Keywords: Methanol, E-fuel, VPD, S&FD, H22CDF-LM

HD Hyundai Heavy Industries Organizing Lineup of Medium-Speed Methanol Engine

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https://doi.org/10.18453/rosdok_id00004644

Abstract

Over the years, the interest in carbon-neutrality is spreading throughout the industry as a whole. Especially, according to international marine organization (IMO), the international shipping should reduce total greenhouse gas (GHG) emissions, at least 100% (net-zero) by 2050 compared to 2008. To achieve carbon-neutrality, it is essential to transition ship fuels from fossil fuel to e-fuels. Representative e-fuels include methanol, ammonia and hydrogen, with methanol-powered engines already being commercially available. HD Hyundai Heavy Industries (HHI) successfully developed the world`s first 3.0~4.5 MW medium-speed methanol-powered engine, H32DF-LM, in 2022. This engine is now being supplied to methanol-powered ships worldwide. Furthermore, in March 2024, HHI successfully completed the type approval test for 1.3~2.0 MW medium-speed methanol engine, H22CDF-LM, thereby establishing the world`s first lineup of methanol engines. HHI is currently developing 2.0~3.0 MW methanol engine and also in the process of developing engines powered by ammonia and hydrogen. In addition, fuel supply system for each fuel type is being developed. Through these, we are doing our best as a total marine solution provider.

1. Introduction

Recently, various industries worldwide have been actively engaged in efforts to achieve carbon neutrality. Particularly, in the maritime transportation sector, shipowners, shipbuilders, and engine manufacturers are actively responding to carbon dioxide or greenhouse gas (GHG) reduction policies led by the International Maritime Organization (IMO). According to IMO regulations, a 50% reduction in GHG emissions compared to 2008 levels must be achieved by 2030, and a 100% reduction by 2050. [1] While achieving net zero is sufficient since emissions are considered from a life-cycle assessment (LCA), this remains a highly challenging goal. There are various methods to reduce GHG emissions from ships. As shown in the Figure 1, research is being conducted on a variety of technologies and methods, including energy management, ship coating, speed & voyage optimization, etc. However, there is no method as effective as switching from fossil fuels to eco-friendly fuels for ship propulsion. Therefore, there is a glowing global interest in and demand for e-fuels, such as methanol, ammonia, and hydrogen to replace conventional fossil fuels like diesel and LNG.

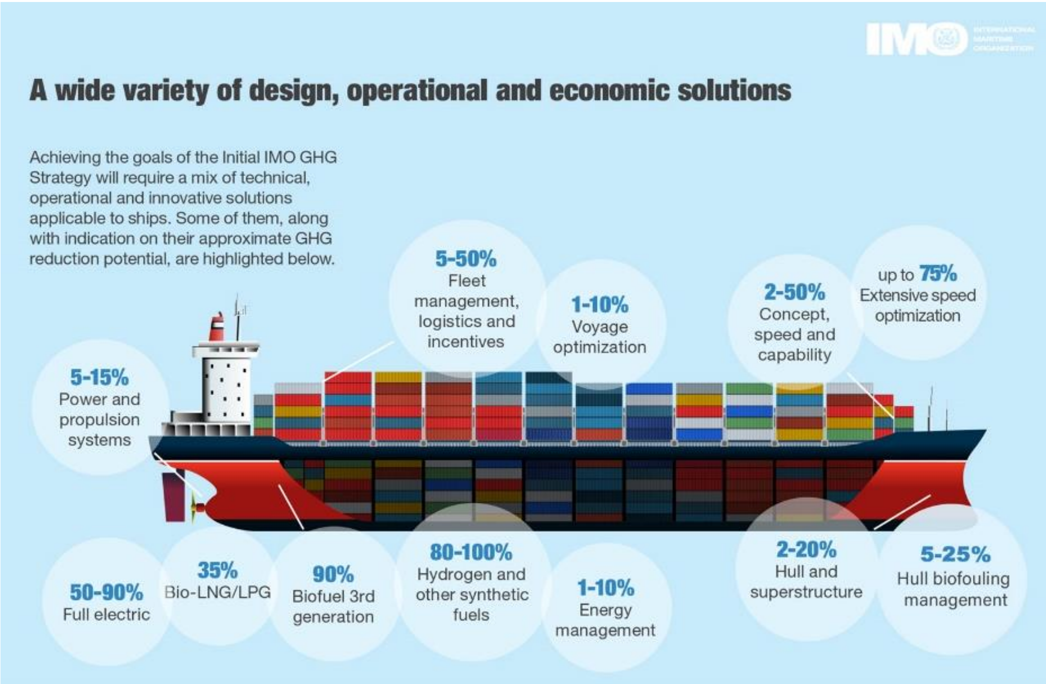


Figure 1: Strategies for reducing GHG emissions from ships [2]

E-fuel is a type of fuel synthesized by combining carbon dioxide captured from the atmosphere with green hydrogen produced though water electrolysis using electricity generated from renewable energy sources such as wind, hydro, and solar power. From a Tank-to-Wake (TTW) perspective, there are GHG emissions; however, from a LCA perspective, the amount of GHG emissions is reduced to nearly zero. [3] Therefore, the use of e-fuel can meet IMO regulations. However, due to limitation in production volume, high production costs, and the specific characteristics of the fuel, it is not easy to apply e-fuel to all ships immediately. To overcome these challenges, active research and development of related technologies are ongoing.

The Table 1 presents the fuel characteristics of diesel, methane, methanol, ammonia, and hydrogen fuels. As can be seen from the table, the characteristics of e-fuels differ significantly from those of conventionally used diesel and methane. In the case of methanol, it has a high boiling point and low saturation vapor pressure, allowing it to remain in a liquid state at room temperature. Therefore, it is the most suitable fuel for utilizing existing fuel systems. However, due to its low heating value, more fuel is required to achieve the same power output, and its high latent heat of vaporization necessitates consideration of combustion stability. In the case of ammonia, although it has a low boiling point, it can remain in a liquid state under moderate pressure, making fuel storage and transportation easier compared to methane. However, issues related to its low combustion speed, toxicity, and corrosiveness need to be addressed.

Table 1: Fuel characteristics

	MDO	Methane	Methanol	Ammonia	Hydrogen
Boiling point (degC)	180-360	-161	64.7	-33.3	-252.9
Lower heating value (MJ/kg)	42.5	50	19.7	18.6	120.0
Latent heat of vaporization (kJ/kg)	250	510	1100	1369	446
Auto-ignition temperature (degC)	210	580	470	650	500
Laminar flame speed (cm/s)	30-40	37	37.6	6.8	265.0
Lower flammability limit (vol.%)	0.6	5.0	6.0	15.0	4.0
Energy density (MJ/L)	35.8	0.9	15.6	13.6	8.5
Saturation vapor pressure (kPa)	0.4-0.7	4600	13	857	2070

In the case of hydrogen, a significant advantage is that it only emits water upon complete combustion. However, despite its high heating value, it has a low energy density. Additionally, its extremely low boiling point presents technical challenges in storage and supply. Furthermore, due to its high combustion speed and low flammability limit, issues such as flashback and pre-ignition need to be addressed to ensure stability.

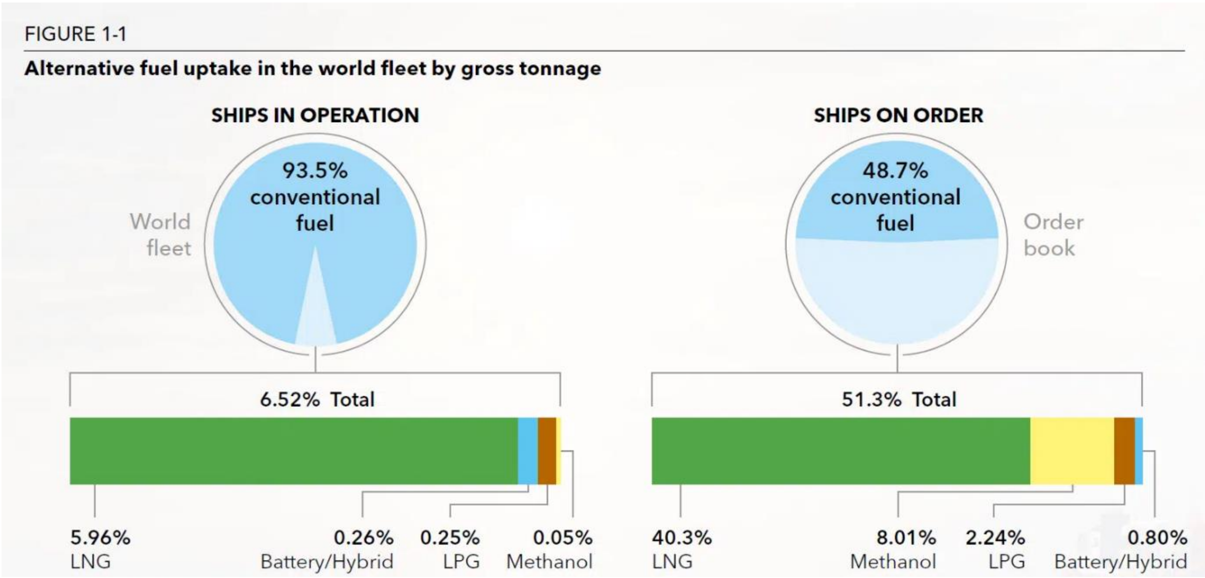


Figure 2: Alternative fuel uptake in the world fleet by gross tonnage [4]

As mentioned above, there are various technical challenges in applying e-fuels. However, numerous institutions worldwide are actively conducting related research, and it is expected that these issues will be resolved as the technology matures. Nevertheless, methanol is being utilized first during the fuel transition period because it can be directly applied using the existing fuel systems. Figure 2 shows the fuel type distribution of the entire fleet in operation and the fuel type distribution of newly ordered ships as of 2023. As shown in the figure, the majority of ships currently in operation are powered by diesel fuel. Only about 7% are powered by environmentally friendly fuels, with LNG accounting for the majority of this percentage. However, nearly half of the newly ordered ships are powered by environmentally friendly fuels. Notably, the proportion of methanol-powered ships has increased significantly. HD Hyundai Heavy Industries (HHI) is developing e-fuel engines, including those powered by methanol, to achieve carbon neutrality. Next, the history of engine development at HHI will be briefly outlined, and the virtual product development (VPD) technology utilized in this development will be introduced. Additionally, the development of HHI`s methanol engines, the H32DF-LM and H22CDF-LM, will be explained.

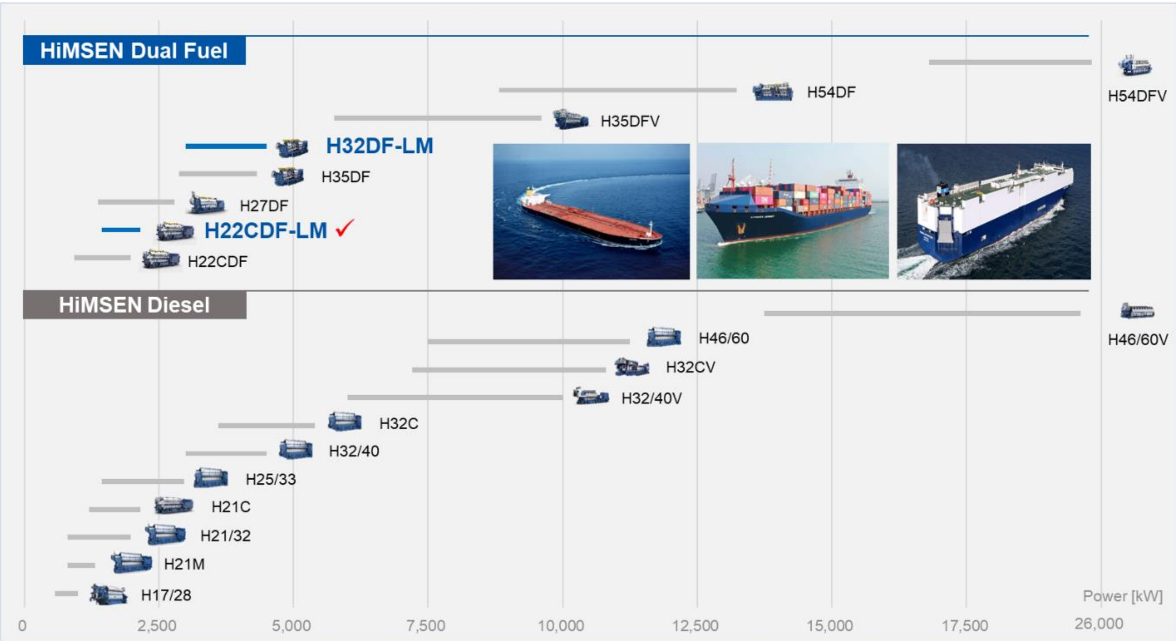


Figure 3: Lineup of HiMSEN

2. HiMSEN methanol engine development

2.1. Introduction to HiMSEN engine

HiMSEN is a brand of medium-speed engines developed by HHI, widely used for marine and power generation application. HiMSEN stands for Hi-Touch Marine and Stationary ENgine, and is designed with a focus on high efficiency, high performance, and low emissions, earning recognition for their reliability and economic benefits in various applications. In the early 2000s, HHI developed its first medium-sized diesel engine using proprietary technology. It took a long span of 12 years to establish an engine lineup ranging from 1MW to 22 MW. On average, developing a single engine took approximately two years. Additionally, in the early 2010s, the first medium-sized LNG dual-fuel engine was developed, and it took six years to establish the lineup. The development period was shortened compared to the diesel engine development, which was due to the application of VPD technology. Meanwhile, in 2022, the world`s first methanol dual-fuel engine was successfully developed, and thanks to advancements in VPD technology, the time required to establish the lineup was further reduced. Through the development and utilization of VPD technology, HHI has been able to respond quickly and precisely to the diversification of fuels, the rapidly changing fuel market, and the needs of customers. Figure 3 shows the entire lineup of HiMSEN diesel, LNG dual-fuel, and methanol dual-fuel engines. Over the past 20 years, an engine lineup covering all power ranges from 1 MW to 26 MW has been established. Next, an introduction will be provided on the VPD technology developed and continuously advanced by HHI. Starting with methanol dual-fuel engines, the e-fuel engine lineup will continue to be expanded.

2.2. Introduction to VPD technology used in engine development

VPD stands for Virtual Product Development. It refers to be a comprehensive approach to product development that involves testing and validating product performance in a virtual environment through simulations, rather than creating prototypes for development. Unlike automobile engines, marine engines are larger in size and have higher power output. Consequently, the cost and time required for production prototype are substantial, and the manpower and expenses involving in testing are significantly higher. Therefore, a simulation-based development process is essential for the development of marine engine.

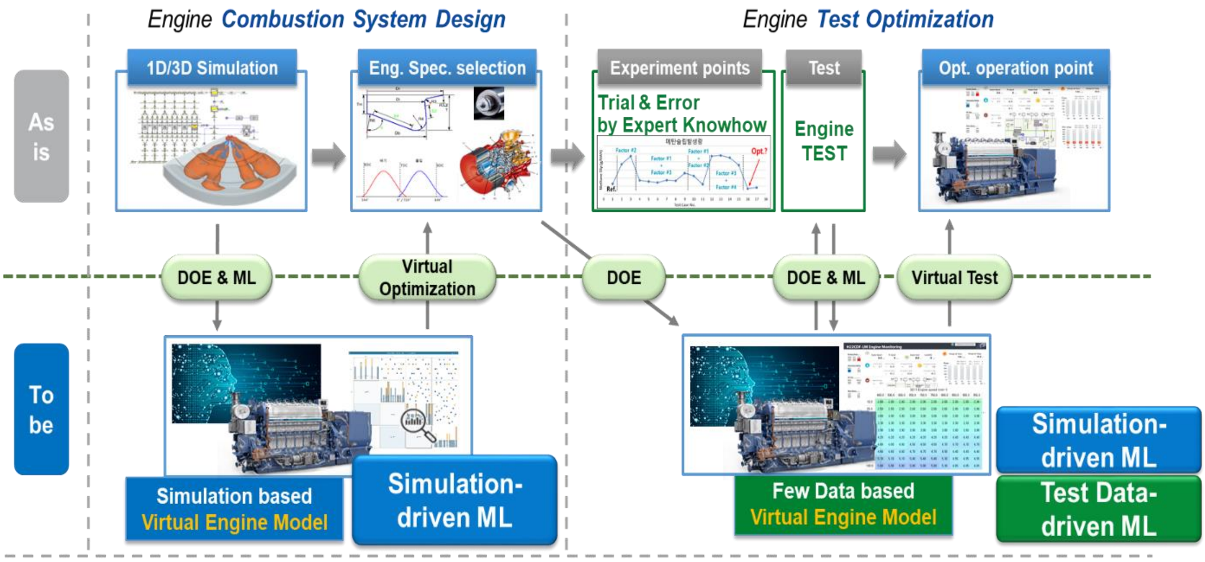


Figure 4: Utilization of virtual engine model in HiMSEN development

While simulation-based development offers many advantages over prototype-based development, the increasing variety of fuels, as well as the growing number and complexity of technologies and components applied to engines, have led to rising costs and time requirments for simulations. HHI has integrated various simulation techniques with artificial intelligent (AI) and machine learning (ML) technologies to create a virtual engine model. This model has been utilized in engine development to reduce the time required for simulation while ensuring high accuracy in the results. Figure 4 shows a schematic diagram of the virtual engine model utilized by HHI in engine development. For example, during the engine combustion system development stage, 1D and 3D simulations are conducted for the basic and detailed design. Previously, it required changing many design variables one by one to investigate their impact on sensitivity and performance, resulting in significant time and effort needed for simulation and evaluation. Additionally, after prototype production, there are tests that need to be conducted to achieve stable engine operation and identify the optimal operating points. Previously, conducting all these tests consumed a significant amount of time and cost. However, recently, design of experiment (DOE) and ML have been utilized to build performance prediction models based on simulation and measurement data. By utilizing these models, virtual optimization was performed, enabling efficient development instead of numerous simulations and engine tests. Next, specific examples of the development and application of virtual engine models based on test and simulation data will be introduced.

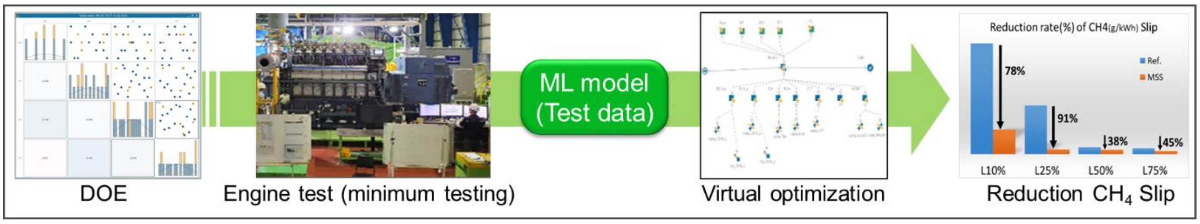


Figure 5: Utilization of a measurement data-based virtual engine model

First, the development of virtual engine model based on measurement data. HHI possesses a technology called Methane Slip Solution (MSS) to reduce methane slip in LNG dual-fuel engines. Among the MSS technologies, there is the Multi-Point Injection (MPI) technology, which was developed using a virtual engine model during the development process. [5] When operating with MPI, several new operating variables are introduced in addition to the existing variables of injection timing and injection duration. The optimal operating point, where methane slip is minimized, must be identified by combining various operating variables. Conducting actual tests would require performing tests on dozens of operating points, resulting in significant time and cost expenditures. Thus, virtual engine model based on measurement data was constructed to minimize the number of tests. Firstly, the number of test points required to create the virtual engine model was minimized using DOE, and a virtual engine model was generated using ML. After creating the model, virtual optimization was used to define the optimal points without conducting actual tests. The selected optimal points were then tested to validate the results. Through this process, the number of actual tests was minimized, and the optimal operating point where methane slip is minimized was identified.

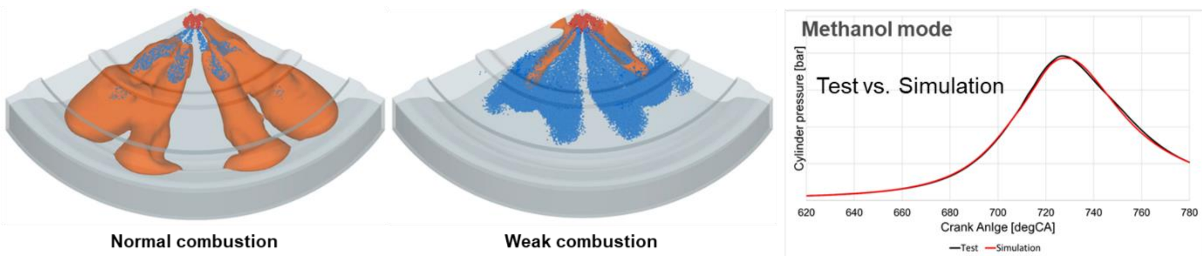


Figure 6: Utilization of a simulation data-based virtual engine model

Next, the development of virtual engine model based on simulation data. During the development of the methanol engine combustion system, a virtual engine model based on simulation data was established and utilized in the basic and detailed design stage. In the basic design stage, fundamental specification of the combustion system, such as intake/exhaust valve timing, compression ratio, and turbocharger specification, are determined. In the detailed design stage, the specification of major combustion chamber components, such as the piston bowl shape and fuel injection valve shape, are determined. To fully consider various variables and constraints, DOE was used to understand the impact or sensitivity of all variables, while selecting the minimum number of simulation cases. And virtual engine model based on simulation data was constructed using ML. This model was utilized to design a combustion system that ensures optimal performance while considering engine operational stability and mechanical limit. Subsequently, the test conducted on the prototype engine exhibited performance consistent with the predictions, demonstrating excellent results.

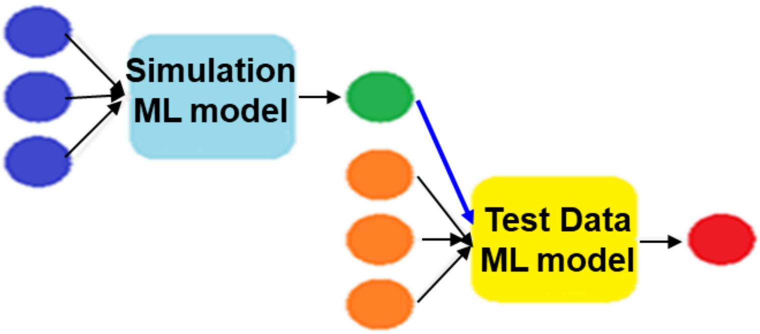


Figure 7: S&FD based PIML model

The last is the development of S&FD (simulation and few data) based Physics-informed machine learning (PIML) model using measurement and simulation data. PIML, which stands for Physics-informed Machine Learning, is a technique that incorporates physical information, such as governing equations, physical constraints, and actual measurement data, into the machine learning process. This approach enables more accurate and reliable predictions compared to purely data-driven methodologies. Additionally, PIML can effectively learn even in situations where data for building predictive models is insufficient. HHI has developed an engine performance prediction model by applying PILM to over 20 years of accumulated engine measurement data and simulation data obtained through advanced modeling. This has been termed the S&FD-based PIML model.

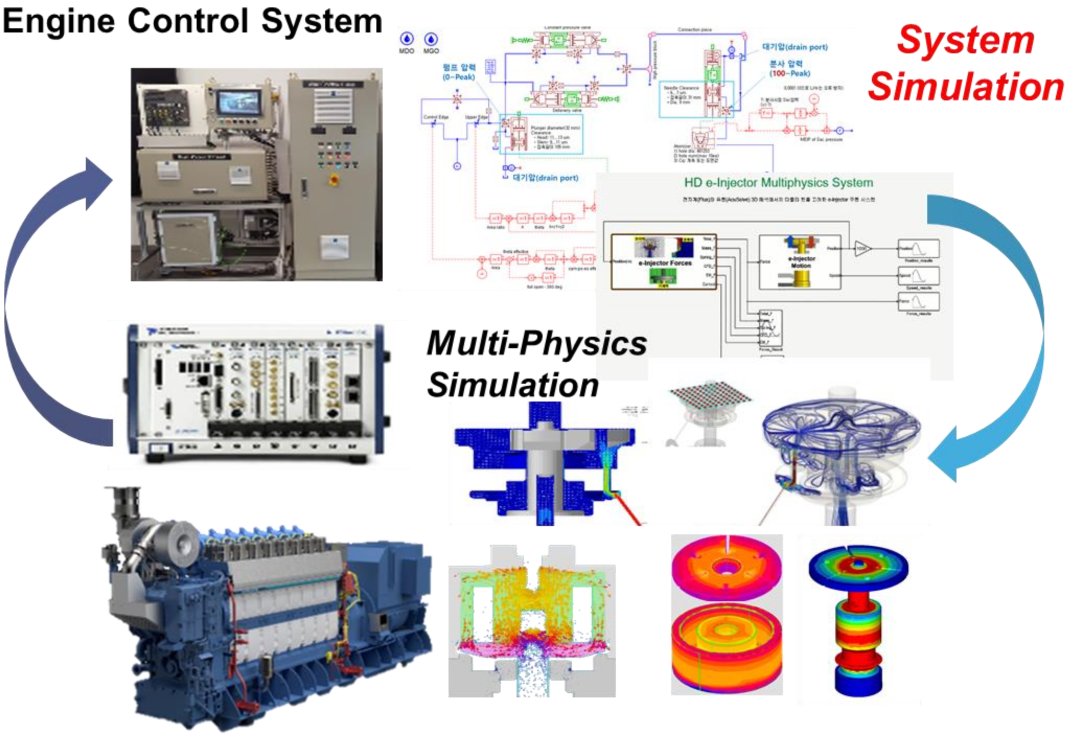


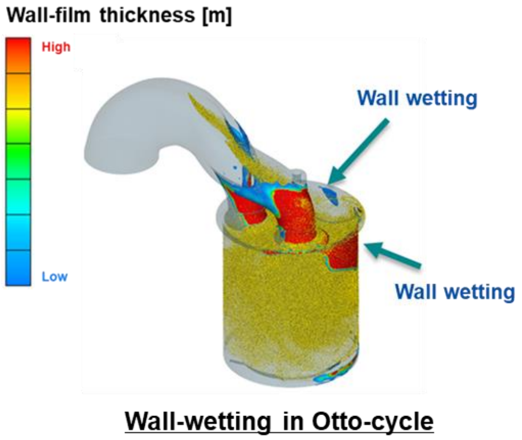
Figure 8: Integrated engine system simulation

There are broadly two types of data for machine learning: high-fidelity (HF) and low-fidelity (LF) data. High-fidelity data is highly reliable and accurate but expensive to produce. Consequently, high-fidelity data is typically scarce. In our context, this category includes measurement data or 3D simulation data. In contrast, low-fidelity data is less reliable and accurate, but it is inexpensive to produce and available in large quantities. Typically, simulation data, particularly 1D simulation data, falls into this category. Figure 7 shows a schematic of the S&FD-based PIML model. As shown in the figure, to construct the S&FD-based PIML model, prediction from the ML model built on low-fidelity data are utilized when developing the ML model based on high-fidelity data. Through this approach, better predictive accuracy was achieved compared to creating ML models using only high-fidelity or low-fidelity data.

HHI plans to continue developing VPD technology beyond this point. By utilizing AI, ML and reduced order model (ROM), HHI aims to develop 1D-3D coupled simulation technology that goes beyond single-dimensional simulation. Ultimately, this will lead to the development of integrated engine system simulation technology. Through this, we expect to perform rapid and accurate engine development in the diversifying fuel options and rapidly changing market trends.

2.3. Introduction to HHI's methanol dual-fuel engine

In September 2022, HHI developed the world's first 3.0-4.5 MW medium-speed methanol dual-fuel engine for marine applications. [6] The engine, named H32DF-LM, began development in 2019. The combustion simulation model was developed to observe the flame behavior during the combustion of diesel and methanol fuel within the combustion chamber. This model was utilized to determine the combustion concept for the methanol dual-fuel engine. In the diesel cycle, pilot diesel is pre-injected and ignited, followed by the injection of methanol. The simulation results confirmed that when methanol is ignited with pilot diesel, the combustion and emission characteristics are similar to those of a diesel engine.



Concepts	Diesel-cycle	Otto-cycle
Power	◎	O
Fuel slip	◎	X
Efficiency	◎	O
NOx	O	◎

(◎: Good, O: Normal, X: Bad)

Figure 9: Simulation results of methanol Otto cycle and comparison between Diesel and Otto cycles

In the Otto cycle, methanol is injected at the port and ignited via pilot diesel. As shown in the figure 8, the simulation results identified wall wetting phenomena of methanol fuel and issues such as fuel slip. Therefore, the diesel cycle was selected as the combustion concept for the HiMSEN methanol dual-fuel engine.

The methanol engine development began based on the well-established HiMSEN H32 diesel engine, which has been previously developed and well-proven in the market. However, there were several technical challenges that needed to be addressed for the application of methanol fuel. A representative example of these challenges is the fuel injection system. Typically, a diesel engine requires only one fuel injection system. However, the methanol engine requires three separate fuel injection systems: one for main diesel, one for pilot diesel, and one for methanol.

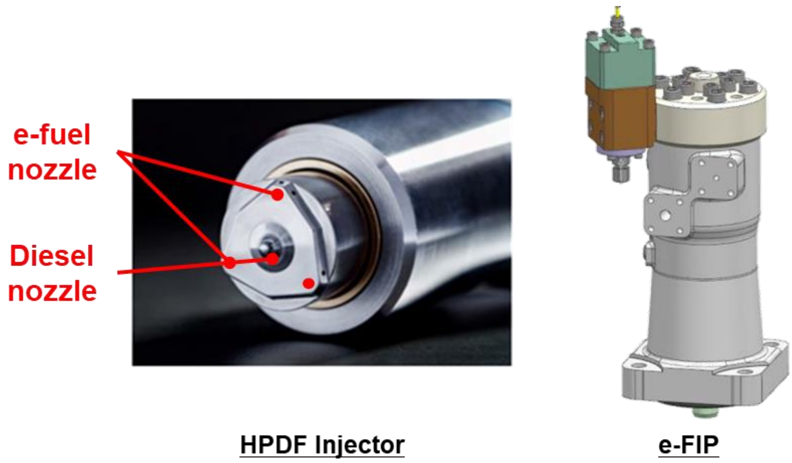


Figure 10: HPDF injector(left) [7] and e-FIP(right)

To overcome this challenge, new designs and simulations were utilized. First, a high-pressure dual-fuel (HPDF) injector capable of performing three fuel injection functions within a single body was adopted.

Additionally, using virtual engine model based on simulation data, the detailed specifications of the diesel and methanol injector nozzles were optimized. Furthermore, a fuel injection pump named electronical-fuel injection pump (e-FIP), capable of electronically controlling the injection timing and fuel quantity for each cylinder was independently developed and implemented. This allows for the optimal operating point settings for specific engine loads to be adjusted according to customer needs. Additionally, many engine tests were replaced with engine simulations. The development tests confirmed very positive results, matching the expectations from the simulations.

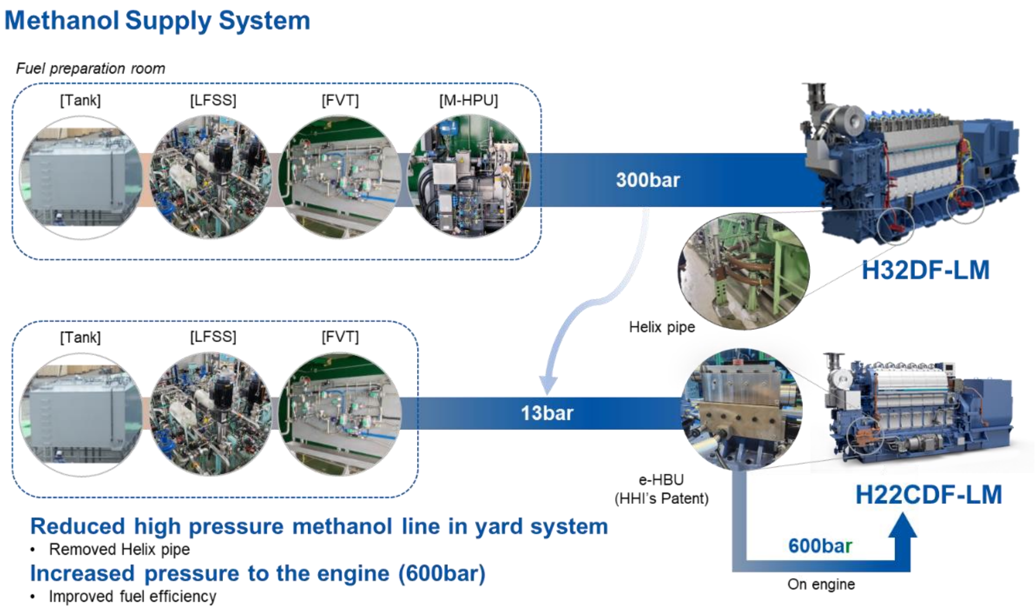


Figure 11: New fuel supply system: e-HBU

In March of this year, HHI leveraged the experience and expertise gained from the development of the H32DF-LM engine to develop a second methanol engine named H22CDF-LM. By developing the H22CDF-LM, a 1.4-2.2MW medium-speed methanol engine, HHI has begun to establish a lineup of methanol engines. This engine incorporates more advanced designs and technologies compared to the H32DF-LM. In the H32DF-LM, a high-pressure double-wall pipe was used to supply high-pressure methanol (300 bar) from the high-pressure methanol pump to the front end of the engine. To reduce the cost of the high-pressure double-wall pipe and to create a more stable engine system, the H22CDF-LM incorporated a newly developed fuel supply system named electronic-hydraulic boosting unit (e-HBU).

The innovation minimized the length of the high-pressure double-wall pipe, allowing for safer engine operation. Additionally, it enabled the pressurization and supply of methanol at over 600 bar, compared to the previous 300 bar, resulting in significantly improved thermal efficiency of engine. The new fuel supply system utilizing the e-HBU is planned to be applied across the entire HiMSEN methanol and ammonia engine product line, including H32DF-LM. The H22CDF-LM, developed in this manner, successfully completed the Type Approval Test (TAT) in March 2024, with the attendance of seven classification societies: ABS, BV, DNV, KR, LR, NK, and RINA. Additionally, as of July 2024, the first order for the H22CDF-LM is imminent.

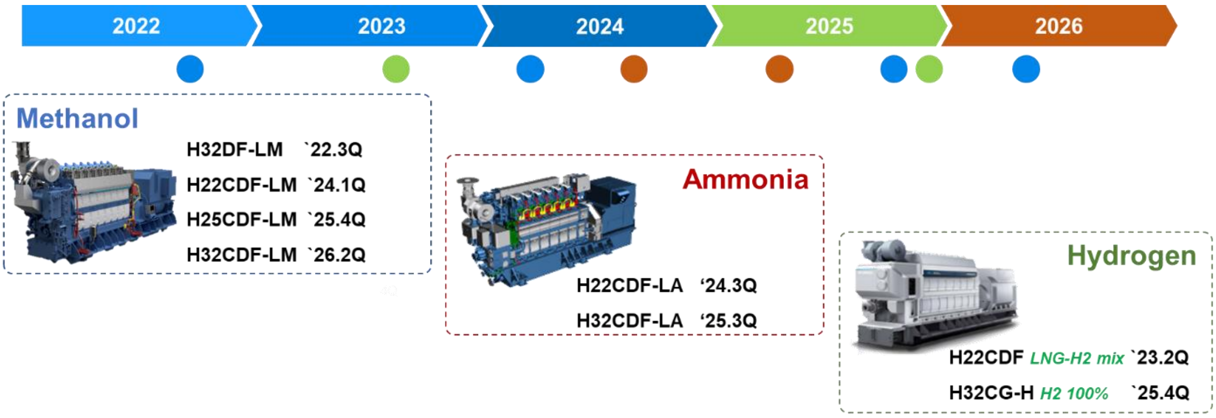


Figure 12: HHI's roadmap for the development of e-fuel engines

Figure 12 shows HHI's roadmap for the development of e-fuel engines. HHI plans to continue expanding its lineup of methanol engines to meet market conditions and customer demands. Furthermore, based on the experience gained from methanol engine development, HHI is also working on developing ammonia and hydrogen engines. The first ammonia engine, the H22CDF-LA, is nearing completion and is scheduled for TAT in September 2024. Additionally, the development of hydrogen engines is underway, taking into account market conditions and technological maturity.

3. Conclusions

HHI has developed its second methanol engine, the H22CDF-LM, and has begun establishing a methanol engine lineup.

1. By developing and utilizing VPD technology, reducing engine development time and advancing the development of high-performance engines.
2. AI and ML technologies are being used to build and utilize virtual engine model based on measurement and simulation data. This approach reduces the time and cost required for test and simulation while providing accurate results.
3. We plan to continuously develop VPD technology to secure integrated engine system simulation technology in the future
4. The development of H22CDF-LM methanol dual-fuel engine marks the beginning of the methanol engine lineup. This engine features a self-developed fuel supply system, enabling safer and more stable engine operation
5. HHI will continue to expand its methanol engine lineup based on market conditions and customer requirements. Additionally, the development of ammonia and hydrogen engines is underway and is expected to be completed in the near future.

Definitions, Acronyms, Abbreviations

GHG: Greenhouse gas

IMO: International maritime organization

LCA: Life-cycle assessment

LNG: Liquified natural gas

TTW: Tank-to-wake

MDO: Marine diesel oil

HHI: HD Hyundai heavy industries

HiMSEN: Hi-touch marine and stationery engine

VPD: Virtual product development

AI: Artificial intelligence

ML: Machine learning

DOE: Design of experiment

MSS: Methane slip solution

MPI: Multi-point injection

S&FD: Simulation and few data

PIML: Physics informed machine learning

HF: High fidelity

LF: Low fidelity

ROM: Reduced order model

HPDF: high-pressure dual-fuel

e-FIP: Electronic-fuel injection pump

e-HBU: Electronic-hydraulic boosting unit

TAT: Type approval test

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