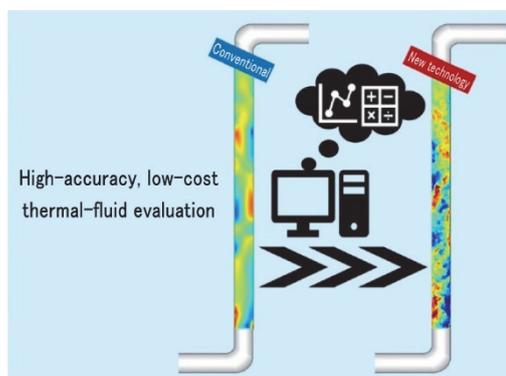


Thermal-Fluid Analysis with Reduced Computational Cost and Improved Accuracy: Construction of a Genetic-Algorithm-Based Turbulence Model



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This report presents a technology for constructing symbolic turbulent stress and turbulent heat flux models using Gene Expression Programming, a type of genetic algorithm, with the aim of achieving high-accuracy and low-cost analysis of complex thermal-fluid fields. The report then demonstrates an application example of the technology where a turbulence model was constructed based on high-accuracy analysis results to achieve high-accuracy thermal stratification phenomena prediction at analysis costs comparable to conventional models. The report also outlines a model construction method currently under development that utilizes test results as training data. These technologies are expected as fundamental technologies that achieve both a reduction in analysis load and an improvement in predictive accuracy in product development.

1. Introduction

In product development at Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI), high-accuracy evaluation of complex thermal-fluid fields is required across a wide variety of fields, such as nuclear power plants, chemical plants, and turbomachinery. To ensure product safety and performance, Computational Fluid Dynamics (hereinafter referred to as CFD) is essential for predicting turbulent behavior and heat transport phenomena in fluids. When applying CFD to design and development, it is a critical challenge to achieve highly reliable analysis while reducing both computation time and analysis load.

While general Reynolds Averaged Navier-Stokes (hereinafter referred to as RANS) analysis has a relatively low computational load, conventional closure models cannot sufficiently capture the anisotropy of turbulence and heat transport in complex thermal-fluid fields, leading to limitations in predictive accuracy. In contrast, high-accuracy analysis methods such as Large Eddy Simulation (hereinafter referred to as LES) offer superior analysis accuracy but their computational costs are very high, resulting in limited practicality in design study processes.

Against such a backdrop, this report introduces a new turbulence modeling method that utilizes Gene Expression Programming (hereinafter referred to as GEP), a type of genetic algorithm, to construct nonlinear turbulent stress and turbulent heat flux models applicable to RANS analysis. **Figure 1** shows the results of applying this technology to a natural convection phenomenon within a vertical round pipe, visualizing the vertical velocity field⁽¹⁾. In this system, by applying the constructed model, it is possible to obtain accuracy equivalent to LES at a fraction of the analysis cost of LES.

This technology is expected to be deployed as a fundamental technology that achieves both improved analysis efficiency and higher predictive accuracy for the diverse thermal-fluid challenges that MHI handles.

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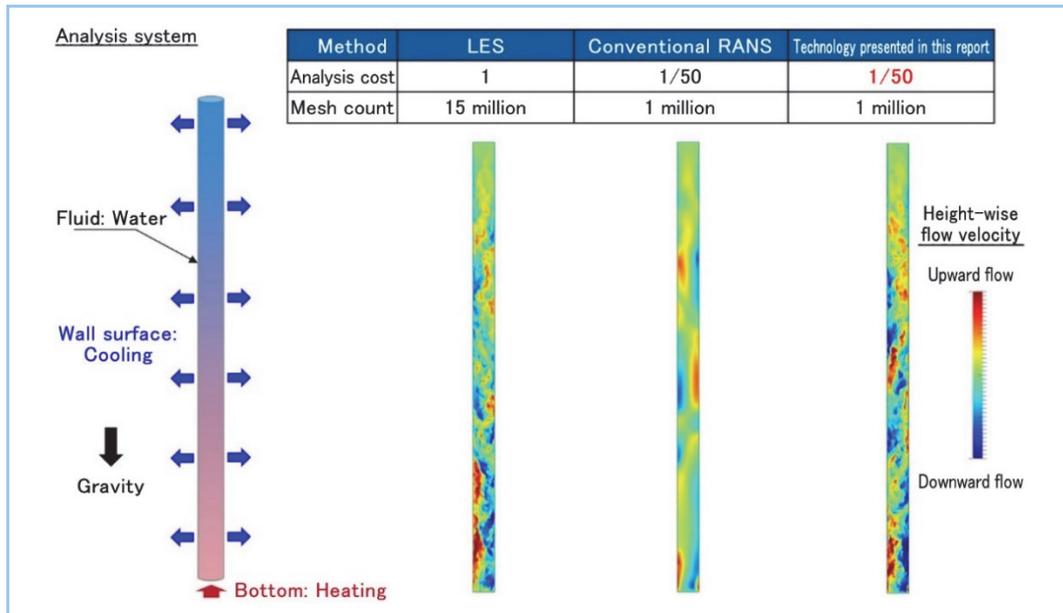


Figure 1 Results of applying this technology to natural convection within vertical round pipe

2. Turbulence modeling using GEP

This chapter describes a turbulence modeling method using GEP, a type of genetic algorithm.

Figure 2 summarizes this technology.

2.1 Overview of GEP

GEP is a type of evolutionary algorithm that represents mathematical functions or model equations as genetic information, and is a method to explore optimal solutions through genetic operations such as mutation and crossover. This method is characterized by its ability to construct relatively flexible models and extract complex nonlinear relationships as explainable algebraic expressions.

2.2 Methods for constructing turbulence models

In this study, the following two types of models to be used in RANS analysis are constructed using GEP based on velocity and temperature field data obtained via LES. By replacing conventional models with these GEP-improved models, the accuracy of RANS analysis is dramatically improved.

(1) Nonlinear Reynolds stress model

Conventional RANS analysis assumes a linear stress-strain rate relationship based on the Boussinesq approximation. In contrast, this method extends that relationship to a nonlinear one by evolutionarily searching for the optimal combination of multiple nonlinear tensor basis functions, using invariants of the velocity gradient tensor as input. This enables the representation of turbulence anisotropy, which was difficult with conventional models.

(2) Turbulent heat flux model

Instead of using a constant turbulent Prandtl number based on the conventional gradient diffusion hypothesis, this method models the turbulent Prandtl number as a nonlinear function using invariants of temperature and velocity gradients as inputs. This enables the representation of anisotropic heat transport induced by turbulence.

2.3 Data preparation and model training process

The training data used consists of the average velocity and temperature fields obtained as results from LES, as well as turbulence statistics. Based on this data, GEP derives the equations for the two models in an evolutionary manner to minimize the cost function (typically the difference between model predictions and reference data).

2.4 Characteristics and practicality of models

The constructed models are represented as algebraic expressions and can be easily incorporated into existing CFD solvers. Furthermore, as demonstrated in the example below, they possess applicability to different thermal-fluid fields not used in training, provided the subject exhibits similar governing phenomena, thereby offering versatility in their scope of application.

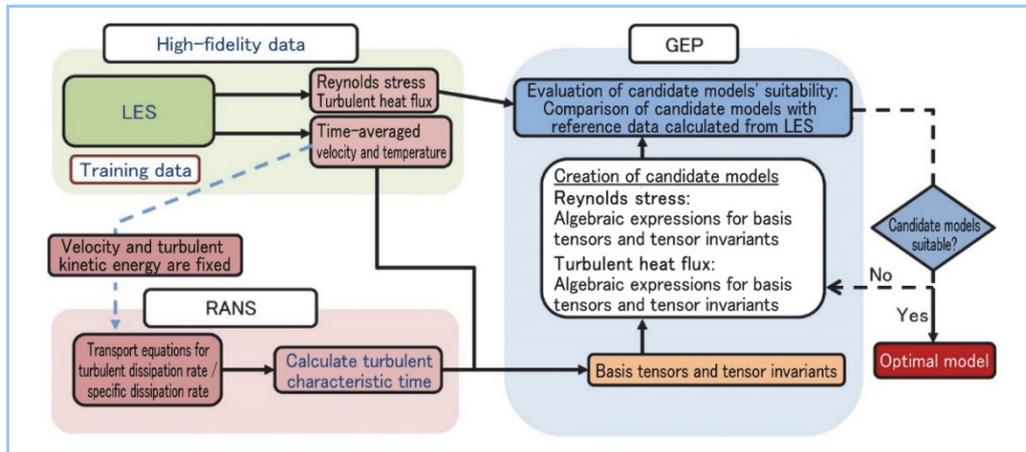


Figure 2 Flow of turbulence modeling using GEP

3. Application examples to thermal stratification problems

3.1 Overview of thermal stratification

Thermal stratification is a phenomenon in which density differences caused by temperature differences generate buoyancy, forming a stable layered structure within a fluid. This occurs prominently when high-temperature fluid is injected into low-temperature fluid in a tank, leading to suppressed fluid mixing and steep temperature gradients. These effects can adversely impact equipment, such as by inducing thermal stress concentrations in structures. Therefore, it is crucial to accurately predict thermal stratification phenomena during the design phase.

3.2 Analysis conditions and model application

This application example addresses the collapse of thermal stratification in a tank as a representative thermal stratification problem. For the training data used to construct the model, LES analysis results verified by test results from the published literature⁽²⁾ were employed. Meanwhile, for the test data, results from elemental tests conducted by MHI were used. Figure 3 shows the analysis systems for the training data and test data. The analysis employed RANS equations incorporating the nonlinear turbulent stress model and turbulent heat flux model presented in Chapter 2. For comparison, analysis was also performed using the conventional RANS model to evaluate the collapse behavior of thermal stratification.

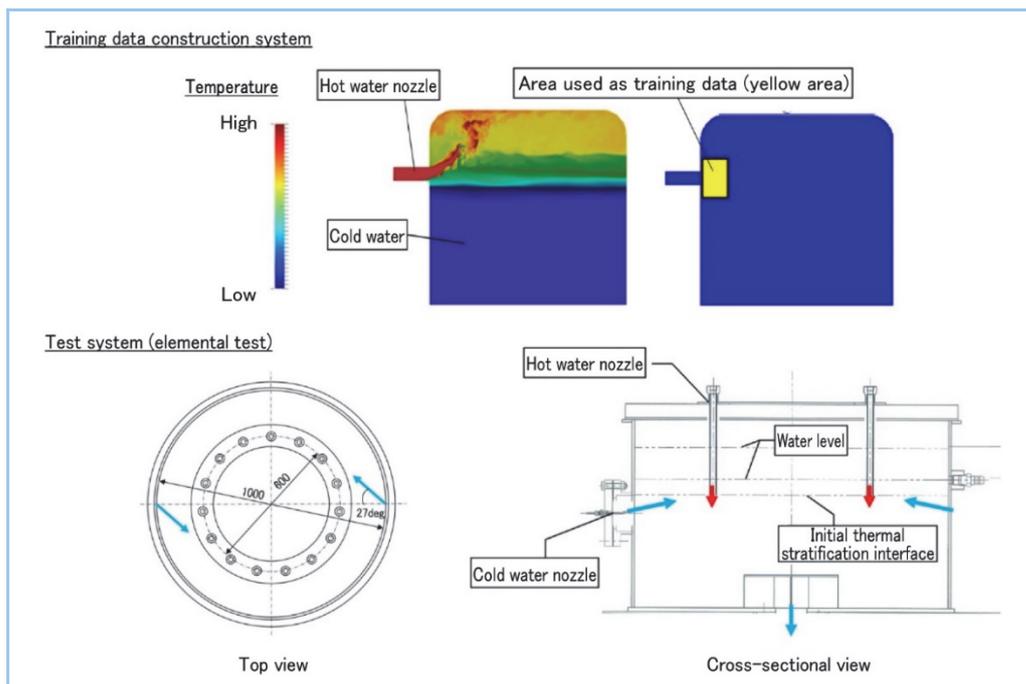


Figure 3 Training data construction system and test system for thermal stratification phenomena

3.3 Analysis results and discussion

As shown in **Figure 4**, the model set constructed using GEP yielded results for thermal stratification collapse behavior that were closer to actual measurements compared to the conventional model. Furthermore, the computational cost was nearly equivalent to that of conventional RANS analysis, achieving a significant reduction in computational load compared to LES⁽³⁾.

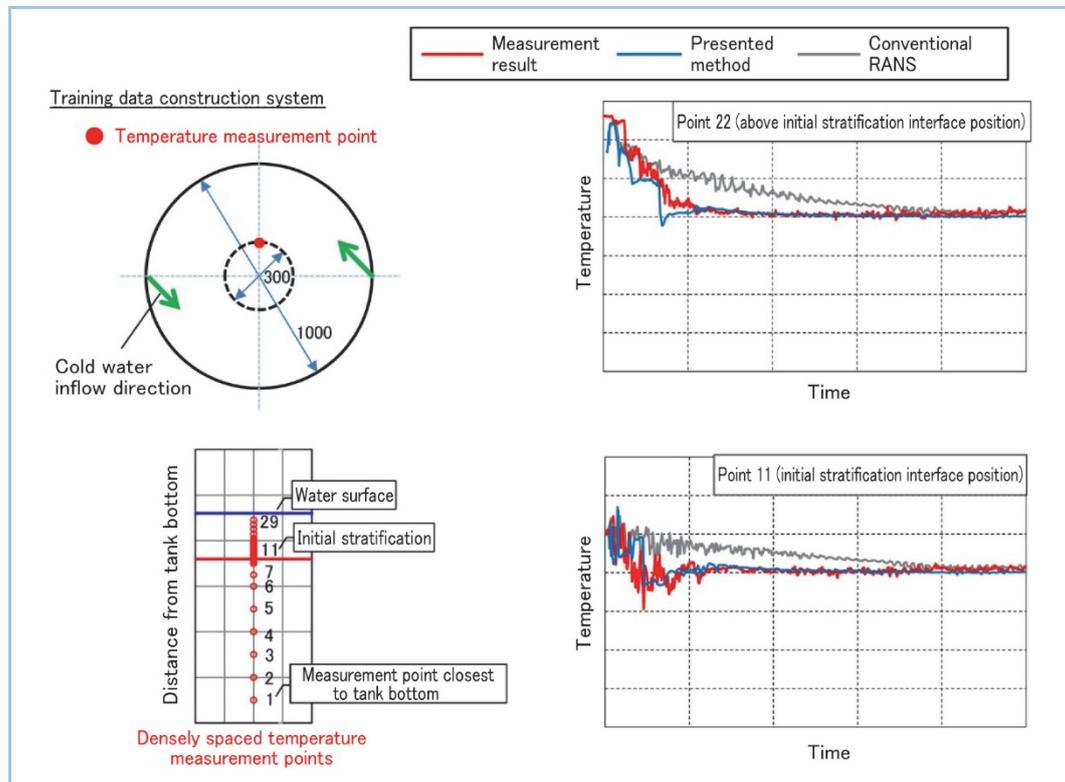


Figure 4 Example of elemental test analysis results

4. Initiatives in model development using limited test data

Currently, MHI is developing turbulence modeling methods utilizing limited test data. Conventional model development methods employed LES data as training data, but acquiring this data required significant computational resources. In contrast, the method currently under development enables the direct use of test data as training data. This eliminates dependence on LES analysis, allowing turbulence modeling to be performed using existing in-house test data, for example.

Specifically, in this new method RANS analysis is integrated into the GEP process. Using the difference between the velocity and temperature field data measured in the test and the RANS analysis results implemented with the two aforementioned models as an evaluation index, the functional form and parameters of the turbulence model are evolutionarily determined with GEP. The objective is to obtain a turbulence model for thermal fluid fields with higher numerical stability and to account for coupling effect between velocity and temperature during the model development. **Figure 5** shows a schematic diagram of the flow of this method. **Figure 6** presents the results of applying this method to natural convection in a horizontal cylinder, demonstrating that results closer to the reference results are obtained compared to conventional RANS analysis. In the future, this method will be applied to actual product-scale issues to confirm its effectiveness.

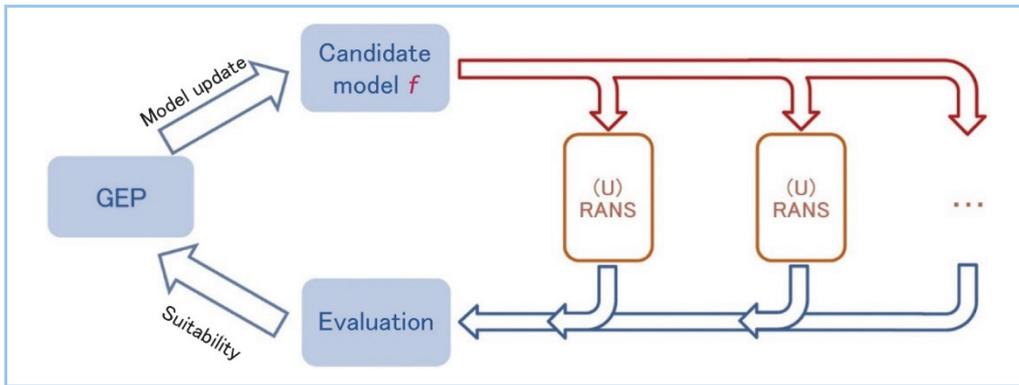


Figure 5 Turbulence modeling method using test data as training data

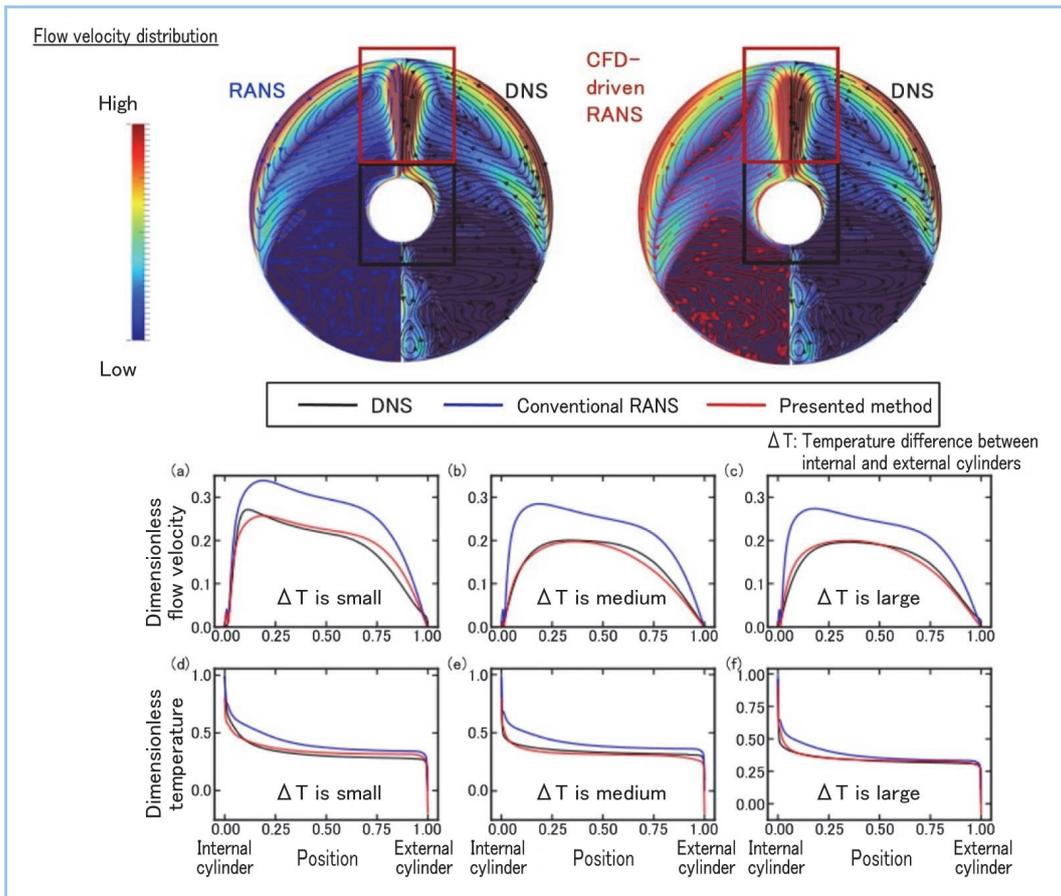


Figure 6 Analysis results of natural convection in concentric horizontal cylinder using method currently under development

5. Conclusion

This report presented a method to construct nonlinear turbulent stress and turbulent heat flux models based on training data using GEP, a type of genetic algorithm. Applying this method to thermal stratification problems demonstrated its ability to accurately predict the collapse behavior of thermal stratification, which had been difficult to evaluate with conventional CFD models. The computational load of this method is comparable to that of conventional RANS analysis, confirming its high practicality during the design phase.

In addition, this report outlined a modeling method under development that directly utilizes test data as training data. This method enables the construction of highly accurate and stable models using actual measurement data, without relying on data from LES, the computational load of which is high. In a simplified example of buoyant flow, this method yielded a model with higher accuracy than conventional models. Currently, the application of this method to product-scale issues and the verification of its effectiveness are underway.

Moving forward, MHI will expand the application of these methods and advance their use for

more complex thermal-fluid phenomena and actual products, thereby contributing to improving the efficiency and reliability of the company's product development.

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References

- (1) Haghiri, A. et al., Improving a Two-Equation Eddy-Viscosity Turbulence Model for High-Rayleigh-Number Natural-Convection Flows Using Machine Learning. *Journal of Engineering for Gas Turbines and Power*, 147(1), (2025)
- (2) Baeten, B. et al., A validated model for mixing and buoyancy in stratified hot water storage tanks for use in building energy simulations. *Applied Energy*, 172, (2016), 217-229
- (3) Oda, T. et al., Study on the applicability of a machine-learning framework to improve modeling for the stratification phenomenon. In *International Conference on Nuclear Engineering*, Vol.86434, (2022)