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천연가스자동차용 LNG용기에서의 차량가속도와 Heat leak 관계 해석

Analysis of heat leak with the car acceleration for LNG tank of Natural Gas Vehicle

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Abstract

LNG is a valuable fuel since it offers some environmental, energy security and economic benefits over diesel. It could be used mainly in heavy-duty trucks and buses. Car acceleration induces the slope angle of the liquid fuel in the tank. Slope angle changes the surface area wetted by liquid fuel and consequently heat leak to the tank. This research is a result of numerical simulation of the heat leak with the car acceleration to LNG tank. The "Pro-HeatLeak" Fortran program is developed and the verification test of the developed program is done. The difference between numerical results and calculated results from MathCad verification test is less than 0.07 percent. The smallest heat leak is correspond to the case without oscillation. For the high car acceleration the value of heat leak is greater than that for the small acceleration. The difference between maximum and minimum heat leak for 10 gallons of fuel vapor in the tank is about 10 percent.

키워드 : *액화천연가스, 천연가스자동차, 열누출*
Keywords : *LNG(Liquefied Natural Gas), NGV(Natural Gas Vehicle), heat leak*

1. Introduction

Natural gas is abundant and is widely used for home heating and industrial processes. It can be made from a variety of feedstocks, including renewables. It is easily transported through pipelines and costs about the same or slightly less than gasoline.

Natural gas is primarily extracted from a gas well or in conjunction with crude oil production; it can also be produced as a "by-product" of landfill operations.

Natural gas allows a change to an alternative fuel without requiring an immediate switch away from internal combustion engines. Natural gas has low CO (Carbon Monoxide) emissions, virtually no PM (particulate matter) emissions, and reduced VOCs (Volatile organic chemicals). Per unit of energy, natural gas contains less carbon than any other fossil fuel, leading to lower CO_2 (Carbon Dioxide) emissions per vehicle mile traveled. Specific emission reductions for NGVs compared to gasoline are: CO, 65-90 percent; non-methane organic gas (NMOG), 87 percent; NO_x (Nitrogen Oxides), 87

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percent; CO_2, by almost 20 percent[1].

Natural gas can be stored on a vehicle either in a compressed gaseous state (CNG) or in a liquefied state (LNG). LNG is the natural gas super-cooled to a temperature of minus 260 F and contained in insulated, pressurized tanks.

There are some areas where LNG vehicles differ from CNG vehicles. These include:

"Higher energy density" a greater volume of LNG can be stored in a smaller space.

Storage pressure for LNG is less than 150 psi; for CNG it is about 3600 psi, safety concern.

"Speed of fueling" large vehicles can often be filled in the "fast fill" time of 4 to 6 minutes.

"Control over fuel composition" the composition of LNG can be determined with a high degree of accuracy since most LNG produced for vehicles is 99 percent methane. By having this control, the vehicle is able to have a more finely tuned fuel system and engine, leading to optimization of engine performance, greater fuel economy, and lower emissions.

"Delivery and availability" LNG is similar to gasoline, in that it can be transported in trailer trucks, railcars, barges and ships. The delivery infrastructure is already in place.

It is possible to have liquids develop in LNG fuels. These liquid "slugs" won't gasify, and reduce the efficiency of the fuel.

The boil-off factor of LNG as a fuel needs to be maintained.

The insulation, as efficient as it is, will not keep the temperature of LNG cold by itself. LNG is stored as a "boiling cryogen," that is, it is a very cold liquid at its boiling point for the pressure it is being stored. LNG will stay at near constant temperature if kept at constant pressure.

The onboard storage tank supplies the engine with a "controlled amount" of fuel. This needs to be accomplished without venting any natural gas, without changing the LNG composition, and with accurate metering. The problem is that since the LNG is kept at cryogenic temperatures heat is continually leaking into the system. The rate of this heat leak causes venting (losses to the atmosphere), weathering (changes in LNG composition with time) and variations in fluid densities, of which phenomena should be avoided as much as possible. This project is focused on the phenomena analysis of the heat leak to LNG tank on the moving vehicle. Research work is done numerically.

2. LNG Tank for Natural Gas Vehicle

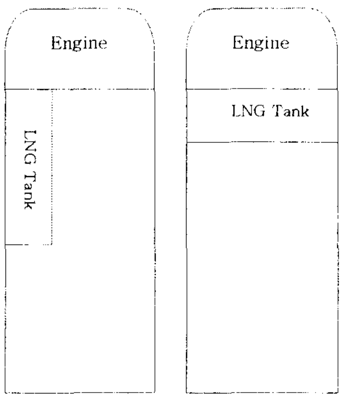
The LNG fuel tank is a cryogenic container. It stores the natural gas fuel as a highly refrigerated liquid at low pressure. Typically the fuel temperature is about minus 260 ° F, and the fuel pressure is about 70 psig. The reason for cryogenic storage is that natural gas is much more dense as a low temperature liquid than it is as a compressed gas. It is possible to get three times as much gas in the same space at about half the weight if it is stored as a cryogenic liquid instead of as a compressed gas.

To contain this cryogenic fuel without the use of any outside source of refrigeration the tank has to be extremely well insulated. To achieve the high level of insulation efficiency the LNG pressure vessel is covered with multi-layer insulation and enclosed by an outer vacuum vessel. Between the LNG tank and the outer shell there is a high order vacuum. This combination of insulation and vacuum, called super-insulation, allows for standby times of over a week with no loss of fuel.

Both the inner pressure vessel and the outer vacuum vessel are constructed of stainless steel. Stainless has both the low temperature strength necessary to contain the cryogenic fuel and the high temperature toughness to allow the vacuum casing to armor the inner pressure vessel.

The driving force for delivery of the fuel to the engine is provided by the fuel pressure itself, there are no pumps in the system. When the engine demands fuel the pressurized liquid natural gas flows out of the tank toward the engine. The cold pressurized fuel then passes through a heat exchanger. The heat exchanger uses engine coolant to vaporize the liquid and turn it into a gas. Once out of the heat exchanger the fuel is a warm gas, at tank pressure, ready to be burned by the engine. Tank pressure is maintained by a tank mounted pressure control regulator that vents excess pressure into the fuel line during periods of engine operation.

There are two positions of LNG tank on the truck: axial and cross position (Fig. 1).



(a) axial position (b) cross position

Fig. 1 Positions of LNG tank on the truck

Tank heat leak has a dramatic effect on the pressure, temperature and density relationships of the LNG. Therefore it is very difficult to control the fuel tank pressure and maintain consistent fuel quality for delivery to the engine. Heat leak depends on the surface area wetted by liquid fuel. (It is assumed that heat leak from the fuel vapor is very small and neglect it).

During vehicular movement, the slope angle of liquid fuel surface changes in the tank because of acceleration or deceleration of the truck. Surface area contacted with liquid fuel is not constant for axial position of tank. Different car acceleration produces the different slope angle of liquid fuel and different surface area. Commonly there is no enough loading space on the truck for cross position of tank. Consequently axial position of LNG tank is the most-used one.

The LNG tank has a cylindrical shape, assume the flat end tank. The dimensions of the LNG tank are introduced in the Table 1 and Fig. 3.

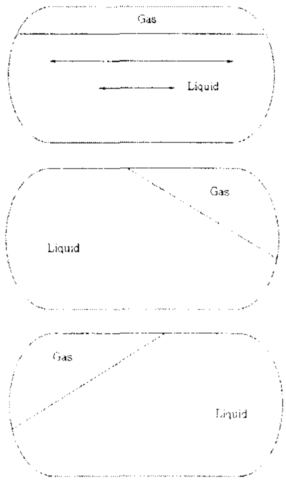


Fig. 2 Mode of oscillation for axial position

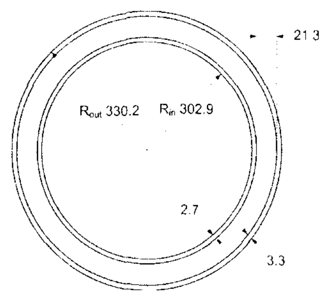


Fig. 3 Cross sectional dimensions of LNG tank

Table 1 Basic specification of LNG tank[2]

Item	Specification
Tank size	26 in. O.D. x 72 in L. (0.66m O.D. x 1.83m L.)
Water volume	110 gallons(0.41635m^3)
Ullage (full tank vapor volume)	10 gallons(0.03785m^3)
Usable fuel	100 gallons(0.3785m^3)
Weight - empty	584 lbs(265.45kg)
Weight - full	929 lbs(422.27kg)
Fuel temperature	-245 F(-154°C) Min (12 to 15 psig saturation pressure)
Total heat leak	11 Btu/hr(3.223W) @ 90 F(32°C)
Nominal operating pressure range	50 to 120 psig

3. Development of program

3.1 Slope angle of liquid fuel surface induced by the acceleration of vehicle

Car acceleration and deceleration effect on the liquid fuel surface area in LNG tank.

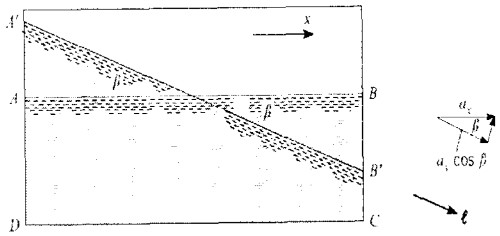


Fig. 4 Slope angle of liquid surface with uniform acceleration of a tank[3]

It is assumed that the tank of liquid shown in Fig. 4 is accelerated to the right, the positive x direction, at a rate of a_x. For this to occur, a net force must act on the liquid in the x direction; this is accomplished when the liquid redistributes itself in the tank as shown by A'B'CD. Under this condition the hydrostatic force at the left end is greater than the hydrostatic force at the right, which is consistent with the requirement of $F = Ma$, taking γ as a constant

$$-\frac{\partial}{\partial \ell}(p + \gamma z) = \rho a_\ell \tag{1}$$

Eq. (1) is Euler's equation of motion for fluid.

Consider application of the Eq. (1) along the liquid surface A'B'. Here the pressure is constant. Consequently, $\partial p / \partial \ell = 0$. The acceleration along A'B' is given by $a_\ell = a_x \cos\beta$. β is the slope angle of liquid surface. Hence, Eq. (1) reduces to

$$\frac{dz}{dl} = -\frac{a_x \cos\beta}{g}$$

But $dz/dl = -\sin\beta$. Thus,

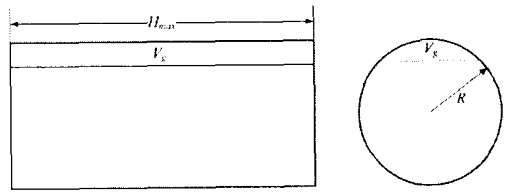
$$\sin\beta = \frac{a_x \cos\beta}{g}$$

$$\beta = \tan^{-1}\frac{a_x}{g}$$

where g is the gravity.

3.2 Wetted surface area and heat leak

3.2.1 Without oscillation



a) front view (b) side view

Fig. 5 LNG Tank without oscillation

The car is motionless therefore the slope angle(β) is equal to zero degree. To find the total surface area wetted by liquid fuel(S_t) the length of the circle arc(l) should be evaluated.

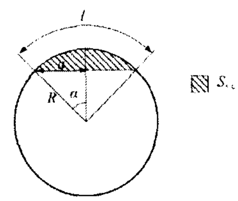


Fig. 6 Definition of symbols for $\beta = 0°$

Area of the segment of circle($S_{s.c}$) corresponds with the volume of fuel vapor(V_g), area of the circle(S_c) (end plate) corresponds with the total volume of LNG tank(V_t) therefore

$$S_{s.c} = \frac{V_g \cdot S_c}{V_t} \tag{2}$$

The area of the segment of circle($S_{s.c}$) is[4]:

$$S_{s.c} = \frac{R^2 (2\alpha - \sin 2\alpha)}{2} \tag{3}$$

where α is the half-central angle of the segment of circle(rad) and R is the radius of the tank(m).

The value of α is determined from Eqs. (2) ~(3). For the liquid-vapor ratio of the fuel $V_g = 0.1 \cdot V_t$, α is equal to 45 degree.

The half length of chord(a) is:

$$a = R\sin\alpha$$

The length of the arc of circle(l) is:

$$l = 2R\alpha$$

The total surface area of tank wetted by fuel for $\beta = 0°$ is:

$$S_t = 2(S_c - S_{s.c}) + H_{max}(2\pi R - l)$$

where H_{max} is the length of the tank(m).

3.2.2 With oscillation

The angle of β is called a critical angle(Fig. 7(b)) when the length of cylinder segment occupied by fuel vapor is equal to the length of tank. For the case of 10 gallons of fuel vapor in a tank, a critical angle(β) is 6 °. Fig. 7(a) is low slope angle, (0 ° < β < 6 °) and Fig. 7(c) is a high slope angle (6 ° < β < 63 °).

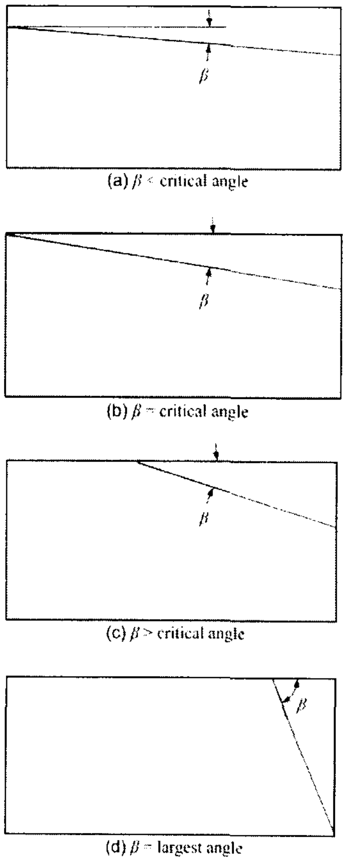

(a) β < critical angle
(b) β = critical angle
(c) β > critical angle
(d) β = largest angle

Fig. 7 Illustration of slope angle

A) High slope angle

High slope angle is shown in Fig. 7(c) and Fig. 8. This case covers slope angle greater than and equal to critical angle. The largest slope angle is 63 degree which is shown in Fig. 7(d). For this largest slope angle, left end of the tank is covered by liquid fuel fully and right end is contacted with fuel vapor completely. For other ratios of liquid-vapor of fuel, critical angles are differ from 6 °.

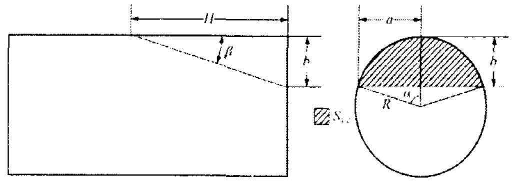

(a) front view (b) side view

Fig. 8 Definition of symbols for high slope angle(6 ° ≤ β < 63 °)

The total surface wetted by liquid fuel for the high slope angle (6 ° ≤ β < 63 °) is:

$$S_t = M_t - M_{s.c} + 2S_c - S_{s.c}$$

where M_t is the lateral surface of the whole tank(m^2) and $M_{s.c}$ is the lateral surface of the segment of cylinder (vapor part of the tank)(m^2).

$$M_t = 2\pi R H_{max}$$

$$S_c = \pi R^2$$

$$M_{s.c} = 2RH\frac{(b-R)\alpha + a}{b} \qquad (4)$$

where H is the length of the segment of cylinder(m) and b is the height of the segment of circle(m).

The volume of the cylinder segment($V_{s.c}$) is[4]:

$$V_{s.c} = H\frac{a(3R^2 - a^2) + 3R^2(b-R)\alpha}{3b} \qquad (5)$$

One express H, a and α by β and b in Fig. 8(a) and Fig. 8(b) to reduce the number of independent variables, which give one following expressions.

$$H = \frac{b}{\tan\beta}$$

$$a = \sqrt{2Rb - b^2}$$

For $b < R$ (Fig. 8(b)) α is:

$$\alpha = \sin^{-1}\left(\frac{\sqrt{2Rb - b^2}}{R}\right)$$

For $b \geq R$ (Fig. 9) α is:

$$\alpha = \pi - \sin^{-1}\left(\frac{a}{R}\right)$$

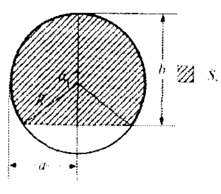


Fig. 9 Definition of α, b, a and S_{sc} for $b \geq R$

For the given slope angle(β), one can find the volume of the cylinder segment, which is the volume occupied by the vapor phase of fuel. This volume depends only on liquid-vapor ratio of the fuel in a tank. In our case, it is constant. The successive substitution method is used to find b for each β from the value of vapor volume and the volume equation of cylinder segment. Followings are the processes to find the value of b and surface areas for each β.

All parameters are expressed in terms of one parameter(b), the height of the circle segment. The initial values of β is set and the values of b are guessed successively for a given β. The volume of cylinder segment is calculated for these values of β and b. Then this calculated value of volume is compared with the real value of vapor volume. If the difference between real value and calculated is greater than convergence criterion ($e=10^{-4}$), vapor volume is recalculated with a new b value which is increased by 10^{-4} successively. This calculation is continued until the difference becomes less than or equal to a preset convergence criterion. The surface area wetted by liquid fuel is calculated from these values of β and b. These calculations of wetted surface area are done with the different values of slope angle.

B) Low slope angle

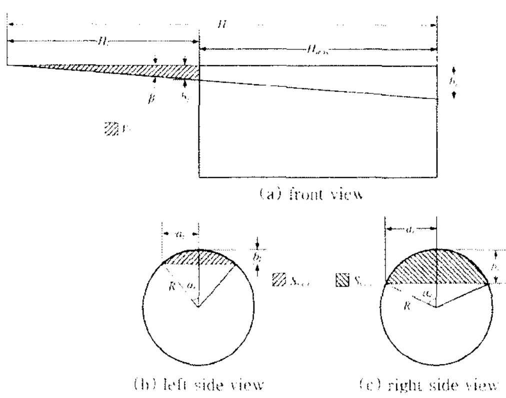


Fig. 10 Definition of symbols for low slope angle ($0^{\circ} < \beta < 6^{\circ}$)

For low slope angle, the shape of fuel vapor volume in the tank is not a full segment of cylinder. That is, it is a part of full cylinder segment. The calculated value of full cylinder length(H) exceeds the length of real tank(H_{max}). The volume of full cylinder segment(V_r) is calculated first and then the volume of elongated part(V_l) is subtracted from the full volume of cylinder segment and so the volume of fuel vapor(V_g) is $V_r - V_l$.

For these full cylinder segment and elongated part of the cylinder, the same equations of volume and surface area like in the previous case (for high slope angle) can be used. The truncated volume is the volume of fuel vapor in the tank(V_g). The vapor volume does not depend on the slope angle value. It is constant for a given liquid-vapor fuel ratio. Using the successive substitution method numerical calculations are continued until the difference between actual value of vapor volume and calculated one will be less or equal to convergence criterion and then parameters of b and β at the final calculation are used to find total surface of tank wetted by fuel.

The volume of full cylinder segment(V_r) and the volume of elongated part of the cylinder(V_l) are determined according to Eq. (5) with the parameters which correspond to full cylinder and elongated part respectively.

The total surface area of tank wetted by liquid fuel(S_t) is:

$$S_t = 2S_c - S_{s.c.l} + S_{s.c.r} + M_t + M_{s.c.l} - M_{s.c.r}$$

where $S_{s.c.l}$ and $S_{s.c.r}$ are the segment areas of left and right end plate respectively, calculated by Eq. (3) with corresponding parameters. $M_{s.c.l}$ and $M_{s.c.r}$ are the lateral surfaces of the cylinder segment for elongated part and for the full cylinder respectively, calculated by Eq. (4) with corresponding parameters.

3.2.3 Calculation of the heat leak rate in the LNG tank

The temperature inside the LNG tank is very low and must stay at the constant. The huge temperature gradient at the wall of LNG tank induces significant heat leak from LNG tank. The heat leak from the wall of fuel vapor part is very small and is neglected. Heat leak from the wall of liquid part in a LNG tank is evaluated.

Heat leak from the tank is governed by

Fourier's law of heat conduction as below:

$$q = \frac{T_{out} - T_{in}}{ln(r_{out}/r_{in})/2\pi kH_{max}}$$

where: q is the heat flow rate(W) radially through the tank, k is the thermal conductivity(W/m·K), T_{out} and T_{in} are the temperatures(K) of outside and inside surfaces of the tank respectively, r_{out} and r_{in} are the outer and the inner radius(m) of the tank respectively and H_{max} is the length(m) of the tank.

The thermal conductivity is evaluated by a following equation for a given q_{max}[2] for a tank. Heat leak depends on liquid-vapor ratio of the fuel in a tank. Therefore factor f_1 is used in this calculation. Factor f_1 is the ratio of surface area wetted by liquid fuel to the total surface area of tank.

$$k = \frac{q_{max} ln(r_{out}/r_{in})}{(T_{out} - T_{in})2\pi H_{max}} f_1$$

To calculate the heat leak from the tank numerically, the factor f_2 is introduced. Factor f_2 allows to take into account the changes of surface area wetted by liquid because of car acceleration. Factor f_2 is the ratio of surface area wetted by liquid fuel for current case to the wetted surface area for the case without oscillation.

The heat leak from the not full tank is:

$$q = \frac{T_{out} - T_{in}}{ln(r_{out}/r_{in})/2\pi k} f_2$$

3.3 Flow chart of the Fortran "Pro-HeatLeak" program

Flow chart of the Fortran "Pro-HeatLeak" program with basic steps is shown in Fig. 11.

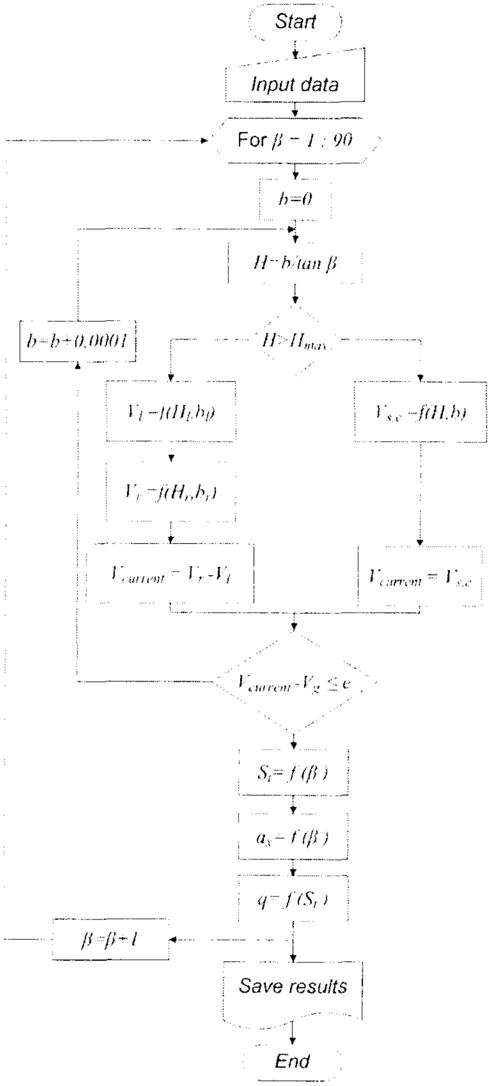


Fig. 11 Flow chart of the Fortran "Pro-HeatLeak" algorithm

3.4 Verification test of the program

To check the accuracy of the "Pro-HeatLeak" Fortran program a verification test in MathCad program is made. MathCad program allows to calculate the surface area wetted by liquid fuel depending on the slope angle in the range of high angles (6° ≤ β < 63°). The basic steps of MathCad program are in Fig. 12.

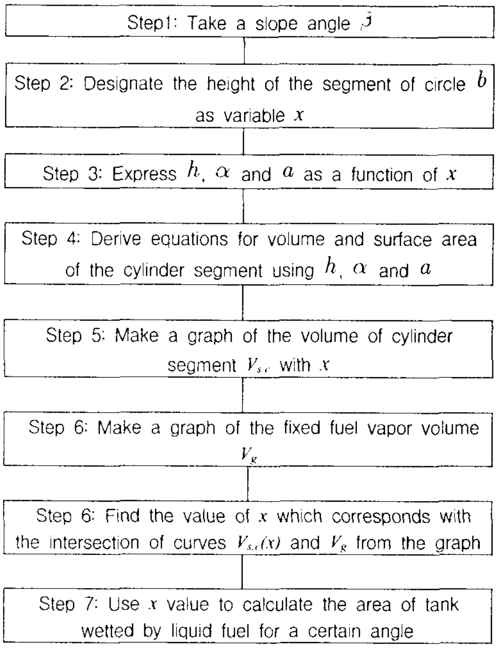


Fig. 12 Flow chart of MathCad algorithm

The results of MathCad calculation and its comparison with Fortran "Pro-HeatLeak" program results are in Fig. 13-14.

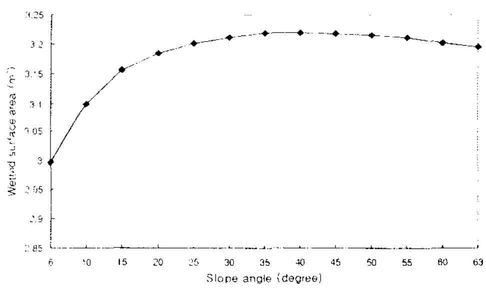


Fig. 13 Calculated results of the wetted surface area by MathCad

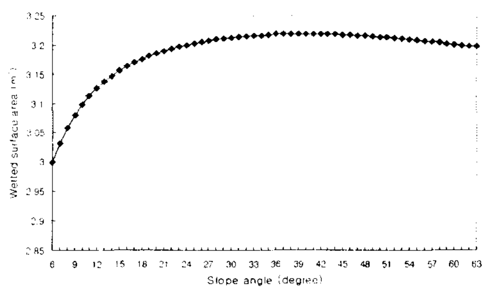


Fig. 14 Numerical results of the wetted surface area by a Fortran program

MathCad calculations are made with the step of 5 degree, Fortran numerical calculations are made for each slope angle degree. Both graphs in Fig. 13 and Fig. 14 have the same shape.

The verification test shows high coincidence degree between Fortran and MathCad programs. The difference between calculated and numerical results is less than 0.07 %.

4. Computational results and discussion

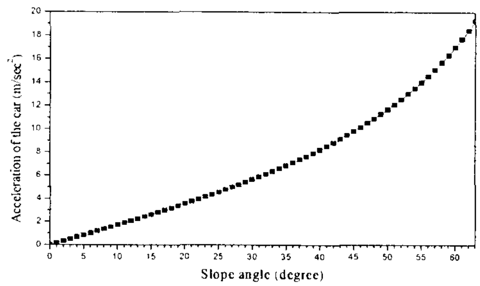


Fig. 15 Relationship between slope angle and the acceleration of car for 10 gallons of fuel vapor

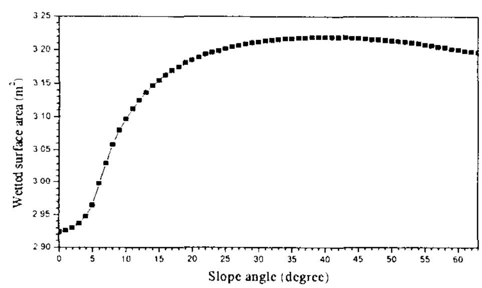


Fig. 16 Relationship between slope angle and wetted surface area of tank for 10 gallons of fuel vapor

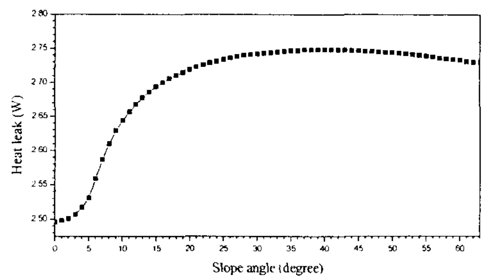


Fig. 17 Relationship between slope angle and the heat leak for 10 gallons of fuel vapor

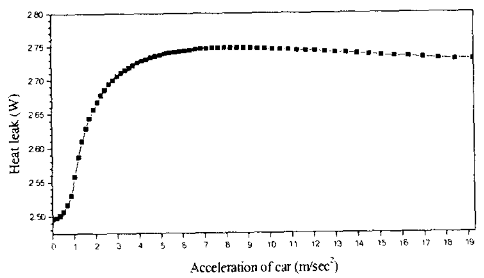


Fig. 18 Relationship between car acceleration and heat leak

The usual truck which has total weight of 15605 kg (sum of the car weight and loaded mass weight) can get a velocity of 60 km/hr for 35 sec [5], which correspond with the car acceleration about 0.5 m/sec^2. 60 km/hr is a usual most energy-saving velocity of the truck. For 10 gallons of fuel vapor, the range of car acceleration under calculation is from 0 to 19.3 m/sec^2 (Fig. 15). Therefore the calculation for the angles from 0 to 63 degree is quite enough. In customary regime only low slope angles can arise.

Fig. 15 shows the variation of the slope angle of liquid fuel in the tank with car acceleration. The rate of slope increase is decreased as the value of acceleration become bigger.

Fig. 16 shows the variation of the surface area wetted by liquid fuel with slope angle. The 6 degree is a inflection point of the curve because it is a critical angle for 10 gallons of fuel vapor (Fig. 7(b)). The largest slope angle is 63 degree, it is a final point of the graph. For this angle left end of the tank is covered by liquid fuel fully and right end is contacted with fuel vapor completely (Fig. 7(d)). As shown in Fig. 16 the minimum surface area corresponds with zero slope angle (the case without oscillation). The maximum surface area corresponds with the slope angle equal to 41 degree. Wetted surface area increases rapidly for the slope angle from the 6 to 15 degree. For the angles from 15 to 41 degree the wetted surface area increases slightly. From 41 to 63 degree surface area decreases slightly.

Fig. 17 shows the variation of the heat leak to the tank with slope angle. The wetted surface area curve (Fig. 16) and the heat leak curve (Fig. 17) have the same shape because the heat leak is directly proportional to the area. Therefore the maximum heat leak to the tank corresponds with the slope angle equal to 41 degree. This slope angle arises from the acceleration of the car equal to 8.53 m/sec^2 (Fig. 15). The difference between maximum and minimum heat leak for 10 gallons of fuel vapor is about 10 percent.

Fig. 18 shows the variation of the heat leak with car acceleration. For the acceleration from 0 to 1.2 m/sec^2 the heat leak increases slightly. The acceleration of 1.2 m/sec^2 is a inflection point of the curve. Heat leak increases rapidly for the acceleration from the 1.2 to 3 m/sec^2. For the acceleration from 4 to 8.53 m/sec^2 the heat leak increases slightly. Heat leak decreases slightly as the acceleration increases from 8.53 to 19.3 m/sec^2.

The "Pro-HeatLeak" Fortran program is applicable to any ratio of liquid-vapor fuel in the tank. In this research the calculations of the heat leak from the full tank (10 gallons of vapor and 100 gallons of liquid fuel) to the "empty tank" (100 gallons of vapor and 10 gallons of liquid fuel) are made. The less liquid fuel is inside of the tank, the smaller slope angles can arise. For the little volume of liquid fuel in the tank the difference between maximum and minimum value of heat leak became smaller.

5. Conclusion

LNG must be maintained cold to remain a liquid therefore the prevention of the heat leak from the tank is very important. The analysis of heat leak with the car acceleration in LNG tank is made. The "Pro-HeatLeak" Fortran program for calculation heat leak with the acceleration of car is developed.

As the car accelerates or decelerates the slope angle of liquid in the tank is changed. This changes cause the changes of the surface area contacted with liquid fuel. Heat leak depends on the wetted surface area, and consequently on the acceleration of the car. For the small acceleration or deceleration of the car the value of heat leak is smaller than that for the big acceleration.

Verification test in MathCad shows the

high coincidence degree between Fortran and MathCad programs, the difference between calculated and numerical results is less than 0.07 percent.

To calculate the surface area wetted by liquid fuel the cases of different slope angles are analysed. The smallest surface area and consequently heat leak are correspond to the case without oscillation. The greatest heat leak is corresponds to the car acceleration equal to 8.53 m/sec^2. The difference between maximum and minimum heat leak for 10 gallons of fuel vapor is about 10 percent.

This results can be used in the developing of LNG tank. LNG tanks are always of double-wall construction with extremely efficient insulation between the walls. The analysis of the heat leak is used in the selection of the insulation type and materials, thickness and material of the vessels, the value of the pressure, loading position, shape and sizes of LNG tank.

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