Development of Biofuel Production System with High Energy Efficiency and Excellent Economic Performance: MMDS® (Mitsubishi Membrane Dehydration System)

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Bioethanol is gaining attention as a clean fuel alternative to gasoline and as a feedstock for next-generation sustainable aviation fuel (SAF). Global ethanol consumption has steadily increased over time, with the exception of a temporary decline caused by the COVID-19 pandemic. Furthermore, if full-scale SAF production begins in the U.S., demand for ethanol as a SAF feedstock is expected to grow rapidly.

For bioethanol to be used as fuel, it is essential to remove moisture from the product during the final stage of production. Currently, approximately 60% of the energy consumed in bioethanol production is used in the distillation and dehydration processes. Therefore, reducing the energy consumption of the dehydration process is crucial.

Many bioethanol plants, built primarily in the 2000s, are now aging, leading to increased demand for facility upgrades. Research and development efforts are underway to create a highly efficient membrane separation dehydration system that reduces energy consumption. This report addresses the proposal to replace existing systems with this advanced technology as part of plant modernization.

Mitsubishi Heavy Industries, Ltd. is actively promoting the development and commercialization of this energy-efficient membrane separation dehydration system for bioethanol—a plant-derived clean fuel. The goal is to accelerate the adoption of decarbonization technologies and contribute to building a sustainable, carbon-neutral society.

1. Introduction

This report focuses on the dehydration process employed to render bioethanol suitable for use as fuel. The distillation and dehydration stages account for the majority of the energy consumed during production, approximately 60%. The distillation of water-ethanol mixtures results in the formation of an azeotrope, which limits the maximum achievable ethanol concentration to approximately 95 vol%. Consequently, an additional dehydration step is required to produce anhydrous ethanol with an ethanol content of at least 99.5 vol%, meeting fuel-grade specifications. Energy consumption during the dehydration process has posed a significant challenge, particularly because pressure swing adsorption (hereinafter referred to as PSA), a widely used conventional technique, necessitates vaporization.

In response, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) developed a membrane separation dehydration system known as the Mitsubishi Membrane Dehydration System (MMDS®), which utilizes monolithic ceramic membranes to enable dehydration in the liquid phase. This report details MHI's achievement in attaining the target product purity using membranes identical to those employed in commercial units, demonstrated through pilot plant operations at the MHI Research & Innovation Center **(Nagasaki Carbon Neutral Park, Nagasaki District)**. The background of the development, the system concept, and the pilot test results pertaining to concentration performance are presented, alongside a discussion of the technological implications

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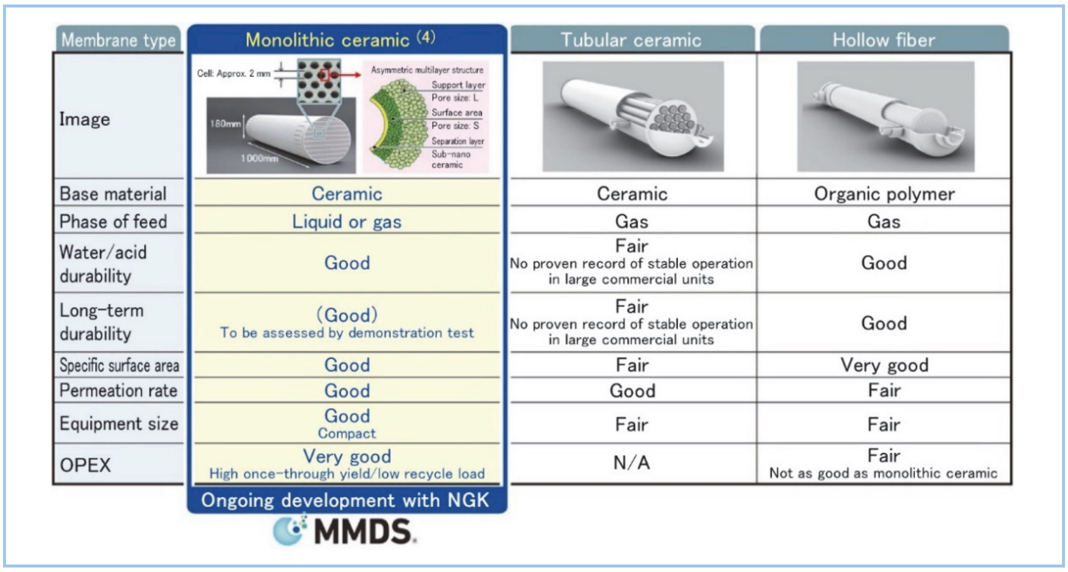
at this stage and the challenges that remain.

Since the 1990s, polymeric and zeolite membrane technologies have been proposed for bioethanol dehydration. However, their widespread adoption has been hindered by limited durability in contact with bioethanol and insufficient permeation rates. MHI's recent success in enhancing permeation performance and achieving ethanol purity of ≥99.5 vol%—a key Japanese fuel standard—in pilot tests employing membranes identical to those in commercial units, has established MMDS® as a viable solution offering both low-energy dehydration and a compact design.

2. About the membrane dehydration system for ethanol

The fundamental principle of MMDS® involves feeding crude ethanol (approximately 90–95 vol%) in the liquid phase under pressure into a membrane module, while maintaining a near-vacuum environment on the permeate side. The driving force for water permeation is the difference between the water vapor partial pressure in the feed liquid and the water partial pressure on the permeate side. This pressure gradient facilitates selective permeation of water through the membrane, resulting in the retention of anhydrous ethanol. The membrane employed in this system is a monolithic ceramic membrane, chosen for its suitability for liquid-phase dehydration.

The MMDS® system primarily comprises the crude ethanol receiving tank, an ethanol preheater, the ethanol dehydration module (consisting of membrane vessels and membrane elements), and a vacuum system on the permeate side. The commercial units are containerized—utilizing 20-foot container-based membrane and equipment modules—to reduce construction costs. The monolithic ceramic membrane offers advantages over other membrane types, such as tubular ceramic or hollow fiber membranes, in terms of liquid-phase feeding capability, environmental durability, and equipment compactness. **Figure 1** enumerates the key advantages of the monolithic ceramic membrane that informed its selection.



Membrane type	Monolithic ceramic (4)	Tubular ceramic	Hollow fiber
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Base material	Ceramic	Ceramic	Organic polymer
Phase of feed	Liquid or gas	Gas	Gas
Water/acid durability	Good	Fair No proven record of stable operation in large commercial units	Good
Long-term durability	(Good) To be assessed by demonstration test	Fair No proven record of stable operation in large commercial units	Good
Specific surface area	Good	Fair	Very good
Permeation rate	Good	Good	Fair
Equipment size	Good Compact	Fair	Fair
OPEX	Very good High once-through yield/low recycle load	N/A	Fair Not as good as monolithic ceramic
	Ongoing development with NGK		

Figure 1 Advantageous features of monolithic ceramic membrane for selection

The principal objectives for enhancing membrane performance include: (1) increasing the permeation rate to minimize the number of membranes required; (2) improving water/ethanol selectivity to prevent ethanol loss into the permeate, thereby enhancing yield; and (3) ensuring membrane stability and effectiveness amid operational fluctuations during long-term use. From an energy perspective, the major benefits stem from liquid-phase separation that obviates vaporization and the reduced load on the upstream distillation process. Our estimates indicate that the total energy consumption for the distillation tower and the dehydration unit in the MMDS® system is approximately 38% lower than that of the PSA method. Similarly, when considering capital expenditure (CAPEX) and operational expenditure (OPEX) over a 20-year period, a reduction of 35–37% is projected for regions such as the Midwestern United States, Japan, and Europe.

Figures 2 and **3** present comparisons between MMDS® and PSA with respect to energy consumption for dehydration and economic efficiency, respectively.

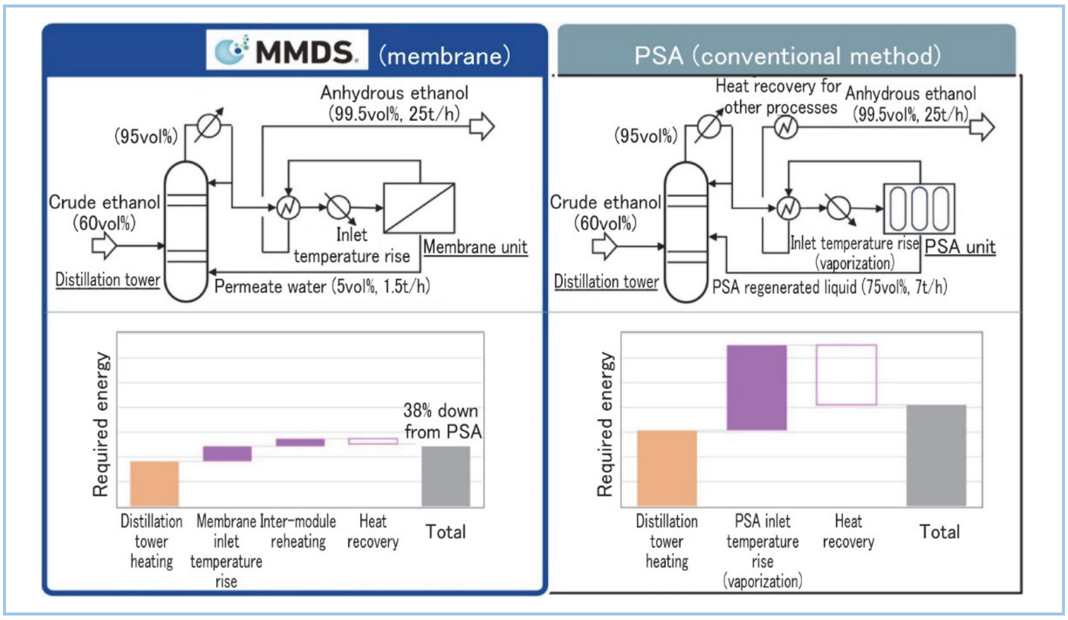

Figure 2　Comparison of energy required for dehydration

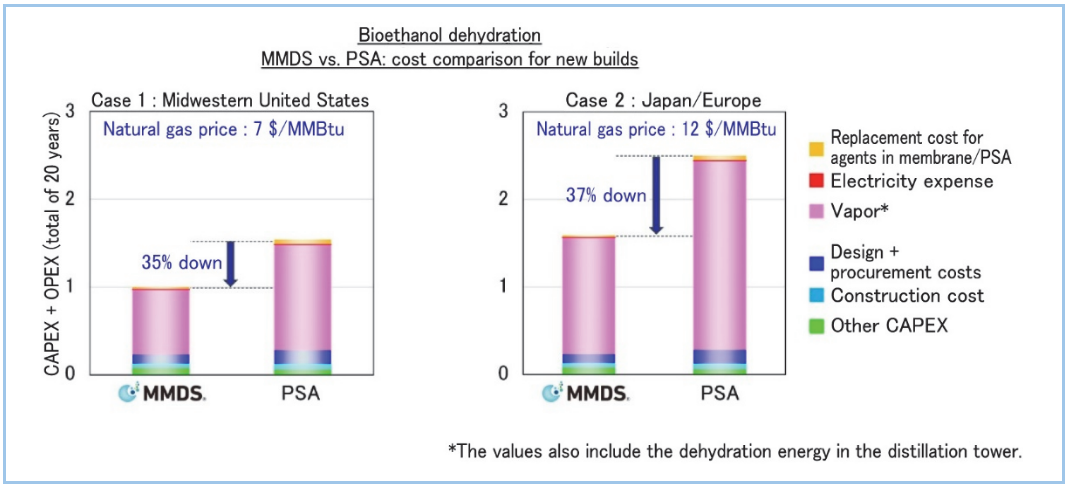

Figure 3　Comparison of economic efficiency between MMDS® and PSA

The key functional requirements for MMDS® are as follows:

- **Product Purity:** Achieve ethanol purity of ≥99.5 vol%, in accordance with Japanese fuel standards.
- **Yield and Energy Conservation:** Maintain a high ethanol recovery rate while reducing overall energy consumption by lowering the regeneration load on the distillation tower.
- **Durability and Contamination Resistance:** Ensure robustness against fouling caused by impurities present in actual bioethanol, enabling reliable long-term operation.
- **Modularity:** Offer a wide range of capacities with short turnaround times through a modular containerized design (based on 20-foot containers), permitting installation flexibility via partial replacement of PSA units and staged implementation. **Figure 4** illustrates a possible configuration of the commercial unit.

The initial phase of the research and development approach involves fundamental assessments using small, laboratory-scale membranes. This is followed by progressive steps, including the construction of a permeation rate model incorporating mass transfer phenomena—accounting for dependencies on concentration, temperature, and flow rate—and the formulation of equations for membrane boundary mass transfer coefficients under laminar and turbulent flow conditions. Subsequently, scalability to large-scale membrane dehydration and pilot testing is evaluated. Throughout these stages, parameters such as permeate water volume, required membrane quantity, and economic viability are estimated with the objective of establishing process design guidelines for commercial deployment.

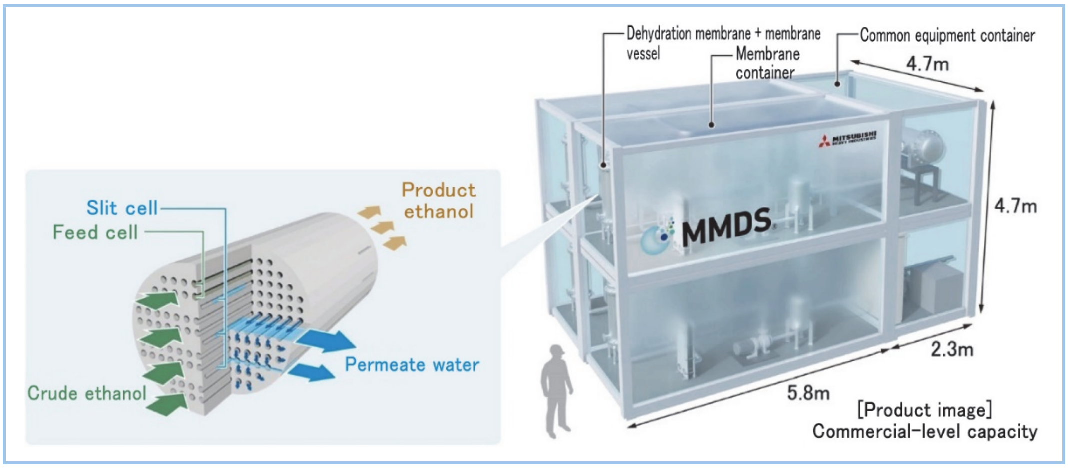

Figure 4　Conceptual illustration of commercial unit

3. Pilot testing

3.1 Summary of pilot test facility

The pilot plant is located within MHI Research & Innovation Center. It consists of a group of modules housing commercial scale dehydration membrane elements of the same type as the commercial unit, a pump and a preheater for boosting ethanol on the upstream side, an ethanol circulation line, a vacuum system on the permeate side, and a skid for installing them.

During operation, the supplied ethanol is heated under pressure before being fed to the membrane in the liquid phase. A vacuum is created on the permeate side of the membrane, enabling the difference between the partial pressure of water vapor within the liquid phase and the permeate-side water pressure to serve as the driving force for permeation. The pilot plant is equipped with the same type of membranes as in the commercial unit in terms of the number of pores and the membrane area. The circulation pump and the preheater are used to keep the circulating flow and temperature at the specified levels. The pressure on the feed side is increased. The test is then conducted under closed-loop circulation conditions. With this pilot plant, the dependence of the water permeation rate on temperature, concentration and flow rate can be examined.

Figure 5 shows the exterior view of the pilot plant installed at MHI Research & Innovation Center (Nagasaki District).

Figure 5　Exterior view of pilot plant installed in MHI Research & Innovation Center (Nagasaki District)

The objective of this test using the same type of membranes as those in commercial units is to confirm the dehydration performance (product purity: ≥99.5%) and the dependence on the parameters of temperature, concentration and flow rate. In conducting the pilot test, the results of laboratory-scale modeling of mass transfer and membrane boundary mass transfer coefficients were taken into consideration, aiming to verify the validity of the simulation model that can be applied to the design of the commercial unit. The operability, safety and procedures for commercial operation were also confirmed.

3.2 Ethanol concentration test/confirmation of parameter dependence of membrane performance

The pilot test was conducted to examine whether the product can meet the fuel standards in Japan in a closed-loop operation using a continuous-concentration system. Crude ethanol as the feed had an initial concentration of ≈92.5 vol%, before being circulated/concentrated. As the concentration increased over time, the ethanol reached ≈99.6 vol%, satisfying fuel standard and meeting the target performance.

Comparison was made between the test using small, laboratory-scale membranes and the pilot test using commercial scale dehydration membranes. The results confirmed that, despite their different sizes, both membranes exhibit similar concentration performance and dependence on the conditions of temperature/flow rate. The measurements of water permeation rate under various conditions were consistent with the mass transfer model constructed based on the results of the small-membrane laboratory test (i.e., a formula incorporating concentration dependency, Arrhenius temperature dependency, and flow rate dependency based on the membrane boundary mass transfer coefficients). This model can therefore be used to predict the performance of the same type of membranes as in commercial units.

The key results obtained from the test are as follows:

- Stable production of high purity product (≥99.5 vol%) was demonstrated using commercial-scale membranes, confirming compliance with the quality standards for blended gasoline fuels via the membrane-based dehydration method.
- Permeate water flux increased as the temperature or feed flow rate increases, in good agreement with model predictions of temperature, flow rate, and feed concentration dependencies.

3.3 Future challenges

Small amounts of impurities originating from fermentation, which are commonly present in actual bioethanol, may lead to a decline in membrane performance or cause membrane blockage. During the pilot test, where industrial ethanol was used as the circulating liquid, no significant performance degradation was observed. However, for the commercial application of the membrane separation dehydration system, it is essential to quantitatively evaluate fouling behavior over long-term operation under real-world conditions and to identify the substances responsible for fouling.

As a countermeasure against fouling, MHI plans to conduct fouling tests using actual bioethanol to assess membrane durability and resistance to impurities. The MMDS® system has already demonstrated highly efficient dehydration via liquid-phase separation—achieving a purity of ≥99.5 vol% in pilot testing—along with significant reductions in energy consumption. To further ensure reliability, MHI intends to perform additional testing with actual bioethanol using laboratory-scale equipment at the Research & Innovation Center, as well as at bioethanol production facilities in the United States. These tests will investigate potential changes in membrane performance and help identify the primary fouling agents.

MHI will continue to advance these assessments as part of the preparation for demonstration testing and commercialization. **Figure 6** illustrates the development roadmap.

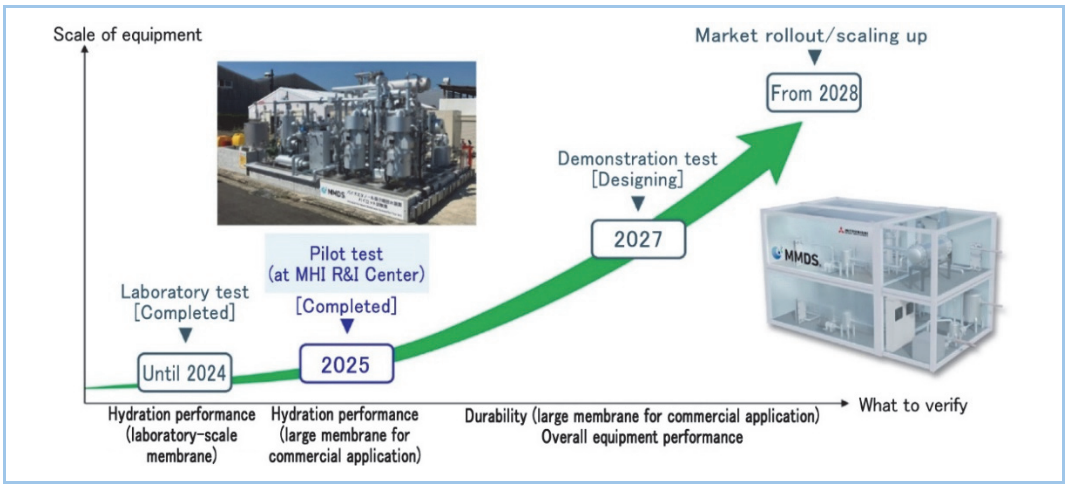

Figure 6　Roadmap for development

4. Conclusion

This report has presented the development of the MMDS® system, which utilizes monolithic ceramic membranes, along with the results of concentration tests conducted at a pilot plant installed at the MHI Research & Innovation Center, and the findings related to membrane parameter dependencies. The concentration test at the pilot plant successfully increased the crude ethanol concentration from approximately 92.5 vol% to about 99.6 vol%, achieving product purity that meets Japanese standards for blended gasoline fuels. This demonstrates that the MMDS® is a promising commercial alternative to PSA technology.

However, certain challenges remain, including the need to develop strategies to prevent fouling caused by trace impurities in actual bioethanol and to verify long-term durability. Further testing is essential, such as laboratory evaluations of fouling behavior and trials using actual bioethanol sourced from the U.S.

Looking ahead, MHI will focus on process optimization based on operational data from the pilot plant, accelerating preparations for the construction of a demonstration plant and facilitating an early market rollout from both technological and business perspectives.

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