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Design of LNG fuel tank for a light duty truck and numerical analysis of heat leak to LNG tank

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Abstract

The LNG tank are properly designed to fit with the limited installation space of a light duty truck, Hyundai Porter II. This designed LNG tank has 36 liter capacity, so two LNG tanks installed on Porter II truck allow it to run about 432 km per fueling. It is almost two times greater than CNG mileage for same truck. To analyze the relationship between car acceleration and heat leak for different fuel vapor/liquid ratios, the modified Fortran program "Pro-Heatleak" is used. Computational analysis shows that the relationship between the heat leak and vapor/liquid ratio is linearly inversed. Heat leak increases with increasing of car acceleration when fuel vapor/liquid ratio is less than 0.5 and decreases when fuel vapor/liquid ratio is greater than 0.5. The difference between maximum and minimum heat leak for full tank is about 12 percents. For the fuel vapor/liquid ratio equal to 0.5 heat leak does not depend on car acceleration.

키워드 : *액화천연가스, 천연가스자동차, 열누출*
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1. Introduction

Natural gas is used as a transportation fuel in many countries around the world, and its use in vehicle applications is growing. Besides displacing imported petroleum fuels, one of the primary benefits of using natural gas as a vehicle fuel is the potential to substantially reduce exhaust emissions of harmful pollutants such as particulate matter (PM), nitrogen oxides (NOx), non-methane organic gas (NMOG) volatile organic chemicals (VOCs), carbon monoxide (CO) and carbon dioxide (CO_2). Natural gas is especially beneficial when it replaces diesel fuel in trucks and buses, because diesel engine emissions are more problematic than gasoline engine emissions, and the high fuel consumption of trucks induces the economic issues.

Natural gas is composed primarily of methane, but may also contain ethane, propane and heavier hydrocarbons. Small quantities of nitrogen, oxygen, carbon dioxide, sulfur compounds, and water may also be found in natural gas.

Because natural gas has a very low density at ambient conditions, it is stored on vehicles in a highly compressed state (CNG) or as a

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cryogenic liquid. Liquefied natural gas (LNG) is natural gas that has been cooled to the point that it condenses to a liquid, which occurs at a temperature of approximately -256 F (-161°C) and at atmospheric pressure. The liquefaction process requires the removal of some of the non-methane components such as water and carbon dioxide from the produced natural gas to prevent them from forming solids when the gas is cooled. As a result, LNG is typically made up mostly of methane. LNG is odorless, colorless, non-corrosive, and non-toxic. When vaporized it burns only in concentrations of 5% to 15% when mixed with air.

Compared with CNG, LNG can provide vehicles with longer driving ranges per refueling. LNG takes up about 1/600th of the volume that natural gas occupies at room temperature and atmospheric pressure. Two and half times more LNG than CNG can be stored in the same amount of space. LNG can be transported between continents in specially designed ocean vessels, whereas traditional pipeline transportation systems would be less economically attractive and could be technically or politically infeasible. Thus, LNG technology makes natural gas available throughout the world[1]-[4].

A lot of factors effect on heat leak to LNG tank, which are insulation characteristics of tank (thickness of insulation, material property, number of layers, vacuum pressure, material of vessel), shape of tank (length/diameter aspect ratio), support system of inner pressure vessel in outer vessel, size of tank (surface area), installation position of tank, operation conditions (car acceleration, road slope, vapor/liquid ratio), surrounding temperature, etc.

All factors except operational conditions are preset in this research and then only operational conditions are left variables. In this research the effect of car acceleration on heat leak for different vapor/liquid volume ratios is analyzed.

2. Design of LNG fuel tank

Light duty truck is a vehicle of which payload capacity is less than 1,815 kg. It can be used for the private or business purposes. The number of this vehicles is increased every year by about 10 percent continuously. In 2002 about two million trucks were in service in Korea. More than eighty percents of trucks in service in Korea now are light duty trucks. Light duty trucks are one of major sources of emitted pollutant. Considerable reduction of environmental pollution from the light duty trucks can be obtained if these trucks will be converted from diesel fuel to natural gas.

One ton truck Hyundai Porter II (Hyundai H-100) produced by Hyundai Motor Company is converted to NGV. This truck is equipped with two 54 liter CNG cylinders on the both sides of vehicle. The dimensions of the cylinders are limited by installation space. One of the drawbacks of CNG is that only limited amount of fuel can be stored in trucks, which reduce the driving range significantly. To avoid this problem LNG fuel can be used instead of CNG.

The side-view of Hyundai Porter II truck and installation space (vehicle chassis dimensions) for LNG fuel tanks are shown in Fig. 1. Porter II is a light duty truck and its space available for installation of LNG tanks is limited by structural features.

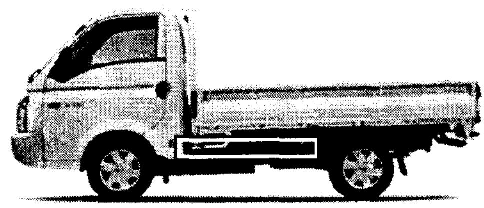

Fig. 1 Side-view of Hyundai Porter II (Hyundai H-100) and installation space for LNG tanks

To design LNG tank suitable to Porter II truck, the outside dimensions of CNG cylinder NGV2-1 with 54 liters capacity, produced by Faber Industry S.P.A.[5] is used.

Porter II truck mileage is the 2.25 km per liter of CNG[6], so two CNG cylinders with 54 liter capacity allow truck to run about 243 km per fuelling. Same truck can run about 6 km per liter of LNG. LNG tank designed for Hyundai Porter II truck has 36 liter capacity, so two LNG tanks installed on this truck allow it to run about 432 km per fueling. So big mileage difference between CNG and LNG is one of the main benefit of LNG fuel.

The LNG fuel tanks are fabricated with an inner shell surrounded by super insulated vacuum space enclosed in an outer shell. The tanks are cylindrical, which offers the optimum pressure boundary shape with respect to weight, volume and cost. Both ends are closed with ASME flanged and dished heads. To hold the maximum volume with a minimum heat leak, the length/diameter aspect ratio should be as small as can be accommodated within the vehicle chassis dimensions. The fuel tanks and their supports should withstand the acceleration of 8 times of gravity in all directions. The basic design concept is the same for all cryogenic liquids, to minimize heat transfer to the stored cryogenic fluid a vacuum-jacketed dewar is normally designed. Vehicle tanks, however, must be designed to withstand severe vibration and abuse, typical of vehicle operations and to interface with a variety of LNG fueling stations[7].

The cryogenic inner vessel and outer shell are fabricated from austenic stainless steel type 304. This material exhibit an increase in tensile and yield strength without loss of ductility at low temperatures. Multilayer insulation, sometimes referred to as "super insulation", consists of multiple layers of aluminized mylar separated by polyester film. It is used in the space between inner vessel and outer shell to minimize radiation heat transfer. A vacuum of about 10^{-7} torr is maintained to minimize convection heat transfer. The inner pressure vessel is suspended within the outer tank using the cylindrical nonmetallic central support beam. Rugged support systems is designed to minimize heat conduction and provide structural strength and integrity. It is constructed of low-conductivity fiberglass-reinforced polymer. Decrease of support junction area decreases the heat leak to the tank. However, the junction area has to be large enough for the strut to support the weight of the tank.

Thickness of multilayer superinsulation has a strong effect on the heat leak to LNG tank. Increase of insulation thickness decreases the heat leak significantly but it is also decreases the tank capacity and increases the cost of LNG tank. Analysis of heat leak allows one to choose the best insulation thickness which is reasonable in the current case, while the cost, amount of fuel and heat leak are taken into account. The insulation thickness of LNG tank for the light duty truck is decided to be equal to the insulation thickness of 110 gallons LNG tank manufactured by CFI[8].

Cross sectional area of support beam in LNG tank for the light duty truck, decided by the weight of fuel, is proportional to the support beam area of 110 gallons LNG tank manufactured by CFI.

The specifications of LNG tank for the light duty truck are shown in Table 1.

Table 1 Specifications of LNG tank

Item	Specification
Tank size	0.276m O.D. x 1.105m L.
Water volume	$0.0406m^3$
Ullage (full tank vapor volume)	$0.004m^3$
Usable fuel volume	$0.0365m^3$
Type	Jacket type
Material of vessels	Austenic steel 304
Insulation material	Polyester film coated by 10 aluminium layers
Thickness of insulation	20 mm
Degree of vacuum	10^{-7} torr
Support beam material	Fiberglass-reinforced polymer
Support beam diameter	12 mm

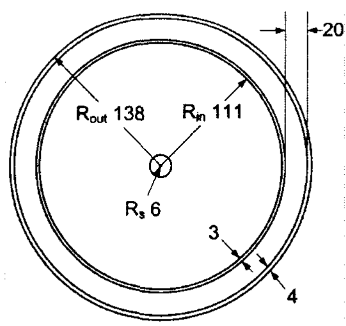

Fig. 2 Cross sectional dimensions of LNG tank

The cross sectional dimensions of LNG tank for the light duty truck are shown in Fig. 2, where R_{out} is the outside radius of tank, R_{in} is the inside radius of tank, R_s is the radius of support beam.

3. Analysis of heat leak and discussion

3.1 Heat leak and boil-off rate

Heat leakage causes the stored LNG to slowly warm and eventually boil. If boiling vapor (CH_4) is allowed to escape from the tank the temperature of the LNG does not increase. In the vehicular tank CH_4 vapor is trapped inside the tank and closed fuel system until it is withdrawn. If CH_4 is not withdrawn, the pressure inside the tank will increase because the volume of the tank is fixed. The temperature of LNG will also increase.

Boil-off of LNG from the vehicular tank can cause excessive pressure build up in LNG tanks. Boil-off is caused by heat added through the shell of tank to LNG fuel during the operation and storage[9].

The thermal resistance of the shell of tank can be estimated as:

$$R = 1/(1/R_m + 1/R_s) \quad (1)$$

where resistance of the multilayer super-insulation is[10]:

$$R_m = \Delta h/(k_m S) \quad (2)$$

parasitic heat resistance of the support connecting the inner and outer shells of tank is[10]:

$$R_s = \Delta h/(k_s S_s) \quad (3)$$

S is the area of inner shell of tank, S_s is the area of support junction, Δh is the thickness of multilayer superinsulation, k_m is the average thermal conductivity of superinsulation, and k_s is the thermal conductivity of support beam.

The heat flow rate across the shell of LNG tank is estimated as:

$$q = \frac{\Delta T}{R} = \Delta T * \left(\frac{k_m S}{\Delta h} + \frac{k_s S_s}{\Delta h} \right)$$

$$= \Delta T (k_m + k_s \alpha) S/\Delta h \quad (4)$$

where $\alpha = S_s/S$ is the ratio of the support junction area and total area. The temperature difference between the ambient and the LNG is $\Delta T = T_\infty - T$, where T_∞ is the ambient temperature.

The thermal conductivity of superinsulation k_m is generally estimated as 5×10^{-5} W/mK[11], and conductivity of fiberglass k_s as 0.04 W/mK. This huge difference in thermal conductivity necessitates a low value of the ratio of the support junction area to the total area of tank. Support junction area is a double cross sectional area of central support beam.

The boil-off rate of LNG due to heat leak through the shell of LNG tank is estimated as

$$\dot{m} = q/h_l$$

where h_l is the heat of vaporization for methane h_l=509.5 kJ/kg. From above equation the boil-off rate of LNG can be estimated as:

$$r = \dot{m}/V\rho$$

where V is the capacity of LNG tank and ρ is the density of LNG, ρ = 424 kg/m^3.

For a motionless truck, boil-off rate ($\dot{m}$) of LNG for one fuel tank with aforesaid dimensions is equal to 0.42 kg per day.

Boil-off rate (r) is what percentage of fuel to be boiled off per day to keep the same temperature when heat is added into the fuel. Daily boil-off rate is equal to the 2.45 percents of fuel mass for the full tank. Therefore about one liter of LNG should be boiled off per day, so daily mileage loss due to heat leak for each tank is about 6 km.

3.2 Effect of vapor/liquid ratio on heat leak

Heat leak depends on the volume of fuel inside the tank. Vapor/liquid volume ratio of the fuel in a tank(Δ) has a strong effect on the heat leak. During normal vehicle operation the volume of liquid in the tank decreases because of fuel consumption, so the surface area wetted by liquid fuel decreases and heat leak decreases respectively. The calculations of heat leak are made for the range of vapor/liquid volume ratio from 0.1 to 0.9. A vapor space or ullage must always be left in the tank after filling to allow for additional vaporization and liquid expansion, which occurs as the temperature and pressure increase. Ullage is about 10 percent of the tank inner volume for the full tank and so the minimum vapor/liquid ratio is 0.1. LNG tank is designed to withdraw "liquid fuel only" from the bottom of the tank for delivery to the engine. Gaseous methane is never withdrawn from the tank during normal operation of the vehicle. The maximum vapor/liquid ratio of fuel is 0.9.

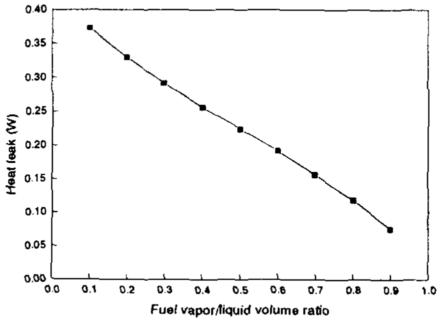

Fig. 3 Variation of heat leak with fuel vapor/liquid volume ratio for the car acceleration equal to 1.78 m/sec^2

As shown in Fig. 3 the relationship between the heat leak and vapor/liquid ratio is linearly inversed, which makes almost a straight line. From the data in Fig. 3, the following equation is obtained:

$$q = -0.3726 * \Delta + 0.4101$$

Heat leak decreases with increasing of vapor/liquid ratio due to fuel consumption. Heat leak is maximum for the full tank and minimum for empty tank. Full tank means that vapor/liquid ratio is equal to 0.1 (gas phase of fuel occupy 10 % of total tank volume).

3.3 Effect of car acceleration on heat leak

Heat leak depends on the surface area wetted by liquid fuel. Even though other things being equal, surface area varies with car acceleration. During vehicular movement, the slope angle of liquid fuel surface changes in the tank because of acceleration or deceleration of the truck. Different car acceleration produces the different slope angle of liquid fuel and consequently different wetted surface area.

Fortran program "Pro-Heatleak"[12]-[14] is modified accordingly to Eq. 1 to 4. and used to evaluate the heat leak to LNG tank with car acceleration. This program allows one to calculate the heat leak for different driving manner depending on vehicle acceleration and various road slope.

It is assumed that heat leak to the vapor phase of fuel is very small and can be neglected. Therefore the surface area contacted with liquid fuel only is calculated to evaluate the heat leak.

The truck can normally get a velocity of 80 km/hr for 45 sec[15], which corresponds with the car acceleration about 1.78 m/sec^2. Therefore the calculation of heat leak for car acceleration from 0 to 3 m/sec^2 is quite enough for a light duty truck. The acceleration of car greater than 3 m/sec^2 is hardly possible and does not concerned it this research.

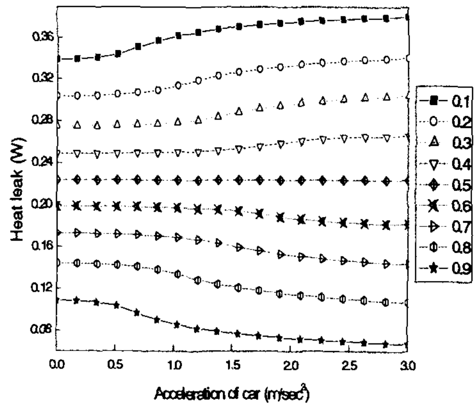

Fig. 4 Variation of heat leak with car acceleration for different fuel vapor/liquid ratios

The computational results of calculations of heat leak with car acceleration for different vapor/liquid ratios are summarized in Fig. 4. Acceleration has strong effect on the heat leak in the figure. The difference between maximum and minimum values of heat leak for full tank is about 12 %. For fuel vapor/liquid ratio greater than 0.5 heat leak increases with increasing of car acceleration. For fuel vapor/liquid ratio less than 0.5 heat leak decreases with acceleration of car. For fuel vapor/liquid ratio equal to 0.5 heat leak is constant and does not depend anymore on car acceleration because for half-full tank the wetted surface area is constant. The graphs are symmetrical about line of vapor/liquid ratio equal to 0.5.

4. Conclusion

Increasing number of light duty trucks promotes the replacement of traditional fuel by a cleaner fuel such as natural gas. Natural gas is a good option to replace Diesel and Gasoline as a transportation fuel, which provides us with well-recognized benefits including reduced exhaust emissions and energy source diversification. LNG is preferred by most truck fleets and many transit bus agencies because its higher density enables smaller and lighter-weight tanks, greater mileage and shorten fuelling time in comparison with CNG.

Hyundai Porter II truck is one of most popular model of light duty trucks in Korea. The conversion of this truck to LNG fuel offers us great environmental and economical benefits. LNG tank for Porter II truck is developed to suit the limited installation space. This designed LNG tank has 36 liter capacity, so two LNG tanks installed on Porter II truck allow it to run about 432 km per fueling. Porter II truck equipped with two CNG cylinders with the same outside dimensions can run only 243 km per fuelling.

Heat leak to LNG tank through its shells is one of the governing parameters for new LNG tank design. In this research influence of car acceleration and effect of vapor/liquid ratio on the heat leak to LNG tank are analysed.

The heat leak is analysed using the modified Fortran program "Pro-Heatleak".

The relationship between the heat leak and vapor/liquid ratio is linearly inversed, which makes almost a straight line.

Analysis of heat leak shows that in the range of acceleration from 0 to 3 m/sec^2 heat leak increases with increasing of car acceleration when the vapor/liquid ratio is less than 0.5, and decreases when vapor/liquid ratio is greater than 0.5. For the vapor/liquid ratio equal to 0.5 heat leak does not depend on car acceleration.

Acknowledgement

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