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Development of the computational program to evaluate heat leak on LNG tank of Natural Gas Vehicle

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Abstract : Car acceleration or deceleration induce the surface slope of liquid fuel in the LNG tank. Slope changes the surface area wetted by liquid fuel in the tank and consequently heat leak to the tank. The Fortran program, "Pro-Heatleak", is developed to evaluate heat leak on LNG tank. The verification test proves the high accuracy of the developed program. The difference between MathCad and computational results is less than 0.07 %. Computational analyses of heat leak are carried out for 10 gallons and 20 gallons of fuel vapor in the tank. With the increasing of fuel vapor volume by 10 percent the wetted surface area and heat leak respectively decrease by 13 percent. The difference between maximum and minimum heat leak is about 10 percent for both 10 gallons and 20 gallons of fuel vapor in the tank.

Key words : LNG (Liquefied Natural Gas), NGV (Natural Gas Vehicle), Heat leak, Fortran program, Computational analysis

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 gas wells 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 emissions, virtually no PM 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 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 87 percent; CO_2, by almost 20 percent[1].

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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.

LNG has several advantages over CNG[1],[2]:

Vehicles can be designed to carry substantially more fuel as LNG than CNG in the same size and weight container.

Safety concern. Storage pressure for LNG is less than 150 psi and for CNG it is about 3600 psi.

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.

LNG is a liquid. It can be pumped, pressurized, and transferred more efficiently than a gas. Vehicles can be fueled as quickly with LNG as with conventional fuels.

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. A small amount of LNG evaporates from the tank during storage, cooling the tank and keeping the pressure inside the tank constant and the LNG at it's boiling point. Rise in temperature is countered by LNG being vented from the tank[3].

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[4]. The rate of this heat leak causes venting (losses to the atmosphere), weathering (changes in LNG composition with time) and variations in fluid densities. These 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 computationally.

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 tank 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 possible positions of LNG tank on the truck: axial (Fig. 1(a)) and cross position(Fig. 1(b)).

Commonly there is no enough loading space on the track for cross position of tank. Consequently axial position of LNG tank is the most-used one.

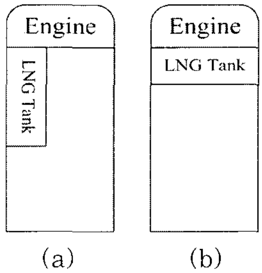


Fig. 1 Axial and cross positions of LNG tank on the truck

Heat leak of tank has a dramatic effect on the pressure, temperature and density relationships of the LNG. 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 to the vapor phase of fuel is very small and is neglected.

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 (Fig. 2).

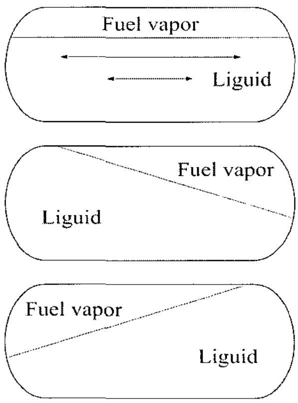


Fig. 2 Mode of oscillation for axial position

The LNG tank has a cylindrical shape and it is assumed that the end plates of tank are flat. The dimensions of the LNG tank are illustrated in Fig. 3.

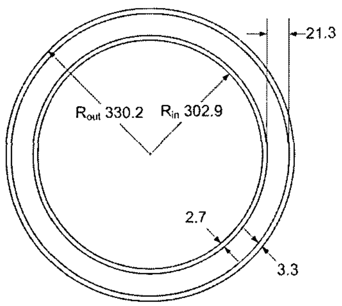


Fig. 3 Cross sectional dimensions of LNG tank

The LNG tank manufactured by CFI[5] is adopted for this research. The outer diameter of LNG tank is 0.6604m and the tank length is 1.83m. Total volume of tank is 110 gallons. Ullage(full tank vapor volume) is 10 gallons and usable fuel volume is 100 gallons.

3. Development of program

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

Car acceleration and deceleration changes the slope of liquid fuel surface in LNG tank, which makes the varying contact area of liquid fuel with the inner surface of LNG tank.

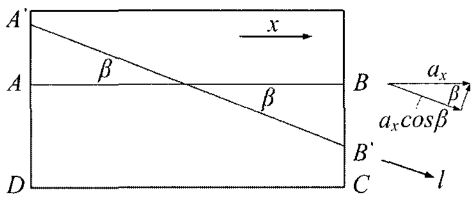


Fig. 4 Slope angle of liquid surface with uniform acceleration of a tank[6]

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. From Eq. (1), a following expression for β is derived.

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

where β is the slope angle of liquid surface and g is the gravity.

3.2 Wetted surface area and heat leak

Illustration of slope angle is shown in Fig. 5. The angle of β is called a critical angle (Fig. 5(b)) when the length of cylinder segment occupied by fuel vapor is equal to the length of tank. Critical angles

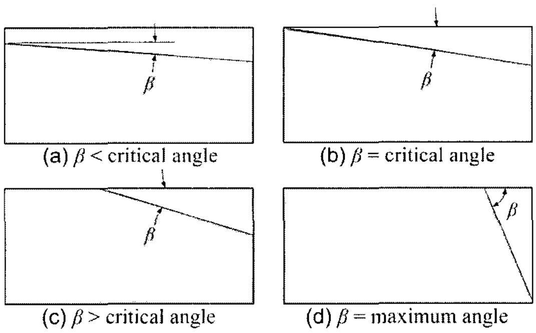
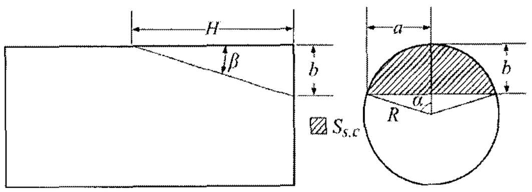


Fig. 5 Illustration of slope angle

are obtained from "Pro-Heatleak". For the case of 20 gallons of fuel vapor in a tank, critical angle is equal to 10°. The case of Fig. 5(a) is called a low slope angle, ($0° < \beta < 10°$) and the case in Fig. 5(c) is a high slope angle ($10° < \beta < 42°$).

3.2.1 High slope angle

The case of high slope angle is shown in Fig. 5(c) and Fig. 6. This case covers the slope angle greater than and equal to critical angle. The maximum slope angle (Fig. 5(d)) for 20 gallons of fuel vapor is 42 degree. For the maximum slope angle, the left end of the tank is covered by liquid fuel fully and the right end is contacted with fuel vapor completely. For other ratios of fuel's liquid-vapor, critical angles differ from 10°.



(a) front view (b) side view

Fig. 6 Definition of symbols for high slope angle ($10° \le \beta < 42°$)

The total surface wetted by liquid fuel(S_t) for the high slope angle ($10° \le \beta < 42°$) 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), $M_{s.c}$ is the lateral surface of the cylinder segment (vapor part of the tank)(m^2), S_c is the area of the circle (end plate) (m^2) and $S_{s.c}$ is the area of the circle segment

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

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

$$M_{s.c} = 2RH\frac{(b-R)\alpha + a}{b} \qquad (2)^{[7]}$$

where H is the length of the cylinder segment(m), b is the height of the circle segment(m), α is the half-central angle of the circle segment(rad).

$$S_c = \pi R^2$$

$$S_{s.c} = \frac{R^2(2\alpha - sin2\alpha)}{2} \qquad (3)^{[7]}$$

The volume of the cylinder segment($V_{s.c}$) is[7]:

$$V_{s.c} = H\frac{a(3R^2 - a^2) + 3R^2(b-R)\alpha}{3b} \qquad (4)$$

where a is the half length of chord(m).

Expressing H, a and α by β and b (Fig. 6(a),(b)), reduces the number of independent variables, the following expressions are obtained.

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

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

For $b < R$ (Fig. 6(b)) α is:

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

For $b \ge R$ (Fig. 7) α is:

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

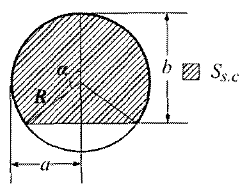


Fig. 7 Definition of α, b, a and Ss.c for $b \ge R$

For the given slope angle(β), the volume of the cylinder segment, which is the volume of fuel vapor, is calculated by Eq. (4). This volume depends on liquid-vapor ratio of the fuel in a tank. In this research, it is constant. The successive substitution method is used to find b for each β from the value of vapor volume and the equation of volume of cylinder segment. The values of b and surface areas for each β are obtained as follow.

All parameters are expressed by a single parameter of b, the height of the circle segment. The initial value 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 value is greater than convergence criterion ($e=10^{-4}$), then cylinder segment 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.

3.2.2 Low slope angle

For low slope angle, the volume of fuel vapor with artificial extension become a full segment of cylinder (Fig. 8). That is, the volume of fuel vapor is a part of 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. Then the volume of elongated part(V_l) is subtracted from the volume of full cylinder segment and so the volume of fuel vapor(V_g) is $V_r - V_l$.

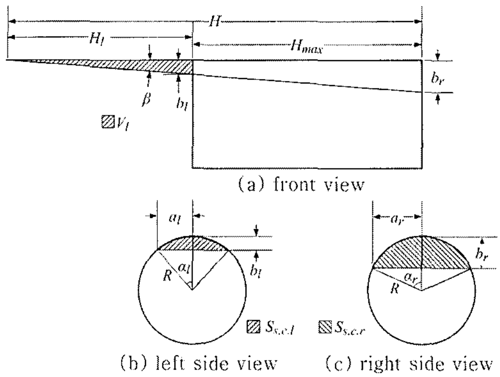


Fig. 8 Definition of symbols for low slope angle ($0° < \beta < 10°$)

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 computational calculations are continued until the difference between actual value of vapor volume and calculated one will be less or equal to convergence criterion. Then parameters of b and β from 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. (4) with the parameters corresponded 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. (2) with corresponding parameters.

3.2.3 Calculation of the heat leak

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

Heat leak to the LNG tank is governed by Fourier's law of heat conduction as it is given below:

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

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 radiuses of the tank respectively and H_{max} is the length of the tank.

The thermal conductivity is evaluated by the following equation for a given total heat leak (q_{max})[5]. 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 computationally, 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:

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

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. 9.

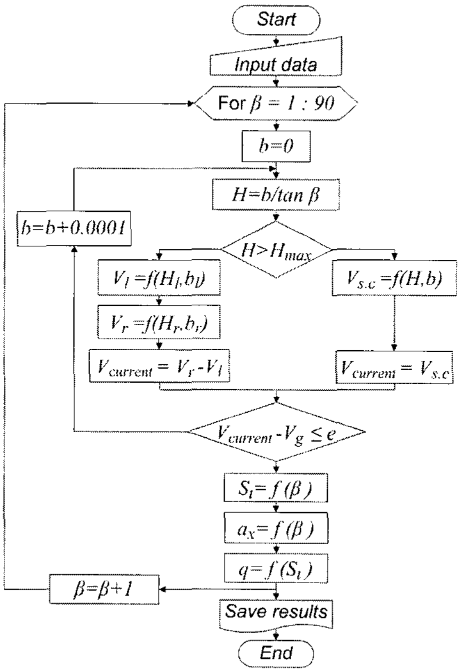


Fig. 9 Flow chart of the "Pro-Heatleak" algorithm

3.4 Verification test of the program

To check the accuracy of the "Pro-Heatleak" Fortran program, a verification test in MathCad program is held. MathCad program allows to calculate the surface area wetted by liquid fuel for 10 gallons of fuel vapor, depending on the slope angle, in the range of high angles (6 ° ≤ β 〈 63 °). The basic steps of MathCad program are in the Fig. 10.

Step 1: Take a slope angle β

Step 2: Designate the height of the circle segment b as variable x

Step 3: Express h, α and a as a function of x

Step 4: Derive equations for volume and surface area of the cylinder segment using h, α and a

Step 5: Make a graph of the volume of cylinder segment $V_{s.c}$ with x

Step 6: Make a graph of the fixed fuel vapor volume V_g

Step 7: Find the value of x which corresponds with the intersection of curves $V_{s.c}(x)$ and V_g from the graph

Step 8: Use x value to calculate the area of tank wetted by liquid fuel for a certain angle

Fig. 10 Flow chart of MathCad algorithm

The results of MathCad calculation for 10 gallons of fuel vapor and its comparison with Fortran "Pro-Heatleak" program results are shown in Fig. 11-12.

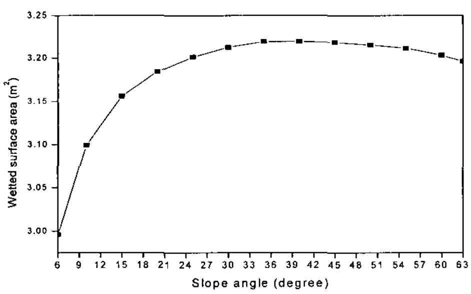


Fig. 11 Wetted surface area by MathCad

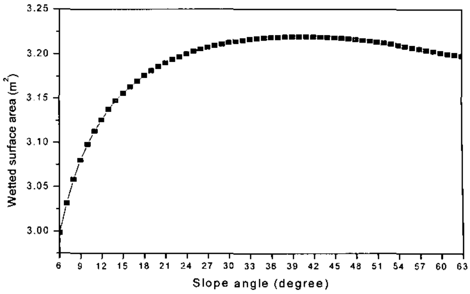


Fig. 12 Wetted surface area by the Fortran program

MathCad calculations are made with the step of 5 degree. Computational calculations are made for each slope angle. Both graphs in Fig. 11 and Fig. 12 are very same. The verification test shows the high degree of coincidence between Fortran and MathCad results. The difference is less than 0.07 %.

4. Computational results and discussion

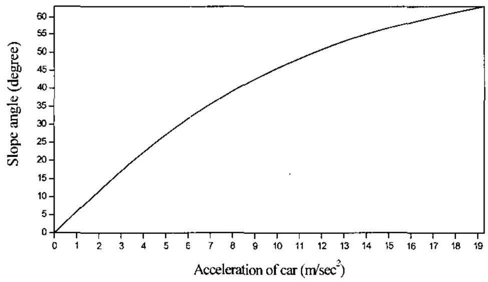


Fig. 13 Relationship between slope angle and the acceleration of car

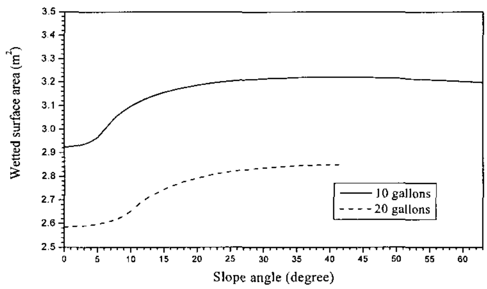


Fig. 14 Relationship between slope angle and wetted surface area of tank

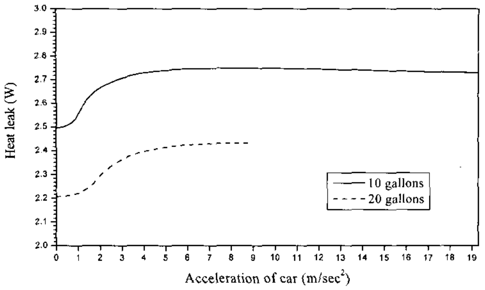


Fig. 15 Relationship between car acceleration and heat leak

Fig. 13 shows the variation of the slope angle with car acceleration for 10 and 20 gallons of fuel vapor in the tank. The car acceleration for this research varies from 0 to 19.27 m/sec^2 for 10 gallons and from 0 to 8.83 m/sec^2 for 20 gallons of fuel vapor (Fig. 13), which make slope angle range from 0 to 63 degree for 10 gallons and from 0 to 42 degree for 20 gallons. The increase rate of slope is decreased as the value of acceleration becomes larger.

Fig. 14 shows the variation of the surface area wetted by liquid fuel with the slope angle for 10 and 20 gallons of fuel vapor in the tank. For 10 gallons the 6 degree is an inflection point of the curve because it is a critical angle for 10 gallons of fuel vapor (Fig. 5(b)). For 20 gallons the 10 degree is an inflection point of the curve because it is a critical angle for this vapor volume. For 10 gallons the maximum slope angle is 63 degree, that is a final point of 10 gallons graph. For this angle the left end of the tank is covered by liquid fuel fully and the right end is contacted with fuel vapor completely (Fig. 5(d)). For 20 gallons the maximum slope angle is 42 degree and it is a final point of this graph. As shown in Fig. 14, the minimum surface areas for 10 and 20 gallons of vapor correspond with zero slope angle (the case without oscillation). For 10 gallons of vapor the maximum surface area corresponds with the slope angle equal to 41 degree. For 10 gallons 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 and from 41 to 63 degree surface area decreases slightly. For 20 gallons of vapor, the maximum surface area corresponds with the maximum slope angle of 42 degree. For 20 gallons, wetted surface area increases rapidly for the slope angle from the 10 to 17 degree and for the angles from 17 to 42 degree the wetted surface area increases slightly.

The heat leak is directly proportional to the surface area wetted by liquid fuel. With the increasing of fuel vapor volume in the tank the surface area wetted by liquid fuel decreases. The volume difference between 10 and 20 gallons is about 10 %, which make wetted surface area and heat leak difference between 10 and 20 gallons about 13 %.

The maximum wetted area (Fig. 14) for 10 gallons of fuel vapor correspond with the slope angle of 41 degree. This slope angle arises from the acceleration of the car equal to 8.53 m/sec^2 (Fig. 13). The difference between maximum and minimum wetted surface area for 10 gallons of fuel vapor is about 10 percent. The maximum wetted area (Fig. 14) for 20 gallons of vapor correspond with the slope angle equal to 42 degree. This slope angle arises from the acceleration of car equal to 8.83 m/sec^2 (Fig. 13). The difference between maximum and minimum wetted surface area for 20 gallons of fuel vapor is about 10 percent.

Fig. 15 shows the variation of the heat leak with car acceleration for 10 and 20 gallons of fuel vapor. For 10 gallons of vapor the acceleration of 1.2 m/sec^2 is an inflection point of the curve. Heat leak for 10 gallons increases rapidly with the acceleration from the 1.2 to 3 m/sec^2. For the acceleration from 3 to 8.53 m/sec^2 the heat leak increases slightly. The maximum heat leak occurs at the car acceleration of 8.53 m/sec^2. For 10 gallons of vapor, heat leak decreases slightly from 8.53 to 19.3 m/sec^2. The difference between maximum and minimum heat leak for 10 gallons of fuel vapor is about 10 percent. For 20 gallons of fuel vapor, the acceleration of 1.9 m/sec^2 is an inflection point of the curve. Heat leak for 20 gallons increases rapidly for the acceleration from the 1.9 to 3.2 m/sec^2. For the acceleration from 3.2 to 8.83 m/sec^2 the heat leak increases slightly. The difference between maximum and minimum heat leak for 20 gallons of fuel vapor is about 10 percent.

5. Conclusion

LNG must be maintained cold to remain liquid. Therefore the prevention of the heat leak to the tank is very important. When the car accelerates or decelerates, the slope angle of liquid in the tank is changed. These change causes the change of the surface area contacted with liquid fuel. Heat leak depends mainly on the wetted surface area, and consequently on the acceleration of the car. For the low acceleration of the car the value of heat leak is smaller than for the high acceleration.

The "Pro-Heatleak" Fortran program for analysis of heat leak with the acceleration of car is developed. Verification test of the developed program in MathCad shows the high accuracy of "Pro-Heatleak" program, the difference between MathCad and Fortran results is less than 0.07 percent. The "Pro-Heatleak" 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 "nearly empty tank" (100 gallons of vapor and 10 gallons of liquid fuel) are implemented. The comparison of the heat leak for 10 and 20 gallons of fuel vapor in the tank is made.

The surface area wetted by liquid fuel for the range of slope angle is calculated. The minimum surface area and consequently minimum heat leak are correspond to the case without oscillation. The maximum heat leak corresponds to the car acceleration equal to 8.53 m/sec^2 for 10 gallons and 8.83 m/sec^2 for 20 gallons of fuel vapor. The difference between maximum and minimum heat leak for 10 gallons and for 20 gallons of fuel vapor is about 10 percent.

With the increasing of fuel vapor volume in the tank the surface area wetted by liquid fuel decreases and heat leak decreases respectively. The comparison of the heat leak for 10 and 20 gallons of fuel vapor in the tank shows that increasing of fuel vapor volume by 10 percent causes the decreasing of the heat leak by 13 percent. The less liquid fuel is inside of the tank, the less slope angles can arise.

These 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 can be 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.

Acknowledgement

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