Thermal Flow Analysis using ROMs of CFD for MCR of Nuclear Power Plants

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1. Introduction

This paper explores the development of a real-time thermal flow analysis system using Digital Twin (DT) technology for temperature control in the Main Control Room (MCR) of a nuclear power plant. DT, which digitally replicates physical systems, allows for advanced simulations and optimizations, particularly in complex environments like nuclear power plants.

The MCR's precise temperature control is critical, yet current methods face challenges due to sensor malfunctions or placement limitations. To address this, the study aims to develop a Reduced Order Model (ROM) based on Computational Fluid Dynamics (CFD) to obtain real-time 3D temperature distributions. The research involves designing a virtual MCR and HVAC system, performing CFD analysis under various conditions, and creating and validating the ROM for real-time application (Fig.1).

The goal is to enhance the safety and efficiency of MCR operations by leveraging Digital Twin technology for improved temperature control.

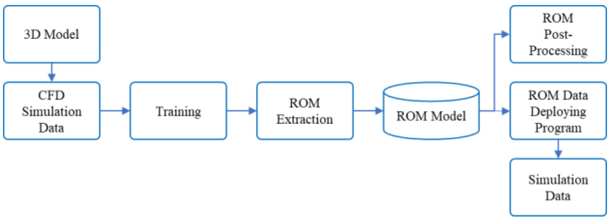


Fig. 1 ROM generation workflow.

2. CFD Analysis

A 3D Computational Fluid Dynamics (CFD) analysis was conducted to obtain the three-dimensional temperature distribution under various operating conditions within a virtual nuclear power plant control room. For this purpose, a 3D CAD model of the control room was created, the flow analysis domain was extracted, and the CFD analysis mesh was generated. By applying various boundary conditions to this mesh, the CFD analysis was performed, and the temperature distribution within the control room under different operating conditions was obtained.

In this study, a total of 96 CFD analyses were conducted to obtain the three-dimensional temperature distribution within a virtual nuclear power plant control room under various operating conditions, as outlined in Table 1 and Table 2. The CFD results of Case 1 are shown in Fig. 3.

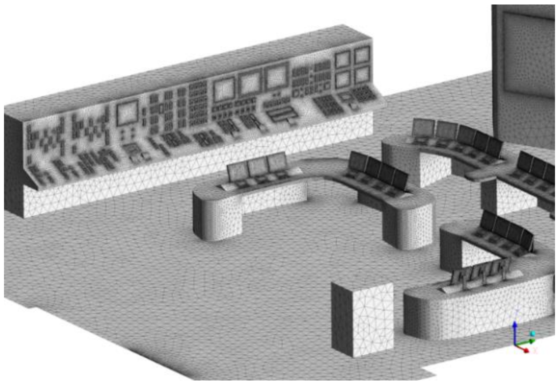


Fig. 2 CFD analysis model configuration and mesh system.

Table 1 CFD analysis conditions.

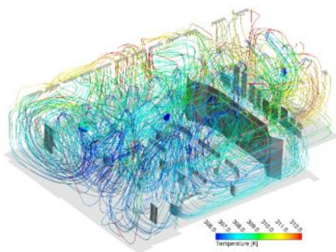
			Unit	Design	Range	No. of Selected Operating Conditions [EA]	No. of Combined Operating Conditions [EA]
Supply Diffuser		Flowrate	[CMH]		20,732 CMH ~24,650 CMH	2	96
		Temperature	[℃]		10.0 ℃ ~ 30.0 ℃	9	
Return/Exhaust Grille		Flowrate	[CMH]		20,732 CMH ~24,650 CMH	2	
Heat load [BTU/hr]	Wall	Floor	[kW]		Fixed	1	
		East	[kW]		Fixed	1	
		West	[kW]		Fixed	1	
		South	[kW]		Fixed	1	
		North	[kW]		Fixed	1	
		Ceiling	[kW]		Fixed	1	
	H_{s1} (Heat Load Ⅰ)	I&C Equip.	[kW]		24.7 kW ~ 42.7 kW (82 % ~ 141 %)	7	
		Elect. Load	[kW]		Fixed	1	
		Operator	[kW]		Fixed	1	
	H_{s2} (Heat Load Ⅱ)	Add. Heat	[kW]		0.0 kw ~ 20.0 kw	3	
	SUM				47.9 kw ~ 85.9 kw	-	-

Table 2 Representative CFD analysis cases.

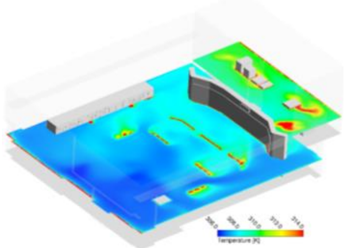
Case	Supply Diffuser		Heat Load					Total
	Flowrate	Temp.	Hs1 (Heat Load Ⅰ)				Hs2 (Heat Load Ⅱ)	
			wall	I&C Equip.	Elect. Load	Operator	Add. Heat	
	[CMH]	[K]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
01	24,650	303.15	19.3	30.2	3.3	0.6	0	53.4
			53.4					
06	24,650	290.65	19.3	30.2	3.3	0.6	0	53.4
			53.4					
52	20,732	295.65	19.3	30.2	3.3	0.6	0	53.4
			53.4					

3. ROM creation and Validation

The study developed a Reduced Order Model (ROM) using Computational Fluid Dynamics (CFD) analysis results for the main control room of a nuclear power plant. ANSYS Twin Builder [1,2], specifically the Static ROM Builder, was used to create the ROM. The Static ROM Builder approximates the solution for a



(a) Streamlines colored by temperature



(b) Temperature
Fig. 3 CFD analysis results (Case 01).

specific set of parameter values in real-time. It employs Singular Value Decomposition (SVD) to compress the solution and recalculates values within the parameter range using interpolation methods.

To evaluate the thermal fluid dynamics of the control room, four input parameters were considered: airflow rate and temperature supplied by the air conditioning system, heat generation from equipment, and compartment heat load. To enhance the reliability of the Static ROM, the study included CFD analysis cases that covered the maximum and minimum ranges of the parameters, with over ten data points per parameter (Table 1, Table 2).

Given the complexity of the control room's airflow due to various installed equipment, a total of 94 CFD analysis results were used as training data for each parameter, exceeding the recommended 10 data points. Out of the 96 CFD analysis cases summarized in Table 1, 94 were used for training the ROM, while the remaining two were used for validation. The Static ROM was created using parameters such as static pressure, temperature, velocity magnitude, and vector from the CFD results. A 14-mode optimization was applied, achieving an average relative temperature error of 0.35%. The ROM was generated using 8,991,000 data points, and 96 monitoring points were added at identical locations for comparison between the ROM and CFD analysis. The computation time for the four generated Static ROMs was significantly faster, taking only under 1 second compared to the CFD analysis (24 cores, 12 hours). Comparison of CFD and ROM results is shown in Fig. 4 and Table 3. The ROM results are almost identical to the CFD results.

5. Conclusions

This study developed a real-time thermal analysis system using Digital Twin technology for temperature control in a nuclear power plant's Main Control Room. By creating a Reduced Order Model (ROM) based on Computational Fluid Dynamics (CFD) analysis, the system achieved accurate temperature predictions with

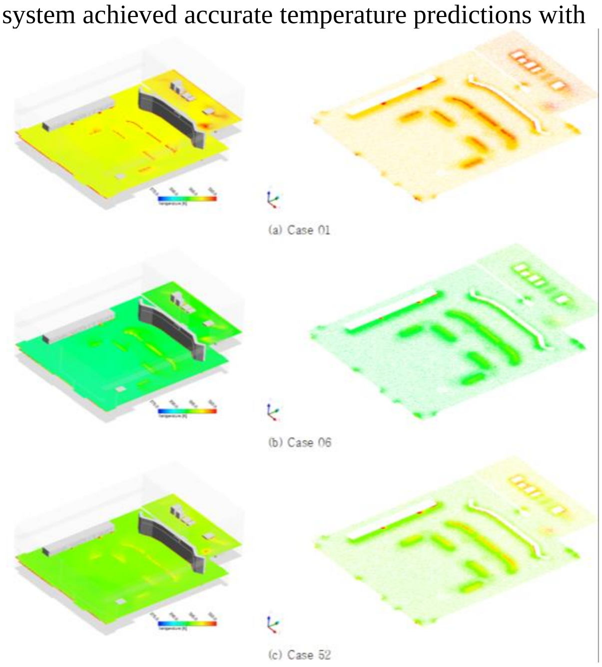


Fig. 4 Comparison of CFD Analysis (Left) and ROM (Right) temperature distribution results.

Table 3 Comparison of CFD and ROM.

Case No.	Result category	Location	CFD (A)	Twin deployer (B)	Difference (A-B)	Difference (A-B)/A*100 [%]
Case 06	Temperature [K]	Outlet	298.5	297.0	1.5	0.5
		All domain	295.9	298.0	-2.1	-0.7
	Velocity Magnitude [m/s]	Outlet	0.901	0.876	0.025	2.8
		All domain	0.237	0.237	0.000	0.1
Case 52	Temperature [K]	Outlet	304.1	303.2	0.8	0.3
		All domain	301.8	304.0	-2.2	-0.7
	Velocity Magnitude [m/s]	Outlet	0.732	0.706	0.027	3.6
		All domain	0.231	0.232	0.000	-0.2

a minimal error and significantly faster computation times. This advancement enhances the safety and efficiency of control room operations.

ACKNOWLEDGEMENT

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