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Space Fitting Design of LNG Fuel Tank for a Small Truck and BOG Analysis of LNG Tank

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Abstract : The 36 liter LNG tank is designed to fit in the limited installation space of a small truck. Two LNG tanks allow one ton truck to run about 432 km per fueling, which is about 1.8 times longer than CNG mileage for the same truck. The variation of BOG with car acceleration for the different fuel liquid/vapor ratios in a tank is analysed by the modified Fortran program "Pro-Heatleak". Computational analyses show that the relationship between the BOG and liquid/vapor ratio is linearly proportional at a given acceleration. Fuel consumption decreases the volume of liquid fuel in the tank but increases the specific BOG. BOG increases with increasing of car acceleration when fuel liquid/vapor ratio is greater than 0.5 and decreases with increasing of car acceleration when fuel liquid/vapor ratio is less than 0.5. The difference between maximum and minimum BOG for full tank is about 12 percents. For the fuel liquid/vapor ratio equal to 0.5 BOG does not depend on car acceleration.

Key words : LNG (Liquefied Natural Gas), NGV (Natural Gas Vehicle), BOG (Boil-off Gas), Heat leak, Acceleration

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

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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 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. CNG density at 200 bar is about 175 kg/m^3 and LNG density is 424 kg/m^3. Two and half times more LNG than CNG can be stored in the same amount of space. Whereas traditional pipeline transportation systems would be less economically attractive and could be technically or politically infeasible, LNG can be transported between continents in specially designed ocean vessels. Thus, LNG shipping and cryogenic storage technology makes natural gas available throughout the world[1]-[4].

Boil-off gas (BOG) is an amount of gas exhausted from LNG tank due to the heat leak. BOG is directly proportional to the heat leak to LNG tank. A lot of factors effect on heat leak, 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, liquid/vapor ratio), surrounding temperature, etc.

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

2. Design of LNG fuel tank

A 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 for this research is a typical light duty truck.

One ton truck 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 one ton truck and installation space (vehicle chassis dimensions) for LNG fuel tanks are shown in Fig. 1. Space available for installation of LNG tanks on one ton truck is limited by structural features. Installation space for LNG tanks enclosed by white line is shown in Fig. 1.

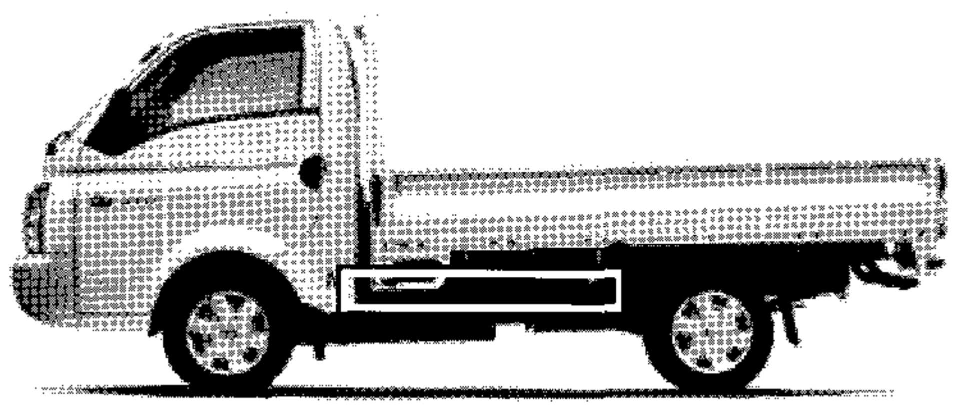

Fig. 1 Side-view of one ton truck and installation space for LNG tanks

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

The gas mileage of one ton truck is the 2.25km per liter of CNG[6]. 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. The volume of LNG tank designed for one ton truck is 36 liter. Two LNG tanks installed on this truck allow it to run about 432 km per fueling. A big gas mileage difference between CNG and LNG is one of the main benefits 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. 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 "superinsulation", consists of multiple layers of aluminized mylar separated by polyester film and a strong vacuum. Multilayer insulation 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 system is designed to minimize heat conduction and provide structural strength and integrity. It is constructed of low-conductivity fiberglass-reinforced polymer.

Thickness of multilayer superinsulation has a strong effect on BOG. Increase of insulation thickness decreases the heat leak and BOG 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 cost, the amount of fuel and BOG are taken into account. To keep heat transfer rate same as heat transfer rate for 110 gallons LNG tank manufactured by CFI[8], the insulation thickness of LNG tank for the small truck is decided to be equal to 20 mm as the insulation thickness of 110 gallons CFI LNG tank.

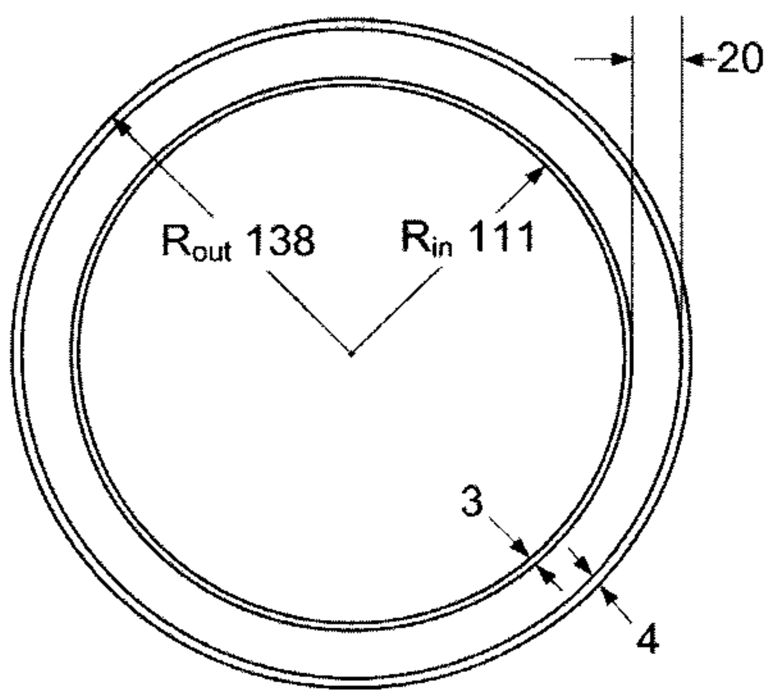

Fig. 2 Cross sectional dimensions of LNG tank

The cross sectional dimensions of LNG tank for one ton truck are shown in Fig. 2, where R_{out} is the outside radius of tank and R_{in} is the inside radius of tank. The specifications of LNG tank for one ton 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 aluminium layers
Thickness of insulation	20 mm
Degree of vacuum	10^{-7} torr
Support beam material	Fiberglass-reinforced polymer

3. Analysis of BOG

3.1 Heat leak and BOG

Heat leakage causes the stored LNG to be slowly warmed and eventually boiled. Boiled fuel vapor is allowed to escape from the tank through the relief valve to keep the pressure inside a LNG tank under the safety limit. In the vehicular tank fuel vapor is trapped inside the tank and closed fuel system until it is withdrawn. If vapor is not withdrawn, the pressure inside the tank will increase because the volume of the tank is fixed.

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

The heat flow rate(q) across the wall of LNG tank is estimated as:

$$q = kS\frac{\Delta T}{\Delta h} \quad (1)$$

where k is the average thermal conductivity of superinsulation, S is the area of inner vessel, Δh is the thickness of multilayer superinsulation and ΔT is the temperature difference between ambient and LNG. $\Delta T = T_{\infty} - T$, where T_{∞} is the ambient temperature.

Heat transfer rate for 110 gallons LNG tank manufactured by CFI is 0.92 W/m^2[8]. Thermal conductivity of insulation for 110 gallons CFI LNG tank is calculated from the CFI Manual, which is 0.1153×10^{-3} W/m·K. This value of thermal conductivity is used to design LNG tank for the small truck.

The BOG of LNG due to heat leak through the wall of LNG tank is estimated as

$$\dot{m} = q/h_l \quad (2)$$

where h_l is the heat of vaporization for methane, which is 509.5 kJ/kg. From above equation specific BOG (r) of LNG can be estimated as:

$$r = \dot{m}/m \quad (3)$$

where m is the total LNG mass in a tank. Specific BOG is what part of fuel to be boiled off per day.

For a motionless truck, daily BOG of LNG for one full fuel tank with aforesaid dimensions is equal to 0.12 kg. Specific BOG is 0.008 which is equal to the 0.8 percents of fuel mass for the full tank. About 0.3 liter of LNG would be boiled off in a day. Daily mileage loss due to heat leak for each tank is about 1.8 km.

3.2 Effect of liquid/vapor ratio on the BOG

BOG depends on the volume of fuel inside the tank. During normal vehicle operation the volume of liquid in the tank decreases because of fuel consumption. As the surface area wetted by liquid fuel is reduced, heat leak and BOG decreases. The evaluations of BOG are made for the range of liquid/vapor volume ratio from 0.1 to 0.9. The maximum liquid/vapor ratio is 0.9 because 10 percent of full tank inner volume must be ullage. A vapor space or ullage must always be left in the tank after filling to allow additional vaporization and liquid expansion, which occurs as the temperature and pressure increase. The minimum liquid/vapor ratio of fuel is 0.1 because LNG tank is designed to deliver liquid fuel only to the engine from the bottom of the tank. Gaseous methane is never withdrawn from the tank during normal operation of the vehicle.

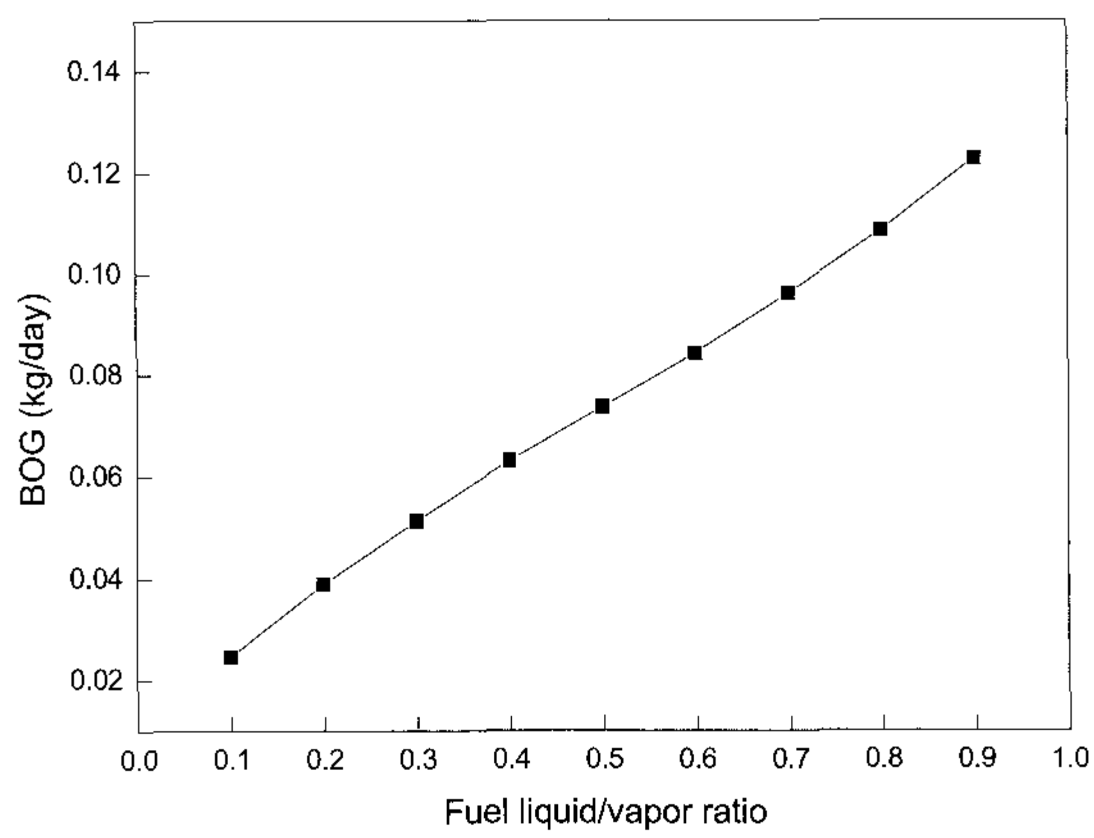

Fig. 3 Typical variation of BOG with fuel liquid/vapor volume ratio

As shown in Fig. 3 the relationship between daily BOG and liquid/vapor ratio at the car acceleration of 1.78 m/sec^2 is nearly linear and proportional, which makes almost a straight line. Acceleration of 1.78 m/sec^2 is the common value of truck acceleration. Other values of acceleration will make the slope of line different but still straight line. From the data in Fig. 3, the following equation is obtained:

$$BOG = 0.1226 * \Delta + 0.0123$$

where Δ is liquid/vapor volume ratio.

BOG increases with liquid/vapor ratio, which means that fuel consumption reduces BOG. BOG is maximum at the full tank and minimum at the empty tank. When liquid/vapor ratio is equal to 0.9 (liquid phase of fuel occupy 90 % of total tank volume), the fuel tank is called a full tank. Empty tank means that liquid/vapor ratio is equal to 0.1.

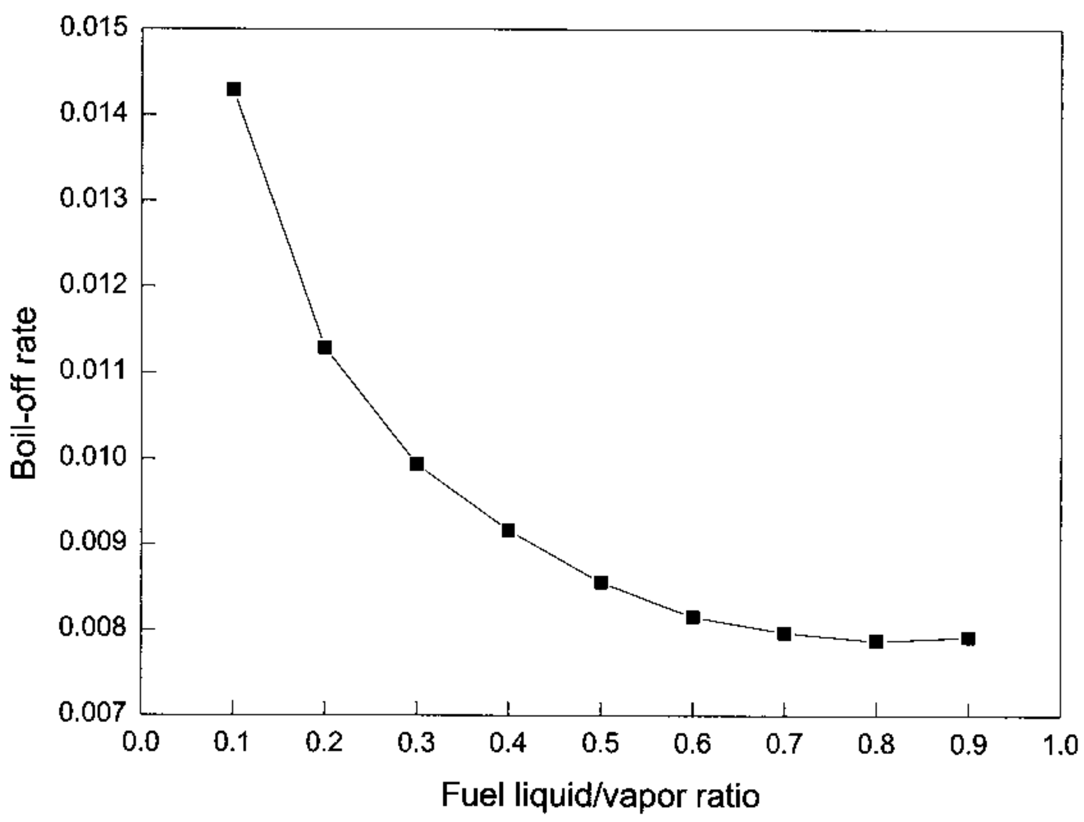

Fig. 4 Variation of specific BOG with fuel liquid/vapor volume ratio

Fig. 4 shows the relationship between specific BOG and liquid/vapor ratio at the car acceleration of 1.78 m/sec^2. Specific BOG is the ratio of BOG and total LNG mass at a certain liquid/vapor ratio. Curve begins with severe negative slope and end horizontally, which says that specific BOG decreases very rapidly as the fuel liquid/vapor ratio increases, and then the change of specific BOG becomes smaller, because BOG is proportional to the surface area wetted by liquid fuel but heat capacity of liquid fuel is proportional to the volume of liquid in the tank. Fuel consumption decreases the volume of liquid fuel in the tank but increases the specific BOG.

3.3 Effect of car acceleration on the BOG

BOG depends on the heat leak to LNG tank and therefore on the surface area wetted by liquid fuel. 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, which changes wetted surface area.

Fortran program "Pro-Heatleak"[10]-[12] is modified accordingly to Eq. (1) to (3) and used to evaluate the BOG with car acceleration. This program allows one to calculate the BOG 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 used to evaluate the heat leak and BOG.

The truck can normally get a velocity of 80 km/hr for 45 sec[13], which corresponds with the car acceleration of 1.78 m/sec^2. Therefore the calculation of BOG for car acceleration from 0 to 3 m/sec^2 is quite enough for a small truck. The acceleration of car greater than 3 m/sec^2 is hardly possible and does not concerned it this research.

The computational results of calculations of BOG with car acceleration for different liquid/vapor ratios are summarized in Fig. 5. Acceleration has strong effect on the BOG. The difference between maximum and minimum values of BOG for full tank is about 12 %. For fuel liquid/vapor ratio greater than 0.5 BOG increases with increasing of car acceleration. For fuel liquid/vapor ratio less than 0.5 BOG decreases with acceleration of car.

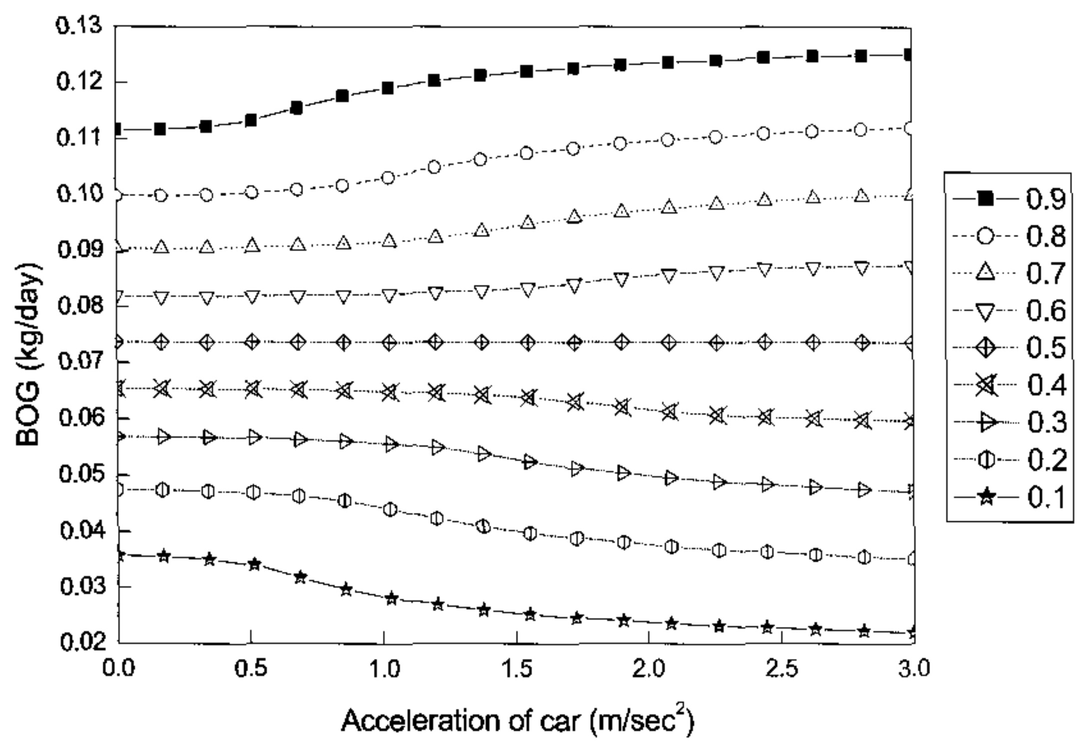

Fig. 5 Variation of BOG with car acceleration for different fuel liquid/vapor ratios

For fuel liquid/vapor ratio equal to 0.5, BOG does not depend anymore on car acceleration because for half-full tank the wetted surface area is constant. The graphs are symmetrical about the line of liquid/vapor ratio equal to 0.5.

4. Conclusion

One ton truck is very popular in Korea. The conversion of this truck to LNG fuel offers us great environmental and economical benefits. LNG tank for one ton truck is developed to suit the limited installation space. Two LNG tanks installed on one ton truck provide it with 1.8 times longer mileage than two CNG tanks with the same outside size.

BOG due to heat leak to LNG tank through its walls is one of the governing parameters for new LNG tank design. In this research the effects of car acceleration and liquid/vapor ratio on the BOG are analysed. The BOG is estimated using the modified Fortran program "Pro-Heatleak".

The relationship between the BOG and liquid/vapor ratio is linearly proportional, which makes almost a straight line. Fuel consumption decreases the volume of liquid fuel in the tank but increases the specific BOG.

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

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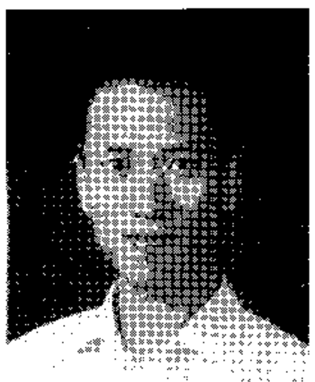

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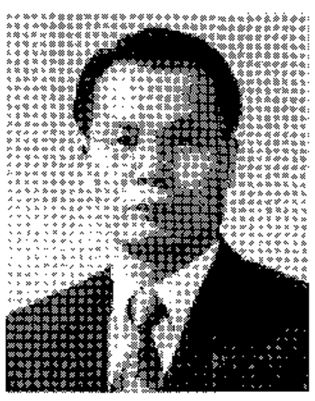

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