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Research on Development of a Simulation Model for an Aircraft Cryogenic LH_2 Fuel Tank

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Abstract - In applying hydrogen as an energy source for aircraft, storing hydrogen in liquid form can increase the energy density of the fuel. However, since hydrogen is liquefied at extremely low temperatures, fuel tanks storing liquid hydrogen (LH2) have the difficulty of having to maintain the storage temperature at cryogenic temperatures. Due to this, heat is easily introduced into the LH2, and when the LH2 is vaporized, a phenomenon occurs in which the pressure inside the tank rapidly increases. This phenomenon is a difference between LH2 fuel tanks and conventional aircraft fuel tanks using fossil fuel. Therefore, in order to design of aircraft fuel tanks using LH2, the phenomena that is ignored in conventional aircraft design such as evaporated fuel need to be considered. In this research, a thermal analysis model is developed to simulate the thermodynamic phenomena of LH2 fuel tanks. The development of the thermal analysis model takes into account tank shape, size, insulation, and fuel operating conditions such as fuel consumption and vent pressure. A simulation model for LH2 fuel tanks applicable to the aircraft's operating altitude and mission profile as wall as fuel operating conditions was developed. Finally, a cryogenic liquid hydrogen fuel tank simulation was performed to confirm that the pressure behavior inside the tank differs depending on the application of the mission profile, and the developed simulation model was confirmed to be applicable to the design of a cryogenic liquid hydrogen tank.

***Keywords*:** Hydrogen Energy; Liquid Hydrogen; Cryogenic; Fuel Tank; Fuel Simulation; Thermodynamic Analysis

1. Introduction

Hydrogen is attracting attention as a future energy source for reducing carbon emissions due to its high specific energy and the fact that it does not produce carbon dioxide when burned. In the aviation field, future aircraft and propulsion systems that use hydrogen as fuel are being developed. Airbus is developing turboprop aircraft, turbofan aircraft, and blended wing body aircraft that use liquid hydrogen as fuel, targeting 2035 [1]. ZeroAvia has developed a 600 kW hydrogen-based powertrain and is aiming to develop a 2 MW powertrain [2]. Likewise, several studies are being conducted on aircraft using hydrogen as fuel and on how to arrange fuel tanks inside aircraft to reduce carbon emissions [3][4].

The method of designing a hydrogen fuel tank varies depending on the form in which hydrogen is stored. When storing hydrogen as a high-pressure gas, the tank must have a thick structural thickness to withstand the high-pressure load. High-pressure gaseous hydrogen tanks are relatively simple to design because the phase change of hydrogen dose not occur. However, the weight of the tank structure increases because the structure must withstand high-pressure. Furthermore, it is difficult to store a large amount of hydrogen relative to the tank volume. To increase storage density, hydrogen needs to be stored in other forms.

Liquefying hydrogen can increase its storage density. However, there is a difficulty in that the storage temperature of the tank must be maintained at extremely low temperature because hydrogen is liquefied at extremely low temperatures. When heat is introduced into the tank, it causes the liquid hydrogen to vaporize. The vaporized hydrogen causes a self-increasing phenomenon that increases the pressure inside the tank. This phenomenon has been ignored in traditional fossil fuel-based aircraft fuel tank. However, since the liquid hydrogen fuel tank cannot be perfectly insulated, the phenomenon must be considered when designing a cryogenic tank.

Predicting the pressure inside the tank is important in designing a cryogenic liquid hydrogen fuel tank. The pressure inside a cryogenic liquid hydrogen fuel tank is affected by the shape of the tank, insulation performance, fuel operating conditions, etc. Reducing the surface area of the tank and increasing its insulation performance reduces the amount of liquid hydrogen evaporated, which reduces the pressure inside the tank. Additionally, if a large amount of hydrogen leaks out of the tank to be used as fuel, this can also rapidly reduce the pressure in the tank. Besides, the tank pressure may vary depending on the aircraft's mission profile. If the aircraft is operated at high altitudes or across multiple altitudes, the amount of heat transferred to the tank will vary due to changes in outside temperature. Therefore, the mission profile of the aircraft needs to be considered when designing cryogenic liquid hydrogen fuel tanks.

This study is about the development of a simulation model for an aircraft cryogenic liquid hydrogen fuel tank. In order to compose a thermal analysis model to predict the internal pressure of a cryogenic fuel tank, the shape of the tank, insulation performance, and fuel operating conditions are considered. Based on this, a simulation model that can reflect a mission profile of aircraft is developed. Finally, the developed simulation model is used to predict the internal pressure of a cryogenic liquid hydrogen fuel tank, and the difference in pressure behavior depending on whether the mission profile is reflected or not is compared.

2. Modelling of Cryogenic Fuel Tank

Cryogenic liquid fuel tanks must take into account the thermodynamic phenomena occurring in the cryogenic liquid storage tank as well as the phenomena occurring due to fuel consumption [5][6]. Figure 1 shows a thermodynamic schematic diagram of a cryogenic liquid fuel tank. The phenomena occurring in cryogenic fuel tanks were modeled and described in section 2.1 to 2.4, and the models were integrated to develop a simulation model that can simulate the internal pressure of cryogenic fuel tanks.

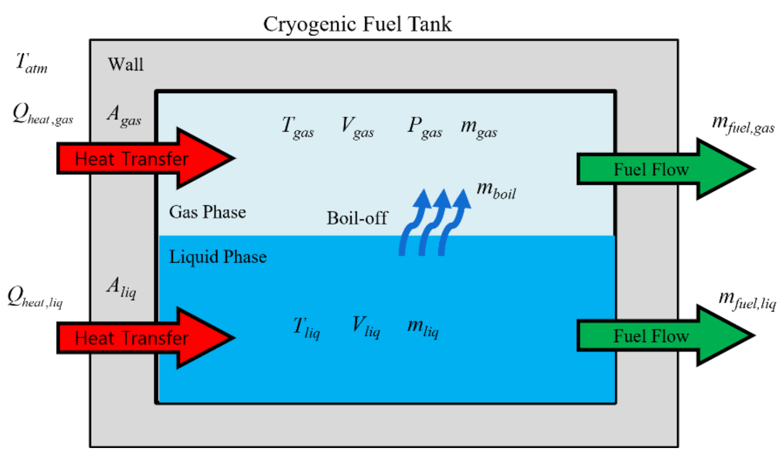

Fig. 1: Thermodynamic diagram of a cryogenic fuel tank.

2.1. Thermodynamics of Cryogenic Tanks

Thermodynamic phenomena occurring in a cryogenic tank include heat transfer from outside the tank, vaporization of liquid hydrogen due to heat transfer, and increase in internal pressure due to heat inflow and vaporization. Since liquid and gas exist inside the tank, the heat transfer from the outside can be expressed by dividing it into the liquid region and the gas region as in Equations (1) and (2).

$$q_{heat,liq} = h_{wall,liq} A_{liq} \left(T_{atm} - T_{liq} \right) \tag{1}$$

$$q_{heat,gas} = h_{wall,gas} A_{gas} \left(T_{atm} - T_{gas} \right) \tag{2}$$

The heat introduced into the liquid region causes the vaporization of the cryogenic liquid. The mass flow rate transferred to the gas region by the vaporization of the cryogenic liquid can be expressed as in Equation (3).

$$\dot{m}_{boil} = q_{heat,liq} / H_{fg} \tag{3}$$

The heat introduced into the gas region increases the temperature and pressure of the gas region. The temperature of the gas region can be calculated using the heat capacity method as in Equation (4), and the pressure inside the tank can be calculated using the ideal gas equation as in Equation (5).

$$T_{gas} = \frac{U_{gas} + dU_{gas}}{\left(m_{gas} + dm_{gas}\right)C_v} \tag{4}$$

$$P_{gas} = \frac{\left(m_{gas} + dm_{gas}\right)RT_{gas}}{\left(V_{gas} + dV_{gas}\right)} \tag{5}$$

2.2. Fuel consumption

Unlike a storage tank, a fuel tank not only stores fuel, but also discharges liquid or gas out of the tank at a certain rate to be used as fuel. When fuel is discharged out of the tank, the mass of liquid and gas inside the tank change, which is expressed as in Equations (6) and (7).

$$dm_{gas} = m_{boil} - m_{fuel,gas} \tag{6}$$

$$dm_{liq} = -m_{boil} - m_{fuel,liq} \tag{7}$$

2.3. Pressure Relief

If the pressure inside the tank is excessively high, it is necessary to vent the internal gas to the outside to reduce the pressure. To do this, a relief valve, a vent valve, etc. are installed in the tank, and the amount of gas discharged through this is expressed as in Equation (8).

$$dm_{gas} = m_{boil} - m_{fuel,gas} - m_{vent} \tag{8}$$

2.4. Inside Pressure of Cryogenic Fuel Tanks

The pressure inside the cryogenic fuel tank can be calculated by considering the heat introduced into the gas region from the outside, the amount of liquid hydrogen vaporized, the mass supplied as fuel, and the gas discharged for pressure relief. In Equation (4), the average temperature of the gas region is calculated by reflecting the energy change and mass change in the gas region, and the pressure inside the fuel tank can be finally calculated through the ideal gas equation in Equation (5).

2.5. Model Integration using MATLAB Simulink

A simulation model for a cryogenic fuel tank was developed based on MATLAB Simulink. The simulation model consists of modules for vaporization of liquid hydrogen by heat inflow, fuel consumption, and pressure relief model, and the heat and mass changes calculated in each module are transferred to the tank thermal analysis module to calculate the pressure inside the tank. In addition, a module was added to consider altitude and atmospheric temperature changes according to the aircraft's mission profile. Figure 2 shows the cryogenic fuel tank simulation model developed based on MATLAB Simulink.

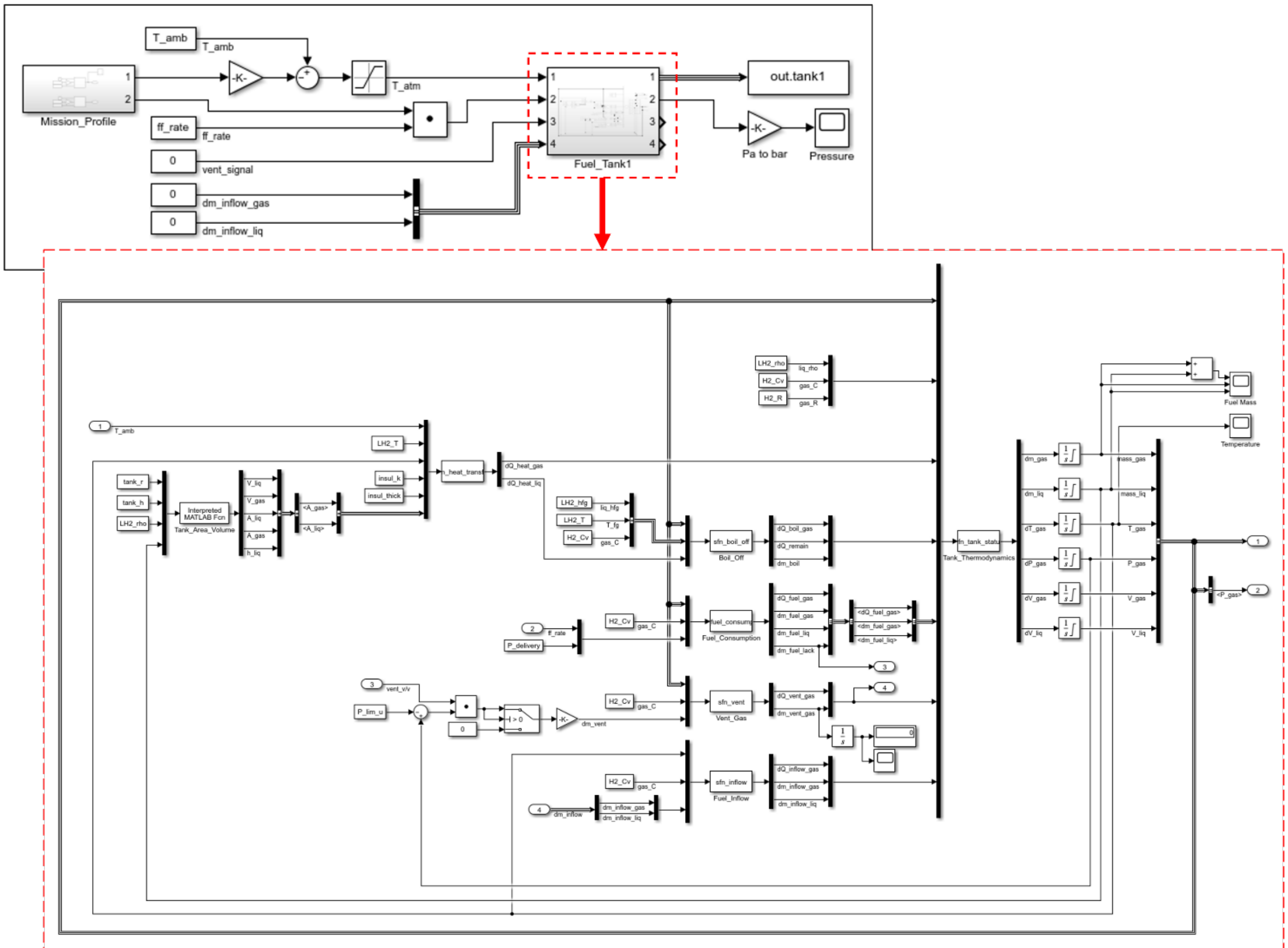

Fig. 2: Configuration of the cryogenic fuel tank simulation model.

3. LH2 Fuel Tank Simulation

3.1. Simulation Conditions

In order to perform a simulation on a liquid hydrogen fuel tank, the shape of the tank and the analysis conditions were set. The liquid hydrogen fuel tank to be simulated is a cylindrical tank with a hemispherical head with an inner radius of 1.8 m and a length of 5.4 m. The liquid hydrogen is filled to 90% of the tank volume, and the temperature of the liquid hydrogen is 21 K. The initial temperature of the gas region is 24 K, and the initial internal pressure is 150 kPa. The outer wall of the tank was applied with insulation with a thickness of 15.7 mm and a thermal conductivity of 0.037 W/m·K [7]. The fuel flow rate was set to 0.06 kg/s, and the simulation time was 10 hours.

3.2. Mission Profile

The mission profile was set as shown in Table 1 in order to compare the difference in pressure behavior inside the tank depending on whether the mission profile is applied. The mission profile used only the altitude of the aircraft over time. The international standard atmosphere was applied for the atmospheric temperature according to the altitude change. Therefore, as the altitude increases, the atmospheric temperature decreases at a rate of change of 0.0065 K/m. The mission profile of the aircraft consisted of ground standby, ascent, cruise, descent, descent standby, and landing.

Table 1: Mission Profile.

Time (hr)	Altitude (m)
0.0	0
0.5	0
1.5	8,000
2.0	10,000
8.0	10,000
9.0	2,000
9.5	2,000
10.0	0

3.3. Simulation Results

The simulation results considered the mission profile showed a difference from when it was not applied. Figure 3(a) represents the internal pressure behavior of the tank when the mission profile was not considered. Since the altitude change of the aircraft was not reflected, the atmosphere temperature was maintained at the initial setting temperature, and the internal pressure of the tank was at a maximum of 306 kPa. However, in Figure 3(b), when the mission profile was considered, the maximum pressure of the tank decreased to 292 kPa. This is because the atmosphere temperature decreased as the aircraft altitude increased, so the amount of heat transfer into the tank decreased, and less liquid hydrogen was vaporized. In this case, the reduction in the maximum pressure experienced by the tank allows the thickness of the tank structure to be reduced to make the tank lighter. Therefore, it is necessary to perform a simulation considering the mission profile when designing an aircraft cryogenic liquid hydrogen fuel tank, and the simulation model developed through this study can be sufficiently utilized in designing a cryogenic liquid hydrogen fuel tank.

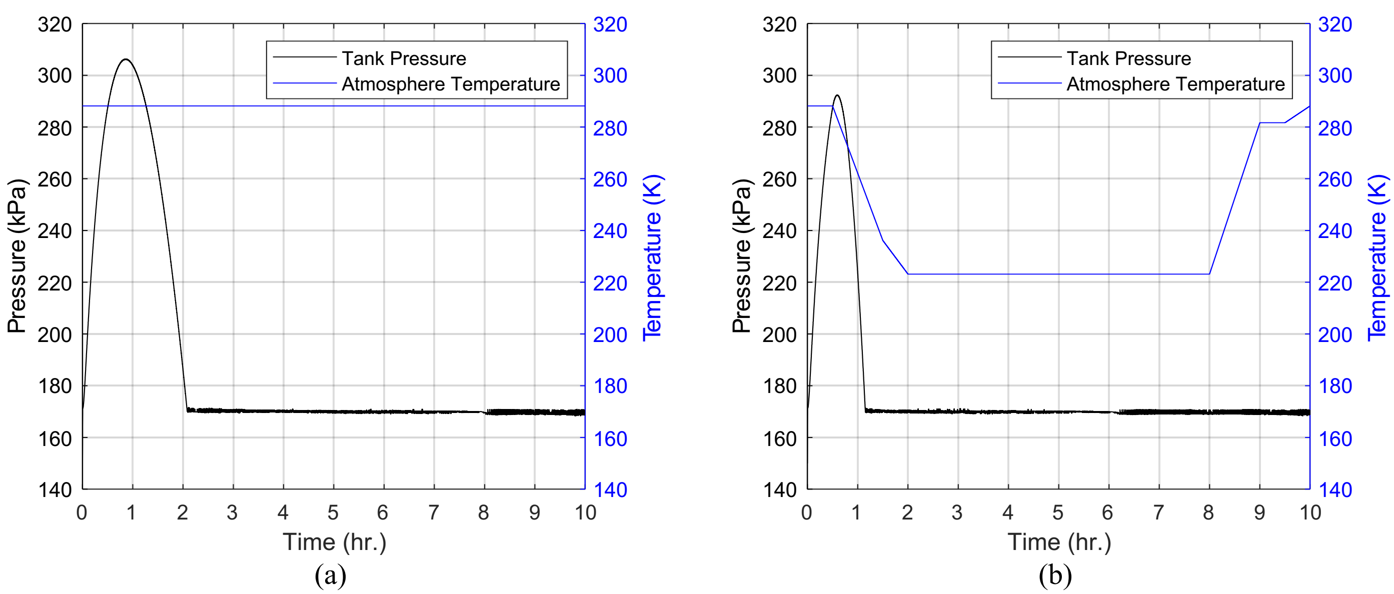

Fig. 3: Tank pressure simulation results: (a) without mission profile, (b) considered mission profile.

4. Conclusion

A simulation model was developed to perform simulation of a cryogenic liquid hydrogen fuel tank. The simulation model was consisted of a thermal analysis module for a cryogenic fuel tank and a module that can apply the mission profile of an aircraft. The thermal analysis module was considered heat transfer outside the tank, vaporization of liquid hydrogen, fuel consumption, and pressure relief, and the simulation model that can apply the mission profile was developed using MATLAB Simulink.

The simulation results of the internal pressure behavior of the cryogenic liquid hydrogen fuel tank using the developed simulation model showed that the internal pressure of the tank was different depending on whether the mission profile was applied. This means that if the internal pressure of the tank is different, the structural design of the tank should also be changed. Therefore, when designing an aircraft cryogenic liquid hydrogen fuel tank, a simulation that considers the mission profile should be performed, and the simulation model developed through this study can be sufficiently utilized in designing a cryogenic liquid hydrogen fuel tank.

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