Validation of a model of a methanol fuel supply system for a two-stroke dual-fuel marine diesel engine

Courtesy of Alfa Laval

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Methanol is one of the strategic fuels to achieve the International Maritime Organization's ambitious decarbonization goals over the next decades. As an expert in the marine sector, Alfa Laval is a leader in designing and supplying methanol fuel supply systems for marine diesel engines. In this study, Alfa Laval and EnginSoft present the results of a simulation of the methanol fuel supply system currently used on a methanol carrier. The scope of the study was to develop and validate a 1D computation fluid dynamics (CFD) model to reproduce the existing dataset collected from an actual system, in both steady-state and transient conditions, and its interaction with the upstream and downstream parts of the overall fuel line, from tank to engine. The validated model will enable Alfa Laval to simulate the system's behavior under different conditions and to remotely support customers, forming the basis of a new digital approach to product development.

The International Maritime Organization's targets for decarbonization

The shipping sector plays a key role in the global economy, transporting people and goods worldwide. Carrying around 80% of the world's trade volume and 70% of its value, marine vessels are estimated to account for 2.9% of worldwide carbon dioxide emissions [1].

The International Maritime Organization (IMO) has adopted a strategy to progressively reduce the marine industry's greenhouse gas (GHG) emissions, in line with the Paris Agreement on climate change in which in 2015 adhering countries agreed to a commitment to limit the greenhouse effect.

The IMO strategy to progressively reduce the GHGs from shipping, adopted by the Marine Environment Protection Committee (MEPC) in 2018 [2], to progressively reduce the GHG from shipping includes the objectives of:

- reducing CO_2 emissions per transport work, as an average across international shipping by at least 40% by 2030, compared to the levels of 2008
- reducing total annual GHG emissions by at least 50% by 2050, compared to 2008.

Methanol's role as a decarbonization fuel

Methanol (CH_3OH) is a chemical used in thousands of products. While it can be produced from different sources, it is traditionally made from fossil feedstocks via syngas. Renewable methanol, instead, is produced either from biomass (bio-methanol) or from captured CO_2 and H_2 produced from water by electrolysis via renewable electricity (e-methanol). Compared to other fuels, methanol can reduce CO_2 emissions by 65% to 95%, depending on the feedstock [3]. The use of renewable methanol as a fuel is therefore strategic for those sectors, including shipping, which are transitioning to decarbonization. In addition, its combustion is sulfur oxide-free and generates low nitrogen oxides emissions compared to other conventional fossil fuels [3].

Methanol in marine diesel engines

The main marine engine manufacturers have developed technologies to burn methanol in diesel engines [4].

With its expertise in marine fuel handling and conditioning, Alfa Laval has contributed to methanol technology development from the very beginning, working on the first methanol fuel supply system prototype. Today, Alfa Laval has a strong experience in designing and supplying methanol fuel supply systems, with 12 systems currently installed and operating onboard methanol carriers, with a total of 100,000 hours of operation, plus several other systems in the final stages of development.

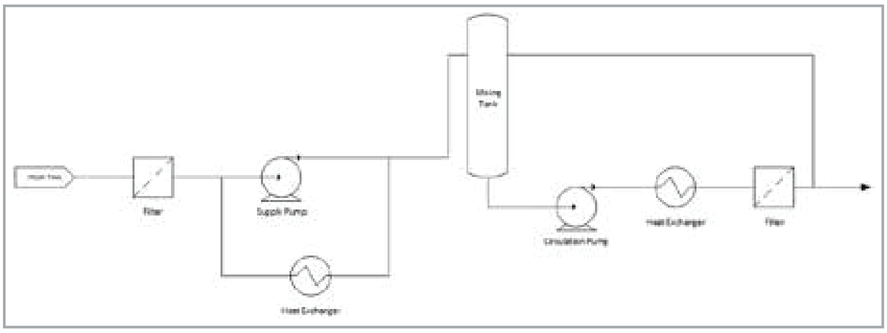

Fig. 1 – Simplified flowchart of the methanol line in the methanol fuel supply system.

The use of methanol as a fuel for the first container vessel is expected by 2023. This is a step towards sustainable zero-emission vessels, in line with the IMO's decarbonization strategy. With its commitment to sustainability, Alfa Laval is fully involved in the development of technology to support methanol and other alternative fuels [5].

Simulation's role in product development at Alfa Laval

In addition to traditional and consolidated engineering practices, Alfa Laval is adopting advanced engineering tools to support the product development process, with the aims of ensuring cost-effective design and increasing the efficiency of methanol fuel supply systems.

One of the first modeling and simulation activities was dedicated to the methanol fuel supply system because of its strategic role in Alfa Laval's portfolio, which is expected to increase in the near future. The objective is to develop virtual models of methanol fuel supply systems and validate them through field data retrieved from operating systems. Once validated, the models can be used as the basis for analyzing the behavior of the process under non-standard conditions, and for providing remote customer support.

Methodology

In this study, Alfa Laval worked with EnginSoft to develop a fluid dynamic model of an existing methanol fuel supply system. This model will generate numerous benefits, such as simplifying the understanding of real system behavior and providing a tool for making better engineering decisions.

Software

The Flownex simulation environment was used to model the system. Flownex is a one-dimensional computational fluid dynamic (CFD) modeling software. The 1D CFD modeling approach is suitable for system simulations and enables the physical behavior of the entire module to be modeled, studied and analyzed, taking into account different operating conditions.

Process description

The methanol fuel supply system modeled in this study is a system designed to feed a two-stroke, dual-fuel marine diesel engine with methanol. It consists of a two-stage pressure module with an intermediate mixing tank (see Fig. 1), designed to pump fuel from the storage tank to the engine at the operating conditions required by the engine, under varying loads. The system also includes heat exchangers, filters, and valves to meet engine requirements for temperature and degree of filtration in a fully automatic mode. The methanol fuel supply system is also equipped with an ethylene-glycol/water solution circuit to provide heating/cooling media for the heat exchangers in methanol operation, preventing contamination of any of the ship's utilities in the event of an internal leakage in the heat exchangers.

Model basis

The main parameters studied were pressures, temperatures, flow rates, and valve opening in both the low-pressure and high-pressure recirculation loops.

Methanol pumps

Both the supply pump (LP) and the circulation pump (HP) were modeled using the "Fan or Pump" component available in the Flownex library. The flow-prevalence curves, the net positive suction head required (NPSHr) curves, and the efficiencies were taken from the datasheets of the pumps installed in the system. This permitted the pumps to be simulated in terms of performance, power consumption, heat transferred to the fluid, and cavitation risk.

Filters

The filters were modeled as pressure drop-generating components, since this is the main effect related to the fluid dynamics of the model. In fact, fuel purity, which is an important parameter in the actual supply system, was not considered as a parameter in the present study.
Therefore, the filters were modeled using the "User specified pressure drop" component. The flow-to-pressure drop curves were obtained from the datasheets of the filters actually installed in the methanol fuel supply system.

Heat exchangers

The modeled system includes two heat exchangers in methanol operation, one in the low-pressure section (LP HE), and one in the high-pressure section (HP HE). The model was implemented and validated against the system's data.

Initially, the "heat exchanger primary" component was used. Four thermal balances at different liquid-phase methanol (MeOH) mass flows and inlet temperatures were used as reference cases to calculate the required heat transfer rate as input to the component.

The pressure drop values were used to interpolate the factors Ck, α, and β used in the following equation:

$$\Delta p = C_k \rho^\beta Q^\alpha$$

Subsequently, to obtain more accurate results, the "Shell Tube Heat Exchanger" component available in the Flownex library was used to model a more accurate geometry[1]. All data needed as input to the model (geometry, fouling factor, materials, etc.) was obtained either from the available datasheet or from Alfa Laval's in-house experience.

Mixing tank

he mixing tank was initially modeled by splitting the model of the liquid portion and the model of the gas portion, and using the "Open Container" and "Air Volume" components available in Flownex Library, respectively, and associating them via a script (see Fig. 2). By doing so, any changes in level during dynamic load variations, or at start-up and shutdown, were automatically reflected in a corresponding change in the available vapor space above the liquid level, and thus in pressure. Later, the "Accumulator" component was used, which simplified the system while obtaining the same results[1].

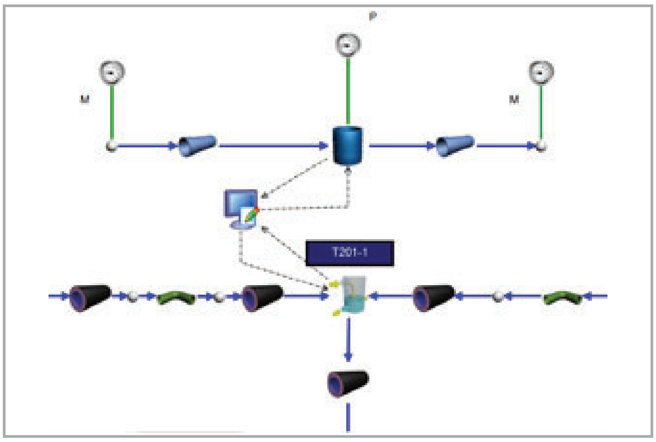

Fig. 2 – Model of the mixing tank.

Other components

All pipes and bends were modeled using the "Insulated pipe" and "Bend" components according to the actual 3D geometry of the methanol fuel supply system. The on/off valves were modeled using the "Basic Valve" component, with the actual valve flow coefficient (Cv) of the valves used in the system. The same approach was taken for the control valves, modeled using the "Ansi control valve" with the actual valve Cv and characteristics. The flow meter, similarly to the filters, was modeled with a "user specified pressure drop".

Glycol-water circuit

The glycol-water circuit consists of a pump that circulates an ethylene glycol-water (GW) solution to a plate heat exchanger to achieve the desired GW temperature set point. The GW is circulated to the two heat exchangers in methanol operation and then back to an expansion tank. The plate heat exchanger maintains the GW temperature by exchanging heat with low temperature water (LT water). To obtain accurate results and make use of the available data, the GW system was also modeled.

[1]*The validation results presented in the "Results" section refer to the model without this improvement.*

Process control parameters

In order to deliver methanol at the operating conditions required by the engine at varying engine loads, the methanol fuel supply system is operated under pressure control at two points in the process (low-pressure and high-pressure sections), and under temperature control at the outlet battery limit. The control logic that acts on the methanol fuel supply system is based on software developed in-house by Alfa Laval, which enables fully automated system operation.

At this stage of the model development, the pressure and temperature controls were modeled using the proportional, integral, derivative (PID) control available in Flownex. The PID parameters were tuned to reproduce the trends in some actual pressure and temperature datasets.

Validation of the model

To validate the developed model, several datasets from methanol fuel supply systems in operation on vessels were analyzed in depth and used as references. The parameters used as inputs to the model, as well as the resulting outputs, are listed in Table 1.

The boundary conditions applied to the model are the methanol temperatures and pressures at the module inlet and the corresponding flow rate at the module outlet. For LT water, the flow rate, pressure, and temperature conditions provided during

Parameters
LP loop
Methanol pressure at module inlet
Pressure at mixing tank
Methanol temperature at module inlet
Methanol flowrate (before the mixing tank)
LP recirculation valve opening
HP loop
Methanol pressure at module outlet
Methanol temperature at module outlet
HP recirculation valve opening
GW circuit
LT water inlet temperature
GW temperature to MeOH/GW HE
GW circuit pressure at pump discharge
LT water flowrate
GW HE flow control valve

Table 1: Parameters used to validate the model divided into three blocks: the LP loop (from the module inlet to the mixing tank), the HP loop (from the mixing tank to the module outlet) and the GW circuit.

the module design were used as boundary conditions. The GW flow rate is directly dependent on the flow-head curve of the GW pump, and on the GW pressure. Since the latter had already been considered in Table 1, and the characteristic curve was taken from the pump's datasheet, the GW flowrate was not further validated.

The data available for the methanol flow rate refers to a flowmeter placed at the inlet of the mixing tank, i.e. between sections LP and HP. Therefore, this dataset can be used as-is as a boundary condition for the model only in steady-state conditions, assuming the same flowrate at the system outlet. By contrast, during transient phenomena characterized by flow variations over time, this set of measured flowrates cannot be used directly as a boundary condition.

Transient state simulation/test

Outlet battery limit's on/off valve

The validated model was initially used to simulate the transient phenomena that occur:

- at a sudden opening of the on/off valve at the outlet battery limit when the fuel supply system is in full recycle mode (startup condition and filling line to the engine);
- at a sudden closing of the on/off valve at the outlet battery limit when the fuel supply system is in operation (in case of engine switch to diesel oil).

The PID parameters of the model were tuned to reproduce the experimental pressure peaks generated during the opening and closing of the outlet battery limit valve.

Cyclic flow variations

The model was used to simulate a cyclic mass flow trend observed in a set of experimental data measured during a sea trial to evaluate the system's functionality assuming extreme sea conditions. Based on the key engine requirements, the methanol fuel supply system must be designed and controlled to withstand load variations without exceeding ± 0.5 bar at the module outlet.

Fig. 3 represents a dataset taken over a 1,000-second time period. This dataset accurately represents very severe conditions under which the system should maintain its pressure variations within

Fig. 3 – Experimental mass flow.

the required limits. These values were rounded off to the following sinusoidal function[2] for input into the simulation software:

$$\dot{m} = 1250 \sin\left(\frac{2\pi}{25} t\right) + 1250$$

where $\pm 1{,}250$ kg/h is the amplitude of change in flow with an average period of 25 seconds and a mean value of 1,250 kg/h, as inferred from the trend shown in Fig. 3.

For the transient simulations, the coefficients of the PID controllers controlling the pressure were specified according to the control logic being used in the actual system. The pressure variation at the LP/HP interstage (before the mixing tank) and at the module outlet were considered as parameters for validation.

Results and discussion

Validation results

Table 2 shows the values of the input parameters to the model as well as the results obtained from the simulation, and the corresponding plant values. The validation refers to a steady-state dataset. A maximum deviation of 5% of the results was considered acceptable for the methanol lines, while a larger tolerance was allowed for the auxiliary lines.

Parameters	Simulation	Plant	Deviation [%]
LP loop			
Module inlet pressure [barg]	-0.02	N/A[3]	
Pressure set point before mixing tank [barg]	3.99	3.94	1.3
Module inlet temperature [°C]	23.0	23.0	0.0
Methanol consumption [kg/h]	1820	1823[4]	0.2
LP recirculation valve opening [%]	94.7	92.8	2.0
HP loop			
Pressure set point at module outlet pressure [barg]	8.99	8.91	0.9
Methanol Temperature after HP HE [°C]	34.9	34.7	0.6
HP recirculation valve opening [%]	77.7	78.0	0.4
GW circuit			
GW circuit pressure (after the pump) [barg]	1.91	2.10	9.0
GW temperature before HP HE [°C]	34.9	34.9	0.0
GW HE flow control valve [%]	100.0	100.0	0.0

Table 2: Simulation and plant results.

The deviations in the LP and HP loop parameters are well below the considered threshold. Therefore, the model can be considered to be in line with the required accuracy.

In the GW loop, there is a larger discrepancy between the simulated and experimental pressure values. This is due to the presence of a manual throttling valve in the loop, an element for which no data was available at the exact opening point from the operational plant.

[2] *The recent software update allows raw data to be entered directly into the simulation.*
[3] *Corresponds to tank atmospheric pressure, liquid static head, and loss of the interconnecting piping.*
[4] *Measured before the mixing tank.*

Transient simulation results

Simulation of the module outlet valve opening

Fig. 4 shows the trend in methanol flow rate and the supply pressure upon the sudden opening of the on/off valve located at the outlet battery limit of the methanol fuel supply system. The two charts on the right in Fig. 4 reveal how consumption increases due to the empty pipe attached to the module outlet and the consequent pressure drop. Due to the sampling rate of the flow meter and the maximum detectable flow, the top right graph has a stepped shape. The charts on the left represent this behavior quite well, although the simulated pressure drop is less significant.

The magnitude of the simulated peak flow cannot be compared, but the trend is reliable. Overall, it can be said that the peak consumption and pressure drop following the opening of the outlet battery limit valve is well represented by the model. However, adjustments to the flowmeter sampling rate and maximum detectable flow will be further evaluated to provide a more reliable dataset.

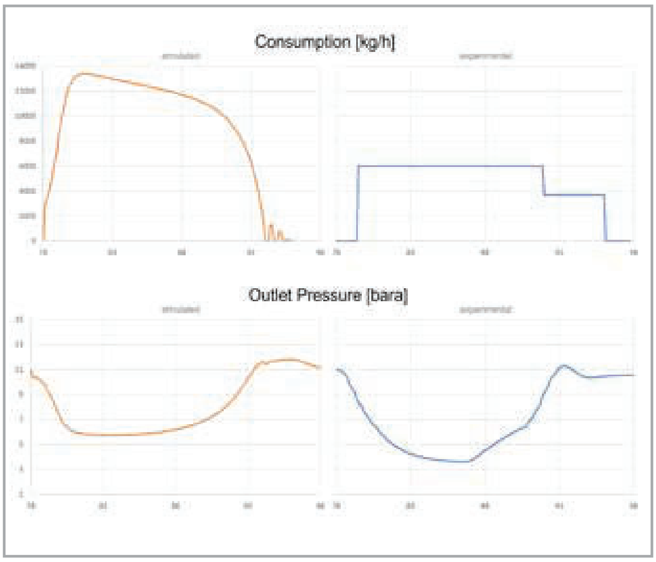

Fig. 4 – The graphs show the methanol flowrate (top) and the module outlet pressure (bottom) trends from the data acquired from the plant (right) and from the simulation (left).

The good correlation between the resulting trends and the actual behavior of the module also reveals that the model represents the real system well, while the control logic can be improved. This will be possible due to the recently added functionality that allows the actual control logic to be implemented in the software, instead of converting it into pre-built PID controllers.

Cyclic consumption simulation

As mentioned in the section on cyclic flow variations, the approximation of the input mass flow data only allows for the study of the resulting pressure variation and its magnitude. Fig. 5 shows the experimental pressure trend at the two control points. At the module outlet, the pressure variation is ±0.1, while before the mixing tank the pressure variation is ±0.05 bar. Fig. 5a shows some pressure spikes that cannot be reproduced as input using the function approximated in the section on cyclic flow variations.

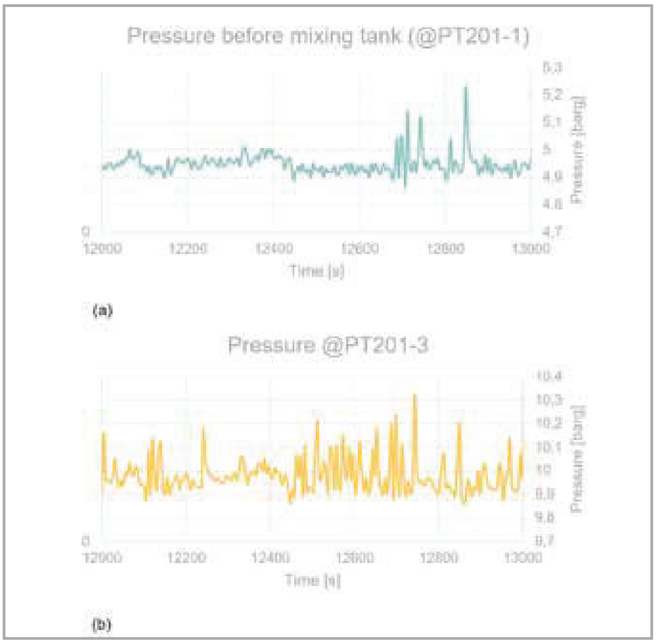

Fig. 5 – Experimental pressure variations at checkpoints.

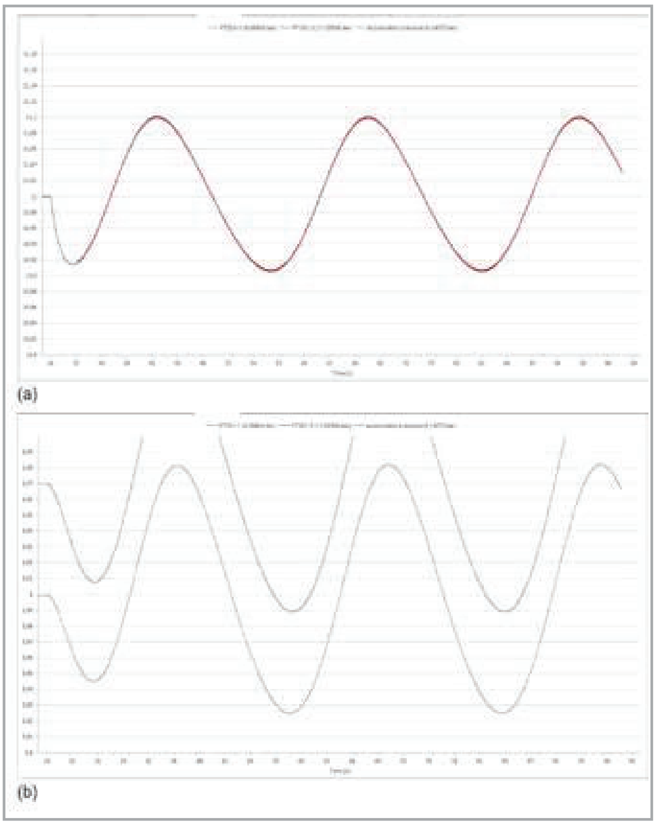

Fig. 6 – Simulated pressure trends.

Fig. 6 represents the simulated trends over a shorter time frame. The outlet pressure (Fig. 6a) has a variation of ±0.1 barg, while the interstage pressure (Fig. 6b) has a pressure variation of ±0.08 barg, slightly higher than actual pressure.

The simulation of the severe cyclic flow variation reflects the experimental pressure variation and complies with the engine requirements. The acceptable accuracy obtained allows this model to be used to simulate other conditions and understand if the resulting pressure variations are within acceptable ranges.

About Alfa Laval

Alfa Laval is active in the areas of Energy, Marine, and Food & Water, offering its expertise, products, and service to a wide range of industries in some 100 countries. The company is committed to optimizing processes, creating responsible growth, and driving progress – always going the extra mile to support customers in achieving their business goals and sustainability targets.

Alfa Laval's innovative technologies are dedicated to purifying, refining, and reusing materials, promoting more responsible use of natural resources. They contribute to improved energy efficiency and heat recovery, better water treatment, and reduced emissions. Thereby, Alfa Laval is not only accelerating success for its customers, but also for people and the planet. Making the world better, every day. It's all about Advancing better™.

Alfa Laval has 16,700 employees. Annual sales in 2020 were SEK 41.5 billion (approx. EUR 4 billion). The company is listed on Nasdaq OMX.

Conclusions

Alfa Laval is adopting new methods of approaching fuel supply system design and development based on data analysis and system modeling.
In this paper, the model-based approach was applied to a fuel supply system processing methanol, which is a key step towards sustainable shipping.

The results of the modeling activities presented show a reliable degree of prediction of the actual system's behavior, fit for purpose, at a degree of approximation that was judged to be acceptable. Further optimization to the same system that can be performed starting from this study includes:

- Implementing Alfa Laval's automation software in the model, instead of using standard simple PID logic;
- Simulating other transient states by directly inputting experimental data without having to define a function to describe the data trend;
- Simulation based on the experimental data related to the configuration of the methanol fuel supply system with the flowmeter located at outlet battery limit;
- Simulation of the system behavior under different boundary conditions.

The availability of additional data from the deployed systems would be useful to further validate the 1D CFD model in various scenarios and to support future modeling activities.

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