Software Simulation of Hydrogen Transport using Dense Phase

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Abstract— Using hydrogen instead of natural gas in pipelines is considered as an alternative energy source. Therefore, it is proposed in this paper to transport hydrogen using one of the new methods of transporting Natural Gas, "dense phase". As it was possible to transport natural gas in the dense phase, the purpose of the study is to know the possibility of transporting hydrogen in the dense phase as well. In a dense phase, gas density remains as high as a liquid, whereas its viscosity is very low, closer to that of a gas. In the present study, the governing equations and conditions are presented in a dimensionless form to define the influential parameters describing flow behavior. The numerical solution of these equations is implemented with appropriate boundary conditions using ProMax software for two cases of Hydrogen to provide user-friendly alternatives and offer a wide range of simulation patterns based on selected sets of equations and components. It was also used for comparison and to ensure it produces the same results as previous studies. Velocity inside the pipes is kept appropriately low to prevent corrosion. Velocity, pressure drop, temperature, density, viscosity, and liquid holdup results are obtained based on the influential dimensionless parameters. The results is then validated with previous studies. Despite its density high value decreases, Hydrogen in the dense phase was found to be in liquid form due to its low critical temperature and pressure. Accordingly, the transportation of hydrogen is not recommended.

Keywords— Dense phase; Hydrogen; Natural Gas; ProMax.

I. Introduction

There are four fluid phases; Solid, Liquid, Gas, and Dense. Dense phase has a liquid density and a gas viscosity. Gradual transitions occur from the gas phase to the dense phase and from the dense phase to the liquid phase. Because of its unique properties, it became very good for Natural Gas (NG) transportation. Moshfeghian [1] de-scribed a pure dense phase, how it impacted the processes in oil and gas industry. Zivdar and Abofarakh [2] mentioned how gas transmission in dense phase (supercritical fluid) was proposed to avoid pipeline limitations. The profits of supercritical natural gas transmission are smaller pipe diameter, density increased, viscosity decreased, reduced pressure drop, less compressor stations, lower maintenance costs and lack of two-phase fluid formation. They [3] recommended NG transmission in dense phase state to solve Iran's fourth national pipeline problems. Consequently, pressure stations number was concentrated from ten stations in the normal manner to four stations in the dense phase manner. Ugwunna et al. [4] had designed natural gas (NG) transmission pipeline for a typical marginal oil and gas field in Niger delta. Shijo and Behera [5] identified that the pressure drop in fluidized dense phase pneumatic conveying of fine particles depended upon mass flow rate, pipe length or diameter. Patchigolla and Oakey [6] reviewed technological and engineering concerns for material corrosion, related to high pressure supercritical Carbon dioxide (CO_2) pipeline transport. They designed typical CO_2 pipeline to operate at high pressure in the dense phase. Chaczykowski and Osiadacz [7] stated that CO_2 mixtures from separation plants usually contain some impurities. Their results showed that the quantity and type of impurities had a signifi-cant influence on the transportation system. Also, Chen et al. [8] stated that impurities had an impact on pipeline transportation parameters. They took 300,000 tons/year carbon capture, utilization and storage (CCUS) project in China. Aghajani et al. [9] investigated the flexibility that occurs within a dense phase CO_2 pipeline system to ac-commodate turbulent conditions in a carbon capture and storage (CCS) network by using the pipeline as a storage vessel while maintaining flow within the pipeline. Mahlobo et al. [10] stated that CCS is the most promising modern technology aimed at reducing greenhouse gas emissions. CCS had faced major challenges, i.e. failure of pipeline transportation due to corrosion. Wang et al. [11] declared that CO_2 pipeline transportation of CCUS technology is effective and economical when it is in dense phase. Wang et al. [12] stated that CO_2 pipeline transportation is the most convenient and economical way for CO_2 transportation because of its features. Mualima et al. [13] designed CO_2 pipeline from a technical and economic aspect. They assessed four CO_2 transport process conditions to obtain the most practical and cheaper transport design. Vera et al. [14] set out the profits of using dense phase gas transport in the Carib-bean Sea projects in target fields (Gorgón-1, Kronos-1 and Purple Angel-1) and gas fields in the offshore. Formation and deposition of gas hydrate causes damages to equipment and plugging in pipelines in the gas production and transmission industry. Mokwenye [15] reviewed the conditions of hydrate formation and various mathematical models developed to predict their formation temperature for natural gas.

Phillip and Well [16] assessed the change in mobile phase volume with temperature and pressure in supercritical fluid chromatography. They observed that the elution volume of neon decreased with increasing CO_2 density. For Russia-Ukraine crisis, Albrizio et al. [17] reported an assessment of the supply side reaction on European Union (EU) financial activity in case Russian stopped their gas imports. IEA [18] reported that winter gas season of February 2022 had extreme NG price levels. Stephen and Brown [19] made a review of current market developments and recent researches. Gunes [20] focused on constructing network topology, obtaining an optimal pipelines configuration, and including number of compressor stations with locations. Ogden et al. [21] doubted whether a NG system could help enable a transition to long-term use of hydrogen in transportation. Zaloumi [22] stated that the Liquified Natural Gas (LNG) market rapidly grows. Environmental aims might be accomplished if a certain amount of gas displaced coal. Zhmakin and Samovlov [23] considered how to transport LNG through a pipeline or using cryogenic tank. Thomas and Dawe [24] declared the choices of exporting NG energy; pipelines, LNG, com-pressed Natural Gas (CNG), gas to solids (GtS), gas to wire (GtW), gas to liquids (GtL) and gas to commodity (GtC).

Elhefnawy et al. [25] made simulation and optimization analyses of natural gas liquids (NGL) recovery for two different methods at Egypt (Port Said) in United Gas Derivatives Company (UGDC). It was planned as Improved Overhead Recycle Process (IOR) with a recovery technology named Single Column Overhead Recycle Process (SCORE). Gjertveit et al. [26] constructed a 42" pipeline Asgard transport system to transport rich gas from the Asgard offshore field outside Mid-Norway to the Karsto gas terminal. Turner [27] mentioned how important to build a sustainable energy system and to replace current energy carrier mix with a sustainable fuel in the same system. Hydro-gen is an energy carrier. It is produced from water. It can address subjects of sustainability, environmental releases, and energy safety. Lee [28] forecasted an economic model on behalf of Taiwan General Equilibrium Model-Clean Energy (TAIGEM-CE) model. His analytical results reveal that using wind power is the most hopeful means of producing hydrogen. Lullo et al. [29] studied mixing hydrogen into NG system to decrease greenhouse gas (GHG) emissions. Using ammonia as an industrial chemical carbon-free energy carrier is the most probable for the fertilizer industry. As future energy carriers, Pozo and Cloete [30] evaluated using blue and green ammonia. Moreover, Otto et al. [31] investigated chemical energy carriers ranging from ammonia and methane which have small molecules to more complex hydrocarbons. Mora and Ulieru [32] aimed at identifying pipeline operating configurations that required the smallest quantity of energy to control the equipment at booster stations for specific transportation requirements. Wu et al. [33] reviewed NG pipelines models of optimization operation to maximize the operating economic profit and the quantity of gas delivery.

Falck and Maribu [34] discussed dual-diameter systems pig design and the environmental features of commissioning operations relevant to field experience. From Norway to the UK project, their article elaborated on Statoil's commissioning concept. King et al. [35] stated that differential movement in permafrost terrain due to subzero ground or buried pipelines reliability to transport NG from Prudhoe Bay and the Mac-kenzie Delta. Freezing pipelines were designed to work at traditional pressures and super high pressures. Superhigh pressure dense phase pipelines had thicker walls and smaller diameters, which make them flexible. Al Raees and Alkaabi [36] presented ADNOC's vision for optimization and efficiency and GASCO Company was devoted to guarantee process design optimization. That project was implemented using the same existing pipeline to accommodate extra feed gas from offshore production facilities. They conducted dense phase pipeline transient hydraulic investigation to guaran-tee the pipeline's ability to work with additional capacity.

Corbett et al. [37] discussed the recent development of high-strength steel pipeline that enabled gas producers to recognize savings in long-distance gas transmission pipelines cost and reduce supplying gas cost to market. Yang and Ogden [38] stated that hydrogen delivery affected on the cost. They developed models to describe delivery distances and to evaluate costs, emissions and energy use from different parts of the delivery chain. Esq and Esq [39] stated that long distance transportation of hydro-gen relied upon interstate pipelines.

The contribution of this paper is to demonstrate the possibility of hydrogen transport in the dense phase. ProMax software is used to simulate fluid flow in compressors, heat exchangers, valves, separators, and pipelines. Here, it describes the behavior of fluids through pipes.

Paper organization will be as follow: Section II Simulation Analysis contains transportation of Hydrogen through pipeline in a normal mode (validation case). Section III Transportation of Hydrogen in Dense phase. Section IV Conclusion.

II. Simulation analysis

In this part, pipeline simulations are accomplished with ProMax software [40], which could be an application that employs Microsoft Visio as the graphical client inter-face, enable to demonstrate nearly any handle within the oil and gas industry. One of the important factors in the simulation is appropriate pipeline system components selection, which consists of many vital components; compressors, separators, heat ex-changers, pipes, valves, fittings and other non-vital components.

The purpose of this section is to transport Hydrogen through pipeline in a normal mode (a single phase (not dense)) using ProMax. It will be a validation case. Table 1 shows pipeline information. Simulation used Peng Robinson thermodynamic model. Hydrogen is transported as a pure Hydrogen [42]. Fig. 1 shows hydrogen case transported by two pipes and a compressor in between.

Table 1. Pipeline information of Hydrogen.

Parameter	value
D (in)	36 (914.4mm)
Pin (Psia)	870 (60 bar)
Tin (°F)	166 (348 K)
Tout (°F)	147 (337 K)
L (mile)	210 (338 km)
Overall Heat Transfer Coefficient (Btu/hr-ft2-˚F)	0.028 (0.048 W/Mk)

The simulations start with selecting the components and connecting them by the connecting lines. The appropriate equations are then chosen. The chemical composition is entered through the first line and sent to the compressor. Furthermore, the data from Table 1 is entered, each in its place. For example, the diameter and the length of the line. Finally, the simulation starts and the readings are taken along the pipe.

Fig. 2 shows liquid hold-up which is equal zero, although the phase is gas phase and not Dense. Based on the entry conditions (low pressure and high temperature). In Figs. 3 and 4, pressure and Temperature decrease along the pipe. It is a normal behavior for heat loss as a result of ambient factors and loss of normal pressure along the line. Fig. 5 shows the change in pressure drop with length of pipe. As predictable, the pressure drop increase along the pipe. Fig. 6 shows that the velocity increases and reach high value is almost 90 ft/s (27 m/s). In this phase, a lot of noise as well as corrosion will occur. In Figs. 7 and 8, the density decreases, its value is as small as gas and the viscosity decreases also as the temperature decreases and it still as small as gas too. Figs. 3, 6, and 7 show a comparison between Abbas et al. [42] and present results and a good agreement is also achieved.

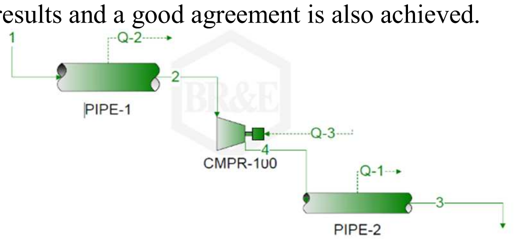


Fig. 1. Hydrogen dense phase simulation using ProMax.

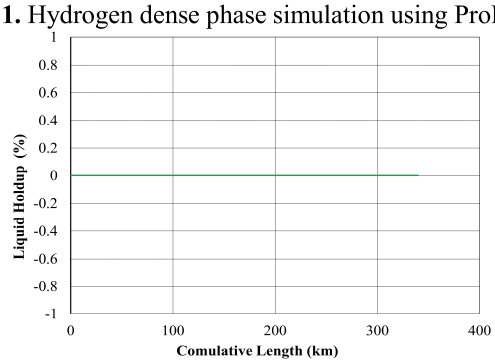
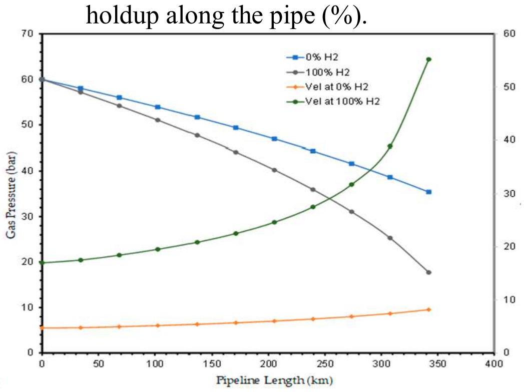
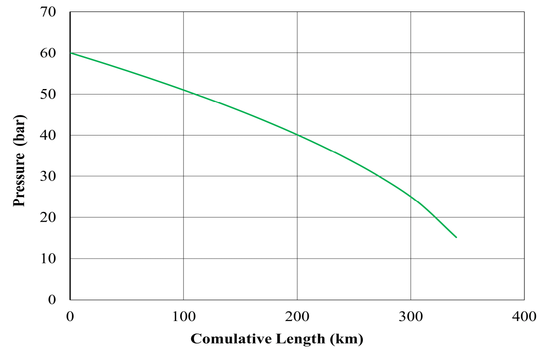


Fig. 2. Relation between length of pipe (km) and liquid holdup along the pipe (%).



(a)



(b)

Fig. 3. Relation between length of pipe (km) and Gas Pressure (bar) along the pipe for (a) Abbas et al. [42] and (b) Present.

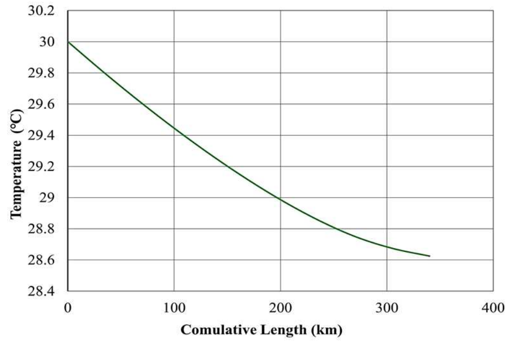


Fig. 4. Relation between length of pipe (km) and Gas Temperature (°C) along the pipe.

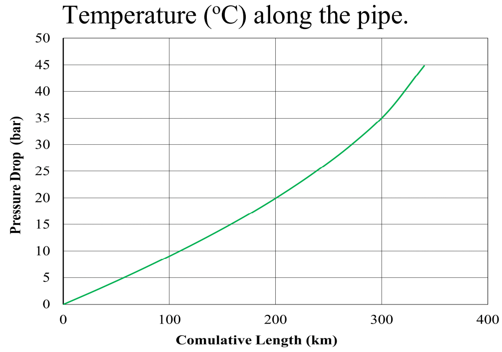
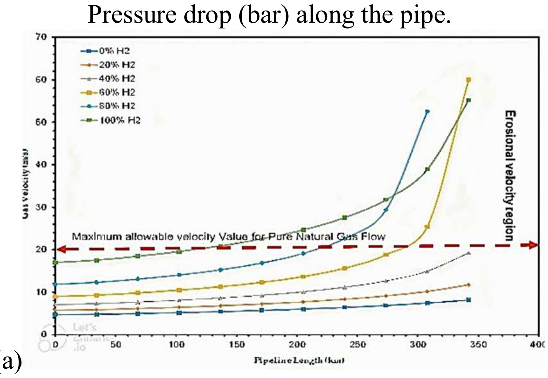
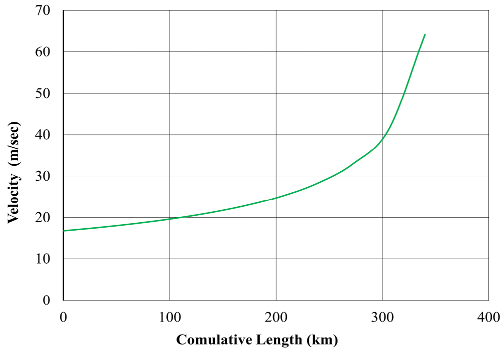


Fig. 5. Relation between length of pipe (km) and Gas Pressure drop (bar) along the pipe.



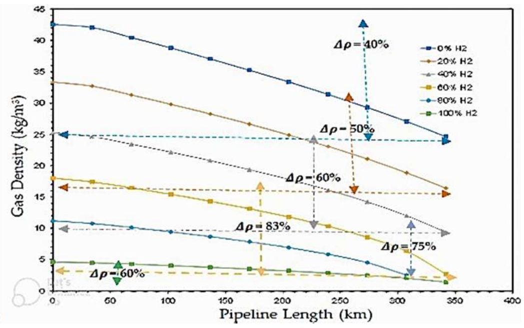
(a)

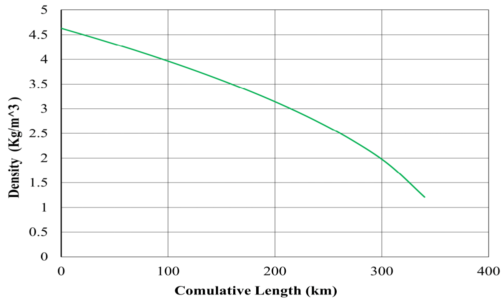


(b)

Fig. 6. Relation between length of pipe (km) and Gas Velocity (m/s) along the pipe for (a) Abbas et al. [42] and (b) Present.

(a)





(b)

Fig. 7. Relation between length of pipe (km) and gas density (kg/m^3) along the pipe for (a) Abbas et al. [42] and (b) Present.

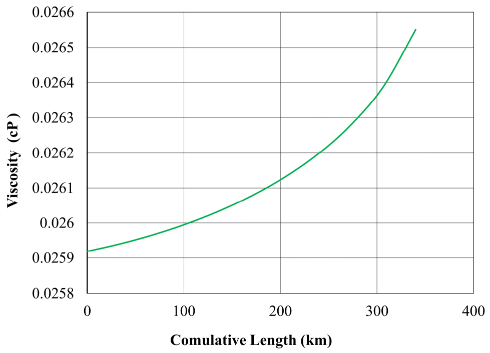


Fig. 8. Relation between length of pipe (km) and gas viscosity (cP) along the pipe.

III. Transportation of Hydrogen in Dense phase

The purpose of clarification, hydrogen transferring in dense phase is studied and monitored and results are analyzed. This will be done through a simple pipeline consisting of a separator and two pressure stations using ProMax. Each station contains one compressor and one heat exchanger to keep the gas in dense phase conditions. Used data in this case demonstrates the properties of Hydrogen in Dense Phase. Transporting 1780 MMSCFD of hydrogen (H_2) is considered. For simplicity, the calculations are done on a dry basis. A long pipeline of 340 km (211.3 miles) with an inside diameter of 0.91m (36 in) is reserved. Inlet conditions are 70 bar (1030 psi) and 333.15 K (140ºF) Peng-Robinson thermodynamic model was used. The following assumptions and correlations are used:

- Steady state
- Minimum delivery pressure is (inlet) 1030 psia (70 bar).
- In separators, no pressure drops.
- For horizontal pipeline, no altitude change.
- Inside surfaces has roughness of 0.018 inch (0.46 mm).
- Multiphase flow relation: Beggs and Brill.
- Colebrook is friction single Phase Factor used.
- Number of Length Increments: 10 (10 mile per Each Segment.)
- Overall Heat Transfer Coefficient: 0.003 Btu/hr-ft-˚F (0.018 W/m-K).
- Polytropic efficiency of Compressor is 75%.

The process is as follows, using the compression stations mentioned in Fig. 9. At each stage, the compressor raises the pressure to above the critical pressure 1871 psia (129 bar) and the heat exchanger maintains the temperature -420ºF (22 K) below the critical temperature of -400ºF (33.15 K). The Joule Thompson gas coefficient is 0.5 K / bar for natural gas, while for hydrogen, it has a negative value equal to -0.035 K/ bar. This is the reason for adding two heat exchangers in the hydrogen system because it is difficult to control the temperature and the liquid phase can be transformed into ice in the pipeline. Applying these conditions, the process flow diagram (PFD) must be considered and the pipeline outlet pressure must end in dense phase region. In Fig. 10, this case has a steadily declination in the pressure but the lowest pressure value still higher than the critical pressure of hydrogen. In Fig. 11, the pressure drop increases along the length of the pipe. However, pressure remains higher than critical pressure. Pressure drop reached a value of 25 psia (1.7 bar) across a 250 km pipeline.

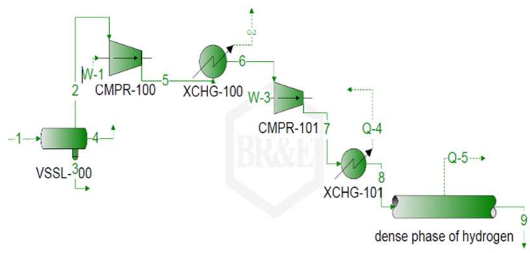


Fig. 9. Hydrogen transportation pipeline simulation using ProMax .

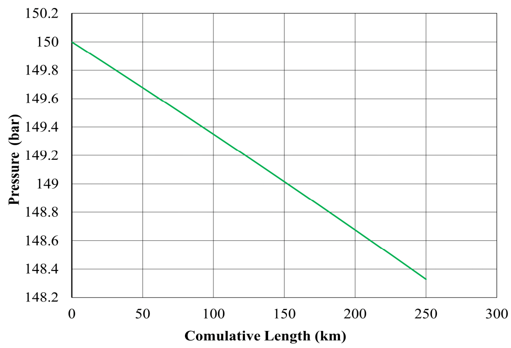


Fig. 10. Relation between length of pipe (km) and Pressure (bar) along the pipe.

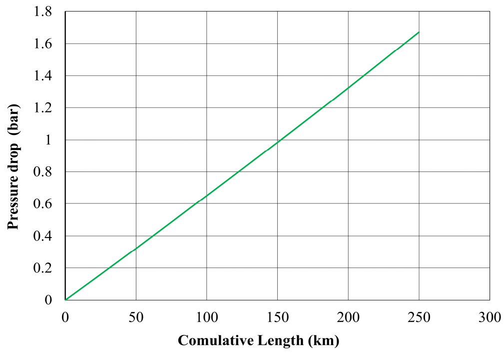


Fig. 11. Relation between length of pipe (km) and Pressure drop (bar) along the pipe.

In Fig. 12, the temperature increases linearly, however, the temperature value remains below the critical temperature. The temperature increases, which is a characteristic of a dense phase. In Fig. 13, hydrogen passes through the pipeline with liquid holdup equal 1. This means that it is in a single-phase and this phase is a liquid. As the value of liquid hold up is constant, then there is no phase change in the pipeline. However, any change in temperature may cause a phase change, therefore, it is difficult to preserve the hydrogen phase. In Fig. 14, in dense phase pipeline, the liquid velocity increases steadily and reaches approximately 1m/s (3.3 ft/s). Velocity should be less than 18 to 24 m/s (60 to 80 ft/s) to minimize noise and allow for corrosion inhibition, so the current speed of 1 m/s is ideal. Gas velocity equals to zero because there is no gas.

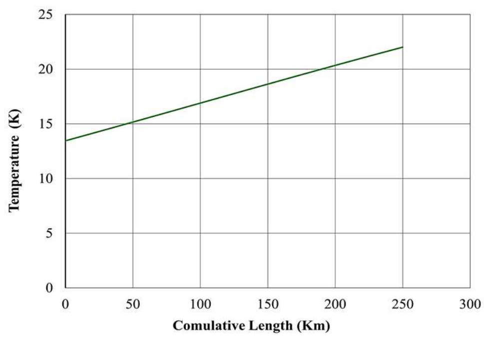


Fig. 12. Relation between length of pipe (km) and Temperature (K) along the pipe.

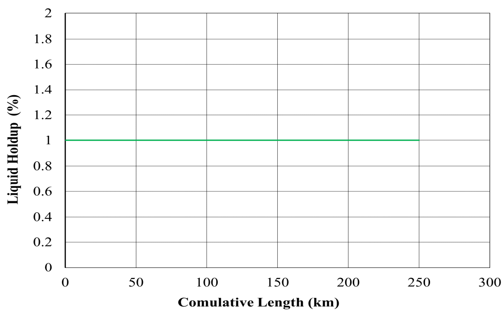


Fig. 13. Relation between length of pipe (km) and liquid holdup along the pipe (%).

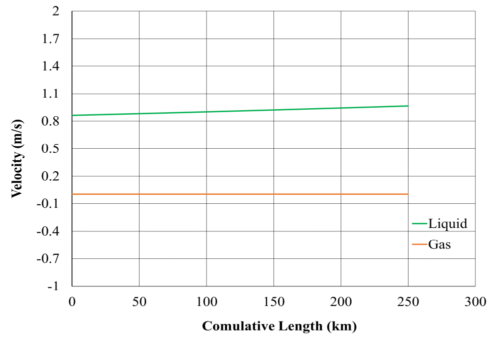


Fig. 14. Relation between length of pipe (km) and Gas & Liquid Velocity (m/s) along the pipeline.

In Fig. 15, although hydrogen was in a liquid phase due to the reached low temperature, the value of hydrogen viscosity is equal (0.025 cP) which it's almost closer to the gas viscosity and decreases steadily.

In Fig. 16, due to the very low temperature, the hydrogen phase is liquid with a high density. As a liquid, the density decreases with increasing temperature, but the hydrogen is still in a liquid phase with a liquid density value.

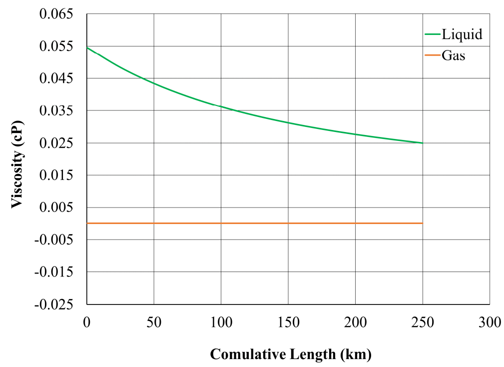


Fig. 15. Relation between length of pipe (km) and Gas & Liquid Viscosity (cP) along the pipe.

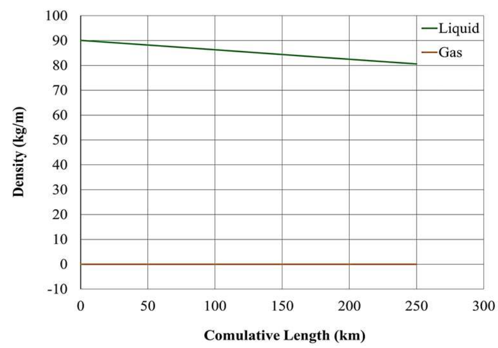


Fig. 16. Relation between length of pipe (km) and Gas & Liquid Density (kg/s) along the pipe.

IV. Conclusion

A numerical study was conducted using ProMax software to state the circum-stances of employing the dense phase in transporting hydrogen through pipelines. It can be concluded that:

1. For Validation Case (transfer of hydrogen in the natural state (as a gas but not dense): As temperature rises above the critical value and the pressure decreases, the liquid holdup does not exist. The temperature intensively decreases as a result of gas density and viscosity values. In this gas phase,

the speed was high, which may cause corrosion and noise inside the pipelines.

2. For Present Case (transfer of hydrogen in the dense phase): It is theoretically discussed in order to know the properties of hydrogen in the dense phase. The results indicate that maintaining the pressure above critical value is important so that the phase change does not occur. The temperature should be properly controlled. The critical temperature is very low and it should be remained low. Because of the conditions of the dense phase, the formation of liquids and ice thus become faster, and a liquid holdup occurs. Thus holdup remains having a constant value and does not cause disturbances inside the pipeline. Due to the low critical temperature of the dense phase of hydrogen in present operating conditions, provision of heat exchangers for cooling the line is a must. In order to reach the dense phase of the hydrogen, it is suggested here to transfer it as part of other gaseous components rather than in its pure state.

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