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Innovative HiMSEN methanol engine development with virtual product development(VPD) technology

Dual Fuel / Gas / Diesel

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ABSTRACT

In the third quarter of 2022, HD Hyundai Heavy Industries(HHI) developed the world's first 3.0-4.5MW medium-speed methanol dual-fuel engine for ships. Following this, in the first quarter of 2024, HHI developed a 1.4-2.2MW methanol engine, establishing the world's first methanol dual-fuel engine lineup.

The reasons for the rapid success in developing methanol engines were the utilization of a platform-based engine development process, virtual product development(VPD) technology, and AI technology. Initially, the development started with previously developed diesel and LNG DF engines whose functionality and excellence had already been verified in the market. New technologies for methanol fuel application, such as double-wall pipes, high-pressure pumps, and diesel-methanol hybrid injectors, were applied, significantly reducing the development period.

Additionally, VPD technology and AI technology were used to build a test-data and simulation-based virtual engine model. A simulation-based virtual engine model was utilized in the development of the engine combustion system to establish an optimal system for both diesel and methanol modes. After developing the prototype engine, a virtual engine model was built based on test-data obtained through R&D tests, reducing the time required for testing.

Through these technologies, HHI can develop engines that meet customer needs and market conditions in a timely manner. Furthermore, the company is continuously striving to lead the e-fuel engine market by applying the same development process to ammonia and hydrogen engines, in addition to methanol engines.

1 INTRODUCTION

HD Hyundai Heavy Industries (HHI) has established itself as a globally competitive company with advanced technological capabilities, not only in the shipbuilding industry but also in the development of marine engines. Figure 1 illustrates the complete lineup of HiMSEN engines, HHI' proprietary engine brand.

In 2001, HHI independently developed the H21/32 diesel engine, marking the beginning of the HiMSEN engine's history. Through continuous research and development, the company expanded its diesel engine lineup and completed the first-generation HiMSEN engine lineup by 2012. These efforts played a critical role in solidifying HHI's technological expertise in engines and strengthening its market position.

In the early 2010s, the International Maritime Organization (IMO) and other regulatory bodies introduced stricter sulfur content regulations for marine fuels, prompting a shift in the primary energy source for ships from diesel to liquefied natural gas (LNG). In response, HHI commenced the development of second-generation HiMSEN engines. In 2012, the company introduced its first LNG-fueled engine, the H35DF, and continued its research and development efforts to complete a full lineup of LNG-powered engines, including the H54DF, by 2018.

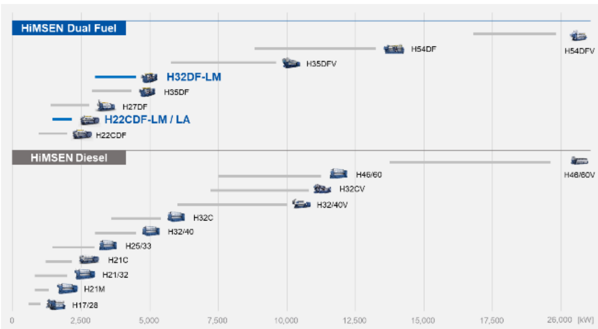

Figure 1. HiMSEN Engine Lineup

Entering the 2020s, with the further tightening of greenhouse gas (GHG) emission regulations, the maritime industry began transitioning from conventional LNG to low-carbon and zero-carbon fuels such as e-fuels (methanol, ammonia, and hydrogen). Aligning with this global regulatory trend, HHI embarked on the development of third-generation HiMSEN engines designed for environmentally friendly fuels. As a result, in 2022, the company successfully completed the Type Approval Test (TAT) for the world's first medium-speed methanol dual-fuel engine.[1] Furthermore, by 2024, HHI not only established a comprehensive methanol engine lineup but also became the first in the world to complete the type approval test for a medium-speed ammonia dual-fuel engine, securing a technological edge in the eco-friendly engine market.

Engines installed on ships can be broadly categorized into two types based on their purpose. The first type is propulsion engines, which transfer power generated by the engine to the propeller through a shaft, providing the thrust needed for ship movement. Propulsion engines are predominantly two-stroke, low-speed engines used in large vessels, excluding small- to medium-sized ships. These engines are characterized by their high efficiency and durability.

The second type is power generation engines, responsible for producing the electricity required on board. Power generation engines typically utilize four-stroke, medium-speed engines, which represent the core market targeted by HHI's HiMSEN engines. These medium-speed engines are widely employed not only for marine applications but also for power generation in land-based power plants.

Marine engines account for approximately 10–20% of the total shipbuilding cost, making them a significant component, and they have a decisive impact on the operational efficiency and economic viability of the vessel. As a result, the performance, fuel efficiency, and reliability of engines are regarded as critical factors in ship design and operation. Additionally, marine engines possess fundamentally different characteristics compared to those used in standard vehicles.

Figure 2 compares the characteristics of automotive engines, marine power generation engines, and marine propulsion engines. As previously mentioned, marine engines primarily operate at medium or low speeds and are designed with durability and stability as top priorities to support long-term continuous operation, which aligns with the operational demands of ships. Additionally, due to the need to propel the massive weight of a vessel and generate significant electrical power, marine engines require high output levels, which inevitably result in substantial engine size and weight.

In contrast, automotive engines operate across a wide range of speeds, from low to high, and are designed to accommodate frequent acceleration and deceleration. Automotive engines prioritize responsiveness and driving performance, and miniaturization and lightweight design are essential to minimize vehicle weight. Moreover, automotive engines typically require lower output levels, leading to significant differences in their design and

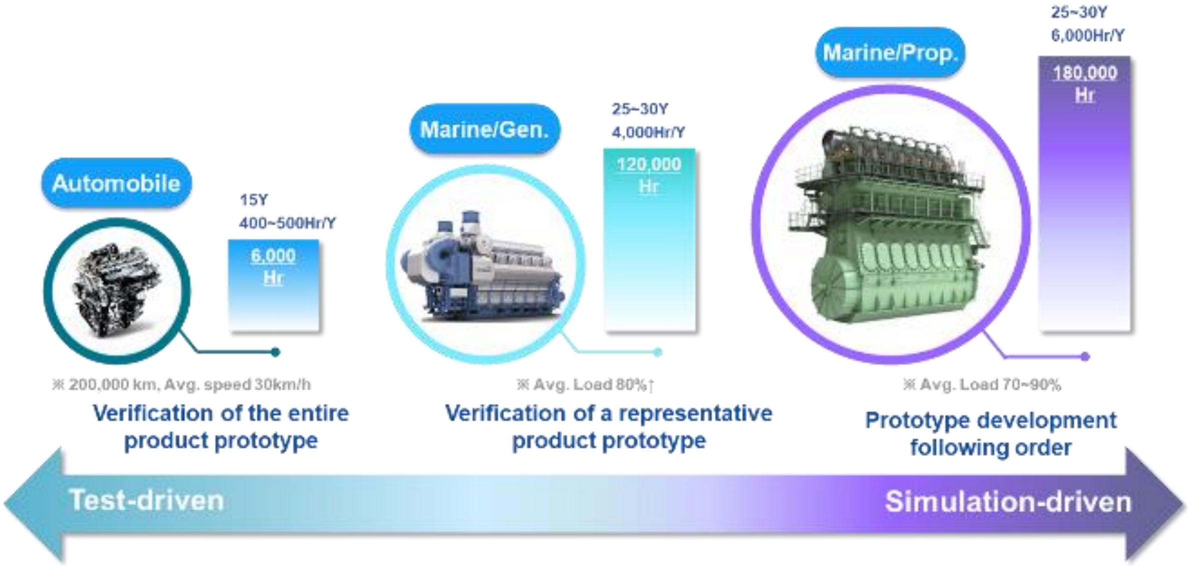

Figure 2. Difference between marine engines and automotive engines

manufacturing approaches compared to marine engines.

To overcome these limitations, Virtual Product Development (VPD) technology is indispensable. VPD utilizes digital simulation and virtual prototyping to enable product design, performance evaluation, and optimization without the need for physical experiments, thereby reducing development costs and shortening time-to-market. Moreover, it allows for the rapid analysis of various design variables and scenarios, contributing to enhanced product quality and reliability.

Simulation-based design complements the limitations of physical testing and has become a crucial tool for optimizing engine performance while minimizing costs and development time. This approach significantly improves the efficiency of marine engine development and plays a pivotal role in expanding the feasibility of adopting new technologies.

This study presents the VPD technology utilized during the development of the world's first medium-speed methanol engines for marine power generation, the H32DF-LM and H22CDF-LM, developed by HHI. It specifically highlights the role and contributions of VPD technology in the engine design and optimization processes.

Additionally, the study introduces the system simulation technology currently under development at HHI, exploring its potential to bring innovative advancements to future marine engine development and its role in performance validation. This discussion provides a detailed examination of how advanced simulation technologies can reduce testing costs and time in the complex engine development process while supporting the design of high-performance and environmentally friendly engines.

2 VPD TECHNOLOGIES UTILIZED IN METHANOL ENGINE DEVELOPMENT

2.1 Introduction to VPD for Combustion System Design

Engine development involves the design of various subsystems, including combustion, fuel supply, intake and exhaust, lubrication, cooling, durability, and vibration. Simulations play a pivotal role in determining the specifications of each subsystem. In particular, the design of the combustion system, a key factor in engine performance, is divided into two main stages: basic design and detailed design.

The basic design is performed based on 1D simulations, which define the specifications of the engine's fundamental parameters. In the detailed design phase, the specifications of key combustion system components, such as the piston bowl geometry and fuel injection valve, are determined through 3D combustion simulations. Once the engine parameters and component specifications are finalized through these basic and detailed design processes, prototypes are manufactured and subjected to a series of developmental tests. Upon performance validation through optimization processes, the engine development is deemed complete. This systematic design approach is made possible through HHI' advanced VPD technology, enhancing design precision and efficiency while achieving the dual goals of cost reduction and development time minimization.

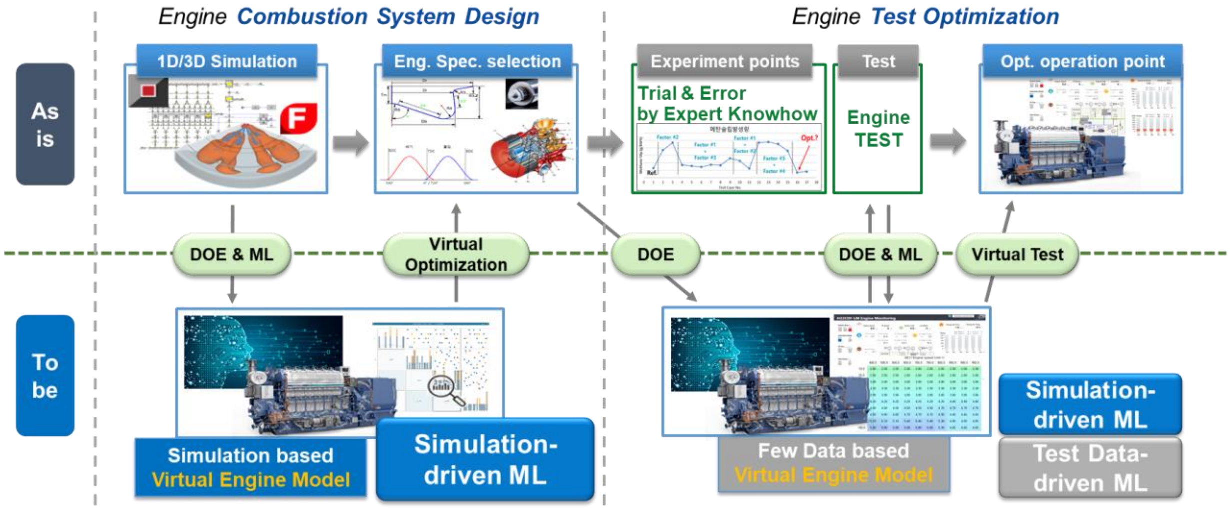

Figure 3 The past and present of engine combustion system development processes

Figure 3 illustrates how VPD technology has been applied throughout the engine development process described earlier. Traditionally, deriving the specifications of the combustion system during the basic and detailed design stages required a significant number of simulation cases. This was due to the numerous design variables that needed to be addressed in the development of the engine's combustion system.

These variables had to be reviewed within limited time and resources, making the selection of variables and the scope of simulation critical steps in the process. At the time, the expertise and experience of specialists played a central role throughout the design process. Experts were essential not only for selecting variables but also for determining the optimal specifications to meet various requirements based on simulation results.

A similar approach was applied during the engine testing phase. Achieving optimal performance under various operating conditions required numerous trials and adjustments, with the success or failure of development heavily dependent on the experience of experts. This traditional methodology demanded substantial time and costs to develop a single engine. Furthermore, instead of comprehensively analyzing the entire range of design variables, optimization efforts were often limited to specific areas based on past experience. This reliance on selective analysis led to constraints in the scope of review during the design and testing stages, ultimately limiting the potential for complete optimization.

Recently, the integration of advanced VPD technologies such as simulation, machine learning (ML), design of experiments (DoE), and virtual optimization has significantly reduced development costs and timelines. These technologies enable the exploration of the entire design space, rather than being limited to specific regions of interest, thereby extending the optimization scope to areas that were previously inaccessible.

This comprehensive approach enhances the precision of the design process and opens new avenues for exploring innovative design possibilities. In the subsequent sections, we will delve into the application of VPD technologies at each design stage and provide concrete examples to illustrate how these tools are effectively utilized in engine development.

2.2 Application of VPD in the Basic Design for Combustion System

In the basic design stage, typically 9 to 10 design variables are considered, and each variable is assigned a minimum and maximum level. Assuming this setup, a total of 2^{10}, or 1,024, simulation cases are required to evaluate all combinations. This large number of cases demands substantial time and computational resources, posing a significant challenge in efficiently performing simulations.

Moreover, due to these limitations, the detailed results within the variable ranges are often estimated using simple interpolation methods. This approach introduces inherent inaccuracies and restricts the ability to capture nuanced interactions between variables, ultimately limiting the precision and effectiveness of the design process.

To address these challenges, the DoE methodology was introduced. DoE is a systematic approach that minimizes the number of simulation or experimental cases required while ensuring that the selected cases are evenly distributed across the entire design variable space. This approach allows for the comprehensive evaluation of how each design variable impacts the results, while significantly reducing unnecessary simulation costs and time.

By performing 1D performance simulation based on the cases selected through DoE, it became possible to efficiently gather the initial data needed to define the engine's fundamental specifications. Compared to traditional methods, this approach greatly improved both the accuracy and efficiency of the design process. Moreover, it enabled a deeper understanding of the design space, uncovering insights that were previously difficult to obtain. DoE thus serves as a powerful tool in the basic design stage, facilitating a more systematic and resource-efficient approach to engine development.

Table 1 Fuel properties of diesel, methanol and ammonia [2-7]

Property	Diesel	CH_3OH	NH_3
Molecular Weight (g/mol)	170-220	32.04	17.03
Boiling Point (°C)	180-360	64.7	-33.34
Viscosity (cP, 25°C)	2-4	0.54	0.01
Surface Tension (mN/m, 25°C)	27	22.6	23.4
Vapor Pressure (kPa, 25°C)	<1	12.3	858.3

Based on the simulation results, we developed a performance prediction model, often referred to by various names such as Response Surface Model, Metamodel, or Surrogate Model. The primary objective of this model is to analyze the relationships between input variables and response variables, enabling predictions of outputs for various combinations of inputs. Numerous methodologies have been devised to model the relationship between inputs and outputs. In recent years, the adoption of ML and Artificial Intelligence (AI) technologies has significantly enhanced the accuracy of prediction models. In this study, we utilized these advanced technologies to develop a high-accuracy 1D performance prediction model.

Subsequently, virtual optimization was conducted based on the developed performance prediction model. Various optimization techniques can be applied during this process. We selected the optimization methodology most suitable for the current dataset and simulation environment to derive the optimal combination of design variables. The integration of the prediction model with optimization techniques maximized design efficiency, effectively reduced the time and resources required during the development process, and simultaneously achieved the goals of enhancing engine performance and reducing pollutant emissions.

2.3 Application of VPD in the Detailed Design for Combustion System

Once the engine's hardware (H/W) specifications are determined through 1D simulations, the specifications of key combustion system components, such as the piston bowl and fuel injection valve, are optimized using 3D combustion simulations. However, prior to conducting 3D combustion simulations, it was necessary to enhance existing diesel-based spray and combustion models to accommodate the unique characteristics of alternative fuels like methanol.

Table 1 compares the fuel characteristics of diesel, methanol, and ammonia, illustrating their distinct physical properties. Methanol, compared to diesel, has a lower molecular weight, higher boiling point, and higher vapor pressure, which significantly increases the evaporation rate of the fuel. Furthermore, methanol's low viscosity and surface tension enhance the atomization process immediately after injection, leading to distinct differences in spray angle and spray penetration behavior compared to diesel.

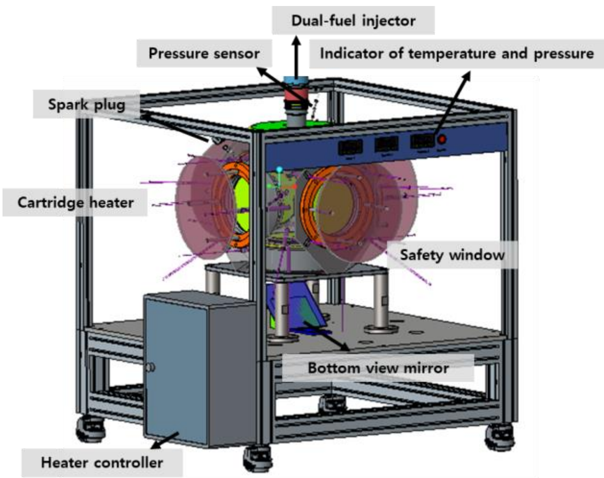

Figure 4 Constant volume combustion chamber

Similar characteristics are observed with ammonia, where the differences in spray properties also have a profound impact on the combustion process and overall engine performance. These observations highlight the importance of accurately modeling these fuel-specific spray behaviors to ensure reliable performance predictions and optimization in engine development.

Consequently, the performance of the diesel cycle heavily depends on the spray characteristics of the fuel, making the development of an accurate spray and combustion model indispensable. To achieve this, HHI collaborated with academia to design and construct the world's largest spray and combustion visualization static chamber. The structure and key specifications of the static chamber are shown in Figure 4 and Table 2, respectively.

Table 2 Specifications of constant volume combustion chamber

Items	Values
Volume	11.95L (Internal)
Material	SCM440
Window diameter	220mm (5ea)
Window material	Sapphire 2ea, Quartz 3ea
Steady condition	T_{max} 200°C, P_{max} 60bar
Combustion condition	T_{max} 630°C, P_{max} 200bar
Visualization	Mie-scattering, Schlieren, High-speed imaging

This chamber was utilized to conduct fuel-specific spray visualization experiments under various conditions, including ambient pressure, ambient temperature, injector temperature, and energizing duration. Additionally, combustion visualization experiments were performed by simulating actual engine combustion conditions, such as varying fuel injection timing and duration.

Based on the experimental data, precise tuning of the spray and combustion models was conducted. As demonstrated in Figure 5, the simulation results closely aligned with the experimental outcomes, confirming the validity of the combustion model tailored to the physical properties of alternative fuels such as methanol and ammonia. This alignment underscores the robustness of the developed models and provides a critical foundation for the development of next-generation eco-friendly fuel engines.

Using the updated simulation model, 3D combustion simulation was conducted, with the selection of simulation cases guided by the DoE methodology, as in the 1D performance simulation. While the number of input variables was smaller compared to 1D simulation, the significantly longer computation time for each 3D case necessitated minimizing the number of cases.

After performing 3D combustion simulation for the selected cases, the results were used to develop a performance prediction model. The objective function for optimization was set to maximize engine thermal efficiency, consistent with the 1D simulation. However, unlike 1D simulation, 3D combustion simulation focuses on determining the detailed specifications of combustion system components, such as piston bowl geometry and fuel injection valve characteristics.

This focus introduces a potential issue: specifications determined during the optimization process might not meet practical manufacturability requirements. To address this, constraints incorporating real-world manufacturability were defined and applied during the optimization process. These constraints ensured that the optimized specifications were not only theoretically sound but also feasible for actual production, thereby enhancing the practicality and effectiveness of the optimization process.

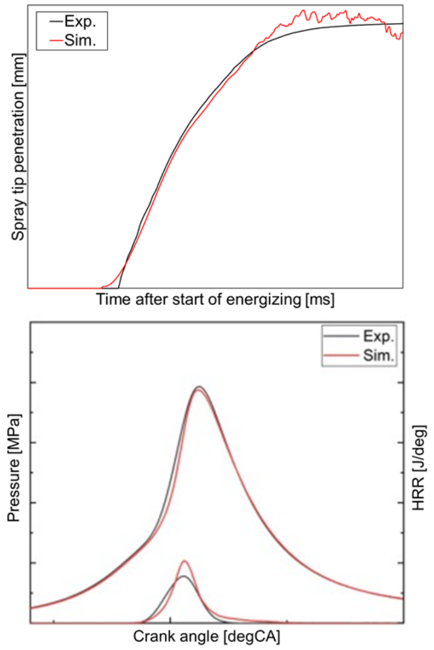

Figure 5. Comparison of test and simulation

Figure 6 illustrates the meta-model of the objective function for various input variables and the piston bowl geometry derived through optimization. As shown in the figure, the Specific Fuel Oil Consumption (SFOC) varies significantly with changes in input variables. Within the constraints previously discussed, the optimal piston bowl geometry was successfully identified. This result demonstrates the effectiveness of the meta-model and optimization approach in achieving precise and efficient combustion system designs.

2.4 Application of VPD in the R&D Test

VPD technology was utilized not only in simulations but also during the prototype testing phase. As previously mentioned, large-scale marine engines require substantial costs and time for testing due to their high output and massive size. Furthermore, the adoption of alternative fuels and the verification of new advanced technologies have further increased the time required for developmental testing. Under these circumstances, the importance of technologies capable of minimizing the number of test cases while deriving optimal performance operating points has become increasingly significant.

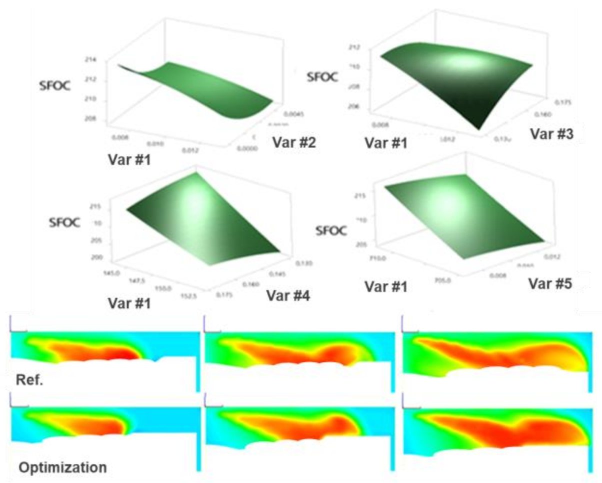

Figure 6. Meta model developed for detailed design of combustion system and piston bowl shape optimization

Hyundai Heavy Industries applied VPD technology during the development and testing phase of the methanol engine. For conventional diesel engines, controllable operating variables were primarily limited to fuel injection timing. However, in the methanol dual-fuel engine's methanol mode, where two fuels are directly injected independently, the number of controllable operating variables increases. Considering this, the DoE methodology was employed to select test points for exploring optimal operating points across different loads through combinations of operating variables.

Figure 7 illustrates the test points for each input variable. Subsequently, actual tests were conducted at these points, and the resulting data were used to develop a prediction model and identify optimal test points. This approach minimized trial and error in the process of identifying optimal operating points, significantly reducing the costs and time required for development.

HHI successfully developed the combustion system for methanol engines by leveraging VPD technology. While the development of conventional diesel and LNG dual-fuel (DF) engines typically required 2–3 years, the application of VPD technology enabled the completion of methanol engine development within approximately 1.5 years for a single type. As a result, in the second half of 2022, HHI achieved type approval for the world's first methanol engine, the 3.0–4.5 MW-class H32DF-LM. Subsequently, in the first half of 2024, HHI completed type approval tests for the 1.4–2.2 MW-class methanol engine, H22CDF-LM, establishing the world's first complete methanol engine lineup.

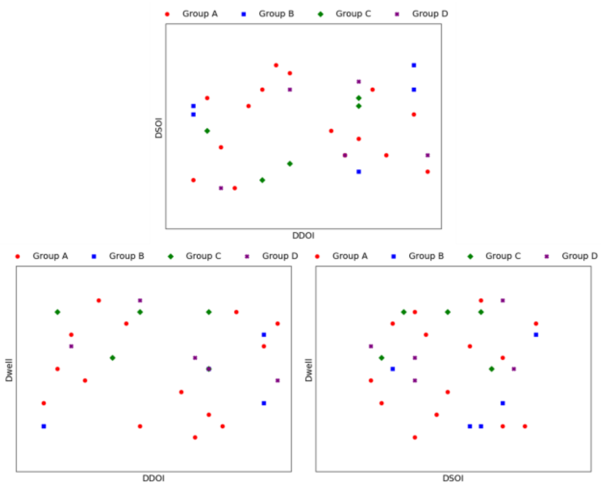

Figure 7. Test point distribution according to engine operating variables

The VPD technology validated during methanol engine development is now being applied to ammonia engine development. In the second half of 2024, HHI became the first to complete type approval for the 1.4–2.2 MW-class ammonia engine, H22CDF-LA, and is scheduled to conduct type approval tests for the 3.6–5.4 MW-class ammonia engine, H32CDF-LA, in the second half of 2025. Figure 8 presents TAT images of the methanol and ammonia engines developed by HHI.

By actively utilizing VPD technology, HHI has enhanced the efficiency of alternative fuel engine development and responded swiftly to evolving market demands. This technological approach not only shortens development timelines but also accelerates the commercialization of next-generation eco-friendly engine technologies, contributing significantly to the advancement of sustainable maritime solutions.

The previously discussed VPD technologies were primarily focused on their application during the engine development phase. However, HHI is expanding beyond these applications by continually advancing VPD technologies to enhance performance prediction and optimization for mass-produced engines.

The following sections will delve into the VPD technologies currently under development at HHI and their potential applications. These emerging technologies are expected to play a pivotal role not only in engine development projects but also in the efficient performance evaluation and optimization of engines during the mass production phase. This forward-looking approach aims to further refine engine performance, reduce operational costs, and meet increasingly stringent market and regulatory demands.

Figure 8. Type approval test for HiMSEN methanol and ammonia engines

3 VPD TECHNOLOGIES UNDER DEVELOPMENT

3.1 Development of Multi-fidelity Data-Driven Model

Let us first discuss the development of prediction models using multi-fidelity (MF) data. MF data refers to an integrated approach that utilizes various types of data sources rather than relying on a single source. Traditionally, engine development has primarily relied on a single data type, such as simulation data or test data, to build prediction models. In contrast, prediction models leveraging MF data aim to create more sophisticated and accurate models by combining analytical data and test data.

Generally, data can be categorized into low-fidelity (LF) data and high-fidelity (HF) data. LF data have the advantage of requiring lower costs, time, and effort during collection but often suffer from lower accuracy. On the other hand, HF data provide high-quality and highly accurate results, although their collection involves significant cost and time investment. Prediction models using multi-fidelity data are based on the concept of integrating the strengths of both LF and HF data to maximize prediction accuracy.

This approach is expected to enable cost-efficient yet high-quality performance predictions, significantly contributing to engine performance simulation and optimization under various atmospheric conditions.

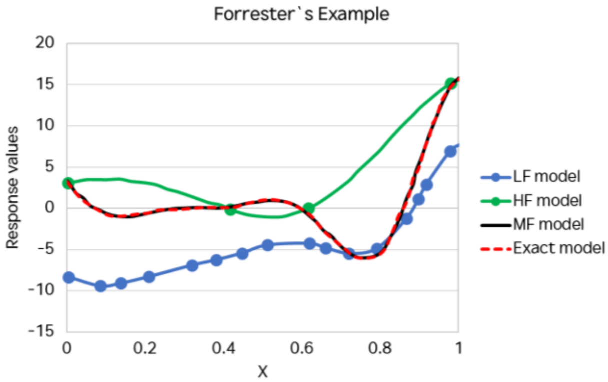

Figure 9. Comparison of LF, HF, and MF models using Forrester`s example

Figure 9 illustrates a comparison of prediction accuracies among models developed using LF, HF, and MF data. As shown in the figure, HF data, despite being limited to four points due to their resource-intensive nature, exhibit very high accuracy when compared to the actual model values. In contrast, LF data, while providing extensive coverage across the entire range, display relatively low accuracy, resulting in significant deviations from the actual values. However, LF data remain valuable for capturing overall trends.

The MF model demonstrated its capability to combine the high accuracy of HF data with the broad-range trend insights provided by LF data, achieving predictions closely aligned with actual values. These findings validate the effectiveness of MF models in leveraging the complementary strengths of LF and HF data to enhance prediction reliability.

HHI successfully developed a platform capable of generating MF prediction models by integrating LF and HF data. The company plans to utilize this platform for developing engine performance prediction models under diverse atmospheric conditions. This platform is anticipated to play a crucial role in precise and efficient performance simulation under complex operating conditions, significantly contributing to engine design and optimization processes.

3.2 Development of System Simulation Technology

HHI is introducing a new approach to engine development through advancements in system simulation technologies. As previously mentioned, an engine is a complex structure comprising

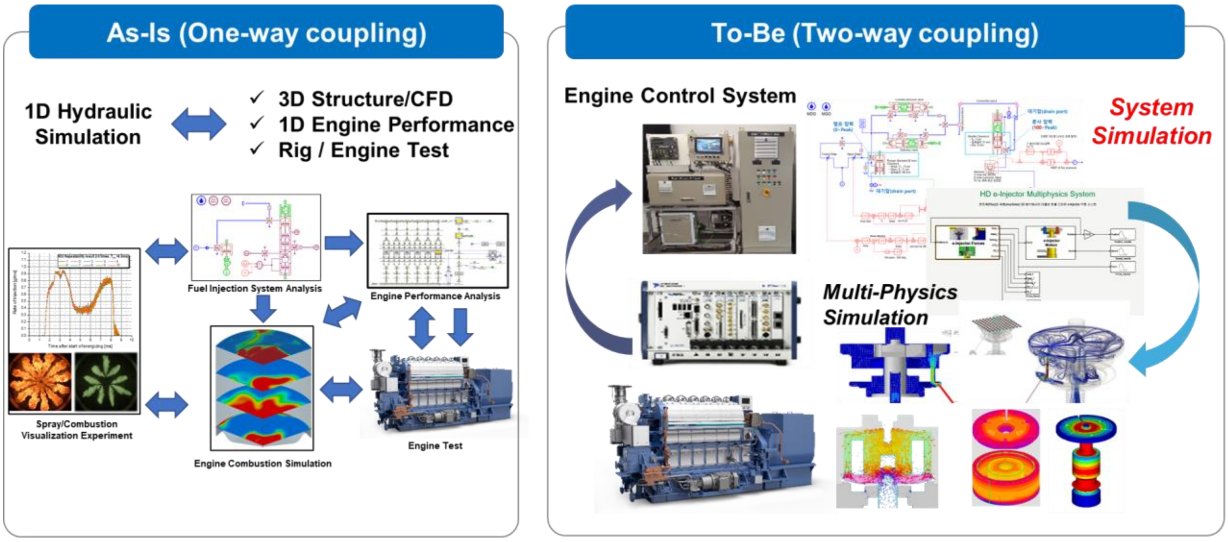

Figure 10. One-way coupling and two-way coupling

various subsystems, including combustion, fuel supply, intake and exhaust, lubrication, cooling, durability, and vibration. The interactions among these subsystems have a significant impact on the engine's overall performance and reliability.

Therefore, accurately predicting the performance of the combustion system requires an integrated utilization of information from subsystems external to the combustion system. This comprehensive approach enables a more precise understanding of subsystem interdependencies, ultimately contributing to the development of high-performance and reliable engines.

For example, as shown in Figure 10, traditional approaches linked subsystem information sequentially using a one-way coupling method. While this method allowed the incorporation of each subsystem's data, it had limitations in effectively integrating feedback after development, as the flow of simulation results was unidirectional. Additionally, gathering information from each subsystem required individually requesting analyses from the respective teams and compiling the data, which was time-intensive.

To address these challenges, HHI is developing a two-way coupling-based system simulation model that enables bidirectional information exchange and feedback integration between subsystems. This approach offers several advantages, including precise replication of complex subsystem interactions, significantly reducing development time, and the ability to promptly integrate feedback even after the development phase. These improvements contribute to more efficient and responsive engine development processes.

4 CONCLUSIONS

HHI successfully leveraged VPD technology during the development of its methanol engine, significantly reducing development timelines and achieving ground breaking milestones. Through these efforts, HHI completed the world’s first type approval test for a marine methanol engine and established a comprehensive methanol engine lineup, securing a leading position in the next-generation eco-friendly fuel engine market. The combustion system development process for the methanol engine incorporated a range of advanced VPD technologies, distinct from traditional development approaches. Key achievements include:

- Efficient Design Process Implementation: VPD technology was employed during both the basic and detailed design stages to maximize development efficiency.
- Optimized Case Selection: Using DoE, the number of simulation cases was minimized while ensuring the consideration of the effects of all design variables.
- High-Accuracy Predictive Model Development: Statistical data analysis and ML techniques were applied to create highly accurate predictive models based on simulation data.
- Enhanced Precision Through Virtual Optimization: Predictive models were used to determine combustion system specifications that satisfied objective functions under various constraints.
- Improved Testing Efficiency: VPD technology was applied during the testing phase to minimize the number of test cases and

effectively identify optimal operating performance points.

- Expanded Design Exploration and Feedback Integration: Prediction models and system simulation technologies utilizing MF data broadened the design exploration scope and established a framework for incorporating feedback post-development.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

HHI: HD Hyundai Heavy Industries

IMO: International Marine Organization

LNG: Liquified Natural Gas

GHG: Green House Gas

TAT: Type Approval Test

VPD: Virtual Product Development

T/C: Turbocharger

ML: Machine Learning

DoE: Design of Experiment

AI: Artificial Intelligence

IVO: Intake Valve Open

IVC: Intake Valve Close

EVO: Exhaust Valve Open

EVC: Exhaust Valve Close

H/W: Hardware

SFOC: Specific Fuel Oil Consumption

DF: Dual Fuel

LF: Low-fidelity

HF: High-fidelity

MF: Multi-fidelity

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