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Dynamic Analysis of Large-Scale Transfer Operations for Liquid Hydrogen

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ABSTRACT

Transfer operations from onshore tanks to ship are a crucial component that needs to be understood and optimized to allow for large-scale seaborne transport of liquid hydrogen (LH_2). In this work, we present a dynamic model that includes the main components required for loading operations of LH_2. An important aspect for scaling-up is to quantify the effect of heat ingress in the pipelines. We implement a detailed pipeline model that we use to compare different insulation alternatives. Due to the nature of loading operations, the dynamic analysis, control strategy and controller tunings play an important role in the dynamic behaviour of the system. Here, we systematically analyse the dynamic behaviour of the system and develop a control strategy for LH_2 loading operations. We implement this control strategy in the simulation model for LH_2 loading.

Keywords: Liquid hydrogen, Dynamics, Process control, Loading, Transfer operations, PID control.

INTRODUCTION

In line with the European Union's commitment to global climate action under the Paris Agreement and the European Green Deal, the EU has a climate neutrality target by 2050 (European Commission, 2023). Hydrogen produced with a low-carbon footprint is expected to be a key player in the decarbonization of the energy system (European Commission, 2020). After production, hydrogen is liquefied or compressed for efficient transportation and storage. Compared to gaseous hydrogen, liquid hydrogen (LH_2) has the benefit of increased density, resulting in a large reduction in the required size of storage, buffer, and ship borne cargo tanks for maritime transport. An important advantage with ship transport is flexibility, since installation of large and fixed infrastructure is avoided. Depending on transport distances, seaborne transport of LH_2 can be an attractive option, both in terms of energy efficiency and CO_2 footprint (Ishimoto *et al.*, 2020).

Loading capacities and equipment dimensions required for loading full-scale tankers are expected to resemble those found in present-day LNG transport. However, the largest LH_2 transfer operations today are far below the scale relevant for large-scale seaborne transport and there are several technology gaps that need to be overcome to allow for its realisation. Since LH_2 terminals of such large capacities do not exist, conceptual work is necessary to understand the expected behaviour of such systems. A useful output from conceptual system simulations can be the identification of requirements for several process units when a certain transfer rate is sought. Due to the nature of loading operations, the control strategy play an important role in the dynamic behaviour of the system.

MODEL DESCRIPTION

The process model was built in Dymola 2020X by using the programming language Modelica 3.2.3 and the TIL suite 3.9.0 with TIL Media libraries for thermal components and for the efficient calculation of

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thermophysical properties. Here we consider para-hydrogen and the thermodynamic properties are based on the REFPROP database (Lemmon, Huber and McLinden, 2010).

1.1. System for LH_2 transfer

Figure 1 shows a conceptual schematic representation of the system considered in this work, which is similar to the one presented by a previous work (Kvalsvik, Berstad and Wilhelmsen, 2019). LH_2 is transferred from a large onshore tank through the LH_2 pipeline to the large seaborne tank, which would be onboard the ship. To maintain the pressure of both tanks within reasonable limits, the boil-off gas (BOG) vapor is returned to a liquefier, which is located onshore and is outside the boundaries of the modelled system. It should be noted that the pump illustrates an element increasing pressure. In the physical system, the pump is expected to be submerged, with connections throughout the top of the tank. Key design parameters are presented in Table 1. These are not optimized parameters and a sensitivity analysis for design is part of further work.

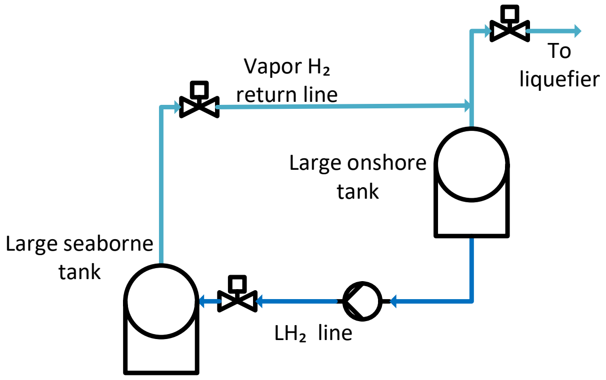

Figure 1: Conceptual schematic representation of the system considered

Table 1. Main parameters of the system

Component	Parameter	Value	Unit
Seaborne tank	Capacity	50 000	m^3
Seaborne tank	Heat ingress	50 000	W
Seaborne tank	Pressure	1.105	bar
Onshore tank	Capacity	50 000	m^3
Onshore tank	Pressure	1.105	bar
Onshore tank	Heat ingress	50 000	W
LH_2 pipeline	Inner diameter	0.3	m
LH_2 pipeline	Length	500	m
LH_2 pipeline	Insulation	0.07	m
Vapor H_2 pipeline	Length	500	m

1.2. Pipeline model

Figure 2 shows the schematic representation of the pipeline model. The pipeline is discretized longitudinally in N=24 segments. Radially, there is an inner pipeline, the insulation, and the outer pipeline. We use the Konakov correlation (Konakov, 1946) for smooth pipes to estimate the pressure drop in the inner stainless-steel pipeline.

An appropriate estimation of the heat ingress across the pipeline is at the heart of understanding the performance of the system. Therefore, it is important to have an appropriate representation of the heat transfer mechanism in each of the layers. The model considers convection between the LH_2 and the inner pipeline as well as between the outer pipeline and the ambient. Conduction is considered across the wall of both pipelines. If ideal vacuum is considered, then the heat transfer mechanism in the insulation layer is radiation. However, there are different potential insulation alternatives, each allowing a different heat ingress to the pipeline. To estimate the heat transfer with different insulation materials, we use the approximation proposed by Hofmann in which the overall resistance is approximated to conduction (Hofmann, 2006), which is applied to each of the pipeline segments.

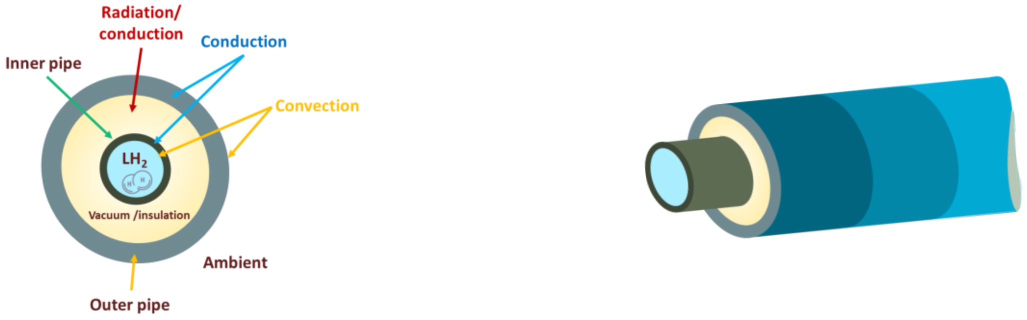

Figure 2: Schematic representation of the modelling principle for the pipeline

DYNAMIC ANALYSIS

In this section we present the dynamic analysis of the system described in Section 2. Large-scale transfer operations would require several steps, e.g., mooring, connection, flushing, pre-cooling, ramp-up, "steady-state" transfer, ramp-down, etc. Here, we focus on the steady-state transfer operations. We first analyse the potential controlled variables and the degrees of freedom (DOF) for operation. Then, we perform a consistency analysis and design the regulatory control layer.

1.3. Analysis of potential controlled variables and degrees of freedom for operation

As mentioned, earlier, the focus is on the LH_2 transfer from the onshore tank to the seaborne tank. The operation of the system is constrained by the model, described in Section 2. To maintain a steady-state transfer operation, the controlled variables of interest are the flowrate through the LH_2 line ($\dot{m}_{LH_2}$), the pressure of the onshore tank (p_o), and the pressure of the seaborne tank (p_s).

The degrees of freedom for operation are the parameters that can be manipulated. They will depend on the control layer we are operating on, i.e., the regulatory control layer or the supervisory control layer. The main objective of the regulatory control layer is to stabilize the process and avoid drifting away from the desired state. On the other hand, the supervisory control layer manages the required switches between the active constraint regions, calculates optimal setpoints for the regulatory layer, and avoids the steady-state saturation of the manipulated variables used by the regulatory layer (Lu, 2003; Skogestad, 2004; Reyes-Lúa, 2020). In this work, we analyse the steady-state transfer and therefore the focus is on the regulatory control layer. Hence, the potential degrees of freedom are the physical valves. Here, we should differentiate between the degrees of freedom for stabilization and the throughput manipulator (TPM). A TPM is a "degree of freedom that affects the network flow and which is not directly or indirectly determined by the control of individual inventory control" (Aske, Skogestad and Strand, 2007). Here, we consider that the valves at the outlet of the tanks are used for stabilization, while the valve in the LH_2 line, which defines the transfer rate, is the TPM.

1.4. Regulatory control layer

The regulatory control layer, illustrated in Figure 3, consists of three control loops, i.e., a control loop to maintain the pressure of each of the tanks, and the control loop to maintain the flowrate of the transferred LH_2.

The PI controllers are tuned using the SIMC tuning rules (Skogestad, 2003) by obtaining an open-loop model from a step response and considering a closed-loop time constant equal to the time delay.

1.5. Consistency analysis

An inventory control system is consistent if it can achieve acceptable inventory regulation for any part of the process, including the individual units and the overall plant (Aske and Skogestad, 2009). Consistency is necessary to ensure a stable process. It should be noted that pressure regulation is very related to inventory control, especially for liquids, and flow controllers cannot be used for inventory control because flow is not a measure of inventory. Figure 3 shows the inventories in the system. There is a liquid inventory in the LH_2 line and a vapor inventory in the H_2 return line. In addition, there is a liquid inventory and a vapor inventory in each of the tanks. The inventory of each phase of any part of the process must be regulated by its in- or outflows or by phase transition.

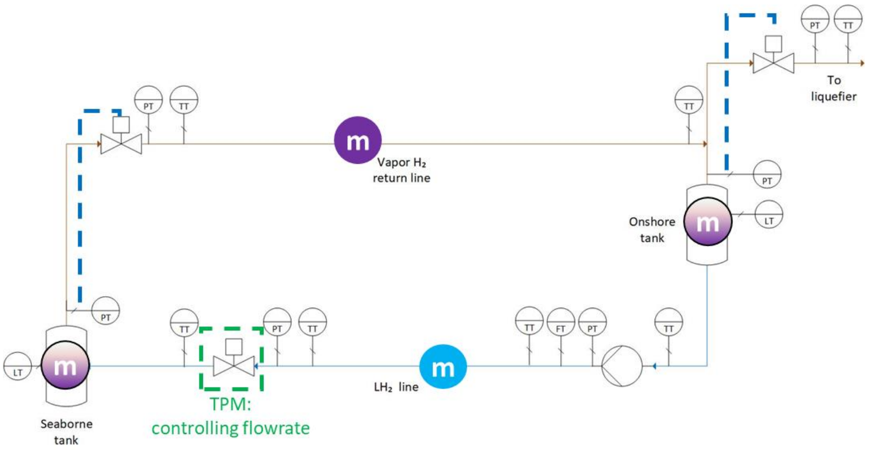

Figure 3: Inventories in the system considered

With the control structure in Figure 3, there is inventory consistency in the H_2 vapor line, as well as for the vapor phases in the tanks because the outflow depends on the inventory, i.e., the valves will open if there is pressure build-up. Here, we study the case in which the onshore tank is already filled and there is no ingress of LH_2. The liquid inventory will depend on the phase transition and the LH_2 outlet flowrate. Note that with the configuration in Figure 3, this flowrate is not directly regulated by the inventory in the onshore tank. For the seaborne tank, the liquid inventory depends on the LH_2 inlet and the phase transition. An important assumption is that the transferred liquid will not exceed the tank capacity. The analysis of the inventory in the LH_2 line is more challenging. It could seem to be a possibility to use the pump as an active manipulated variable, but this would define the flowrate to the LH_2 line. As the outlet flow is defined by the TPM, this would result into an inconsistent LH_2 inventory control. Therefore, the pump should not be actively used for control purposes. Alternatively, the LH_2 flowrate could be defined by the delivery pressure and in this case the TPM would be the pump. Note that this consistency analysis is only valid for the transfer operation of a full onshore LH_2 tank to a seaborne tank with sufficient capacity. When switching between operational modes, i.e., the steps in the complete operation, we would be switching between active constraint regions, and this could be handled using advanced control structures in the supervisory control layer (Reyes-Luá and Skogestad, 2020; Zotică, Forsman and Skogestad, 2022).

SIMULATION RESULTS

1.6. Heat ingress in pipeline

Figure 4 depicts the vapor quality, the heat ingress per segment and the temperature at the inlet, the middle, and the outlet of the LH_2 pipeline when filling it with LH_2. It should be observed that initially, the pipeline is

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filled with hydrogen in vapour state (vapor quality =1) and the ambient temperature is 15°C. The sequential phase change along the pipeline can be appreciated. Also, the heat ingress is varying, which is consistent with the varying temperature along the pipeline and the corresponding temperature difference with the ambient during this process.

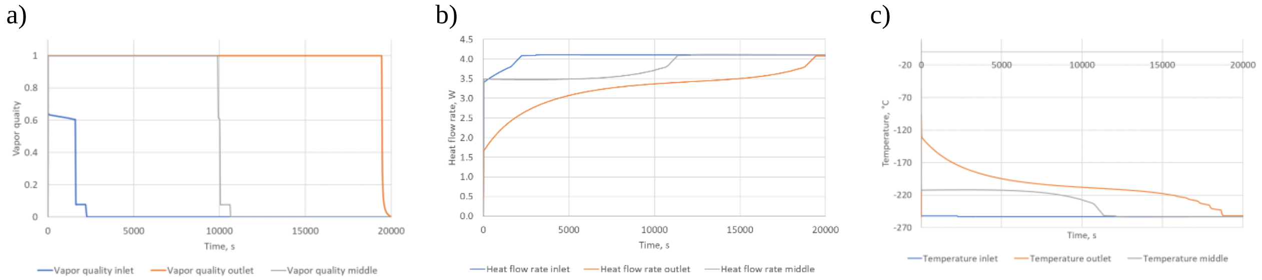

Figure 4: a) Vapor quality, b) heat ingress per segment, and c) temperature in pipeline during priming (cooling and filling with LH_2)

1.7. Loading of liquid hydrogen

In Figure 5 we show simulation results using the control structure described in Section 3.2. Figure 5a) shows an example of the filling of the seaborne tank and the emptying of the onshore tank. With this type of analysis, the filling rate of the tanks, the thermodynamic conditions in both tanks, as well as in the LH_2 and the BOG pipelines can be analysed.

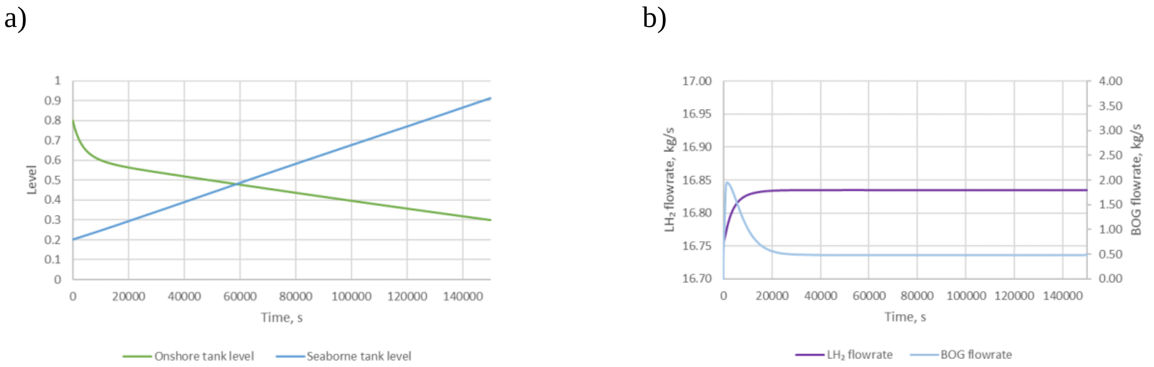

Figure 5: a) Level of onshore and seaborne tanks, b) LH_2 and BOG flowrate

CONCLUSIONS

In this work we presented a dynamic model of a large-scale LH_2 transfer system. The detailed pipeline model allows us to analyse the effect of different insulation alternatives on the dynamic behaviour of the relevant thermodynamic properties. Based on this design, we performed a consistency analysis, which is the basis not only for understanding the dynamic behaviour of the system and developing the control system, but also for understanding the implications and limitations of possible alternatives for loading (e.g., free-flow vs. forced-flow). In this work, we identified the degrees of freedom for operation and designed the regulatory control layer for the transfer system, which allows for the steady-state transfer of LH_2 between tanks. A limitation of the used model is the simplified representation of the tanks and pipeline system, e.g., the fixed value for the heat ingress and neglecting the effect of hydrostatic pressure. Another limitation is the assumption of para-hydrogen at all temperatures. However, the study certainly adds to our understanding of the dynamic behaviour of large-scale LH_2 transfer operations, and the learnings should also be valid when using more detailed models or physical systems. Further work may also include the design of the supervisory control layer, which will allow for optimally switching between different operation modes, e.g., pre-cooling to ramp-up to steady-state to ramp-down.

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NOMENCLATURE

p_i	pressure (bar)	L_i	Length (m)
T	temperature (K)	ID	Internal diameter (m)
TPM	throughput	BOG	Boil off gas
$\dot{m}_i$	flowrate (kg/s)	R_i	Resistance
k	thermal conductivity	r_i	Ratio (m)

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