Displacement Losses from the Refueling Operation of Passenger Cars

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Abstract

Displacement losses occur when vapor from a fuel tank headspace is displaced by the incoming liquid to the tank. This study was undertaken in order to perform a calculation that is used to estimate the displaced hydrocarbon losses. In the calculation, a mixture of hydrocarbon vapor and air is considered as an ideal gas. The volume of vapor displaced equals the volume of liquid dispensed. An experimental study was conducted for measuring the displaced vapor loss to confirm the results from the calculation. Activated carbon was used to absorb vapors that were emitted during refueling. The change of weight of activated carbon was recorded by a digital balance. The loss, as derived by calculation, is compared with experiments carried out at a service station. The study shows that the present model can be used for estimating the displaced hydrocarbon loss during a refueling operation

1. Introduction

Hydrocarbons which contribute to air pollution may affect both public health and the growth of vegetation. Total hydrocarbons are divided between natural and man-made sources. Man-made sources include solvents, automotive emissions and oil industry refining and distribution systems. The automobile is one source of hydrocarbon emissions to the atmosphere. Hydrocarbons from passenger cars are emitted in the exhaust gases and from the evaporation of gasoline in the fuel system. Hydrocarbon loss during a refueling operation is called "Refueling Loss". The expelled vapor during refueling is a mixture of hydrocarbons and air which are expelled during the refueling operation. A study from abroad [1] showed that exposure to gasoline vapor has contributed to kidney tumors. This study also prompted the automobile industry to review the scientific literature relating gasoline vapor exposure to human cancer. Smith [2] investigated hydrocarbon losses during the refueling of a passenger car. Loss measurements were tested in a small sealed enclosure by varying the factors that may affect the magnitude of loss. Statistics were used to analyse and find the significant variables and a mathematical model was developed to estimate the hydrocarbon losses. Koehl et. al. [3] studied the onboard refueling control system using a carbon canister technology and the effectiveness of the technology was shown to comply with the current US EPA (Environmental Protection Agency) requirements for losses during refueling operations.

The objective of this work is to estimate the gasoline vapor emissions from the refueling operation of a passenger car.

2. Derivation of Loss Equation

Consider a tank (Figure 1) which is open to the atmosphere and which is being filled with a volatile liquid. Assume that the liquid and vapor are initially at equilibrium, that is, the partial pressure of substances in the vapor phase is equal to the equlibrium vapor pressure of the liquid. As the temperature and pressure in the tank are changed, a vapor with the same chemical composition as the liquid will result from the evaporation. The loss of vapor from the tank sustained during the filling operation is called displacement loss. The expelled mass of component i can be calculated simply by this equation [4].

$$m_i = \Delta V \, C_i \tag{1}$$

where

m_i = expelled mass of component i, kg
ΔV = volume of air and vapor of volatile liquid expelled from the tank, m^3
C_i = concentration of component i in displaced gas, kg/m^3

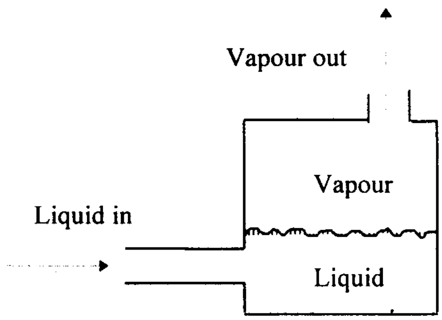


Figure 1. Displacement losses occur when a tank is filled with liquid

Concentration C_i can be expressed as

$$C_i = \frac{y_i M_i}{V_{molar,gas}} \tag{2}$$

where

y_i = mole fraction of component i in the vapor
M_i = molecular weight of component i,kg/kmol
$V_{molar,gas}$ = gas molar volume, m^3/kmol

In low pressure air pollution control, we can assume with only a small error that the vapor mixture behaves as a perfect gas, and that we can estimate the content of a volatile liquid into the vapor mixture using the laws of thermodynamics. Raoult's law states that the vapor pressure of component i in a mixture is

$$p_i = x_i P_i \tag{3}$$

p_i = partial pressure of component i in the vapor mixture,N/m^2
P_i = saturation pressure of pure component i at existing temperature, N/m^3
x_i = mole fraction of component i in the liquid

Furthermore the relationship between partial pressure and total pressure can be found from Dalton's law which states that the total pressure of the vapor mixture is a sum of the partial pressures of the constituents. The partial pressure of the component i is

$$p_i = y_i P_t \tag{4}$$

Combining Eq.(3) and (4), the mole fraction of component i in the vapor is found.

$$y_i = x_i \frac{p_i}{P_t} \tag{5}$$

where

y_i = mole fraction of component i in the vapor
x_i = mole fraction of component i in the liquid
P_t = total pressure, N/m^2

Replacing the vapor mole fraction in Eq. (2) and replacing the gas molar volume by the perfect gas law, and substituting in Eq. (1), we find

$$\frac{m_i}{\Delta V} = \frac{x_i P_i M_i}{RT} \quad (6)$$

where
T = absolute temperature, K
R = universal gas constant, 8.314 kN·m/kmole·K

Eq. (6) is in a general form. It can be applied in order to estimate the total amount of gasoline vapor emitted as refueling losses when gasoline is transferred from underground storage tanks at a service station to the gasoline tanks of the customers' vehicles. The molecular weight of the hydrocarbon vapor is a function of temperature and the 10 % point slope on the curve of distillation.It can be found in table 6. of ref. [5]. For example, assuming Reid vapor pressure, Rvp = 8.0 psi (The vapor pressure of gasoline is specified by the Reid vapor pressure which is found by a standard test [6])and ,S=3 (S is the average value of the 10 % point slope for motor gasoline), the molecular weight of hydrocarbon vapor, M_i at 15.55 °C is 63. For the value of S = 3, the molecular weight increases or decreases by 0.1053 per degree of temperature change which can be calculated by $M_i = 63+0.1053\Delta t$ where $\Delta t = t - 15.55$, (t is the temperature in deg C).The true vapor pressure, P_i at the bulk liquid temperature may also be computed with the aid of the nomograph in appendix V of ref.[7] or the table 7 in ref. [5].

The sensitivity of the displacement loss to Rvp for various temperatures is displayed in (Figures 2 and 3). The effect of the Rvp is plotted in (Figure 2) for fixed values of the temperature equal to 20, 25, 30, 35, 40, and 45 °C . It may be seen more clearly in (Figure 3), where the displacement loss is plotted as a function of the temperature for fixed values of Rvp equal to 7, 8, 9, 10, 11, 12, and 13 psi. They show that the displacement loss increases with increasing Rvp. It should be noted in practice that fuels which have volatilities appropriate to the seasonal temperatures should be used. To reduce the displacement losses, both of them must be optimized.

3. Materials and Methods

To confirm the results from calculations, an experimental study was obtained. A schematic diagram of the experimental set up for the determination of displaced losses is shown in (Figure 4). Details of this experimental system were also described in the former paper [8].The system consists of two main parts, the fuel tank and the carbon canister. An ordinary fuel tank of 40 litres capacity was used with a small modification. On the top of the tank there was a vapor vent, 1/4 inch in diameter which was connected to the canister by a transparent rubber tube. A drainage valve was mounted at the bottom of the tank. The inside diameter of the nozzle was 2.4 cm. All the valves were manually controlled. The carbon canister was designed and constructed for collecting the displaced vapor from the refueling operation. The housing of the canister was fabricated from aluminium sheet. It had a cubical form (0.2m×0.2m×0.23 m). To increase the efficiency of the carbon canister, a two-pass design was performed. The inside of the canister was divided into two spaces by a baffle. Two ball valves were mounted on the top of the canister for vapor entry and exit. The inlet valve was connected to the vapor vent of the fuel tank. The canister contained approximately 3 kg of activated carbon which had an apparent density of 0.28-0.35 g/cc and a particle size 8×30 mesh. Thermocouples were used to measure the ambient, displaced vapor and tank fuel temperatures.

Five litres of gasoline were introduced into the fuel tank. The tank was shaken so that the liquid was vaporized within the tank. Subsequently, the fuel was drained out. The tank was then placed in the experimental position as shown in (Figure 4). Thirty litres of gasoline from an underground storage tank were dispensed through a hose at a flow rate controlled automatically by the nozzle. The flow rate of gasoline was kept constant throughout this experiment. The weight of the canister was recorded every 10 seconds by digital balance until the end of the filling operation. The ambient temperature, the fuel temperature in the tank and the displaced vapor temperature were measured during the experiment.

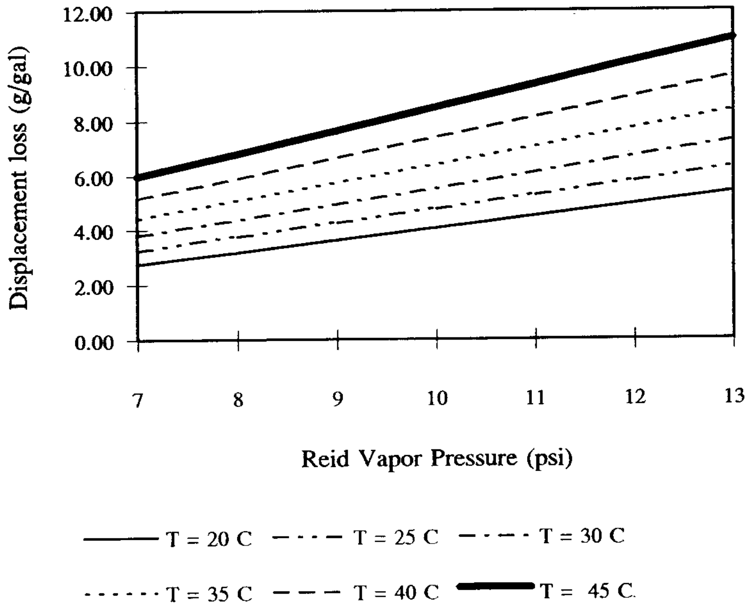


Figure 2 Sensitivity of displacement loss to Rvp at various values of temperature

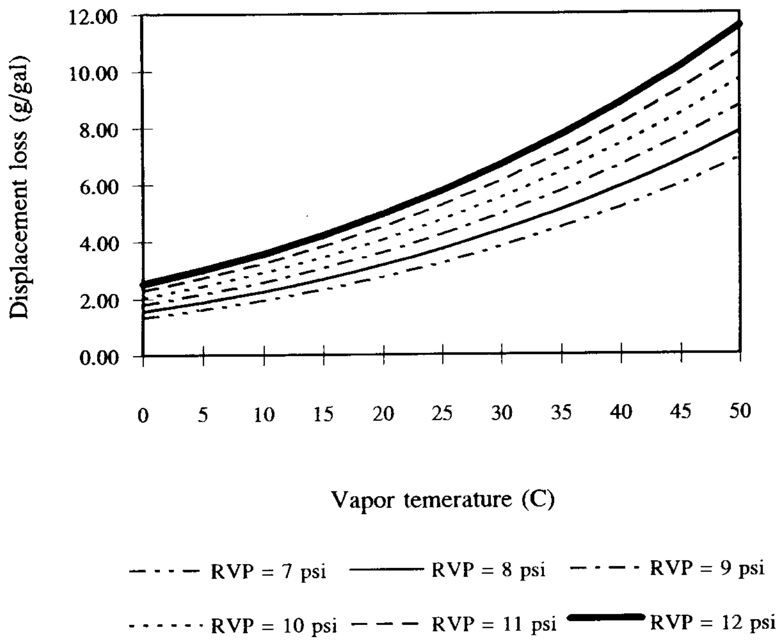


Figure 3 Sensitivity of displacement loss to temperature at various values of Rvp

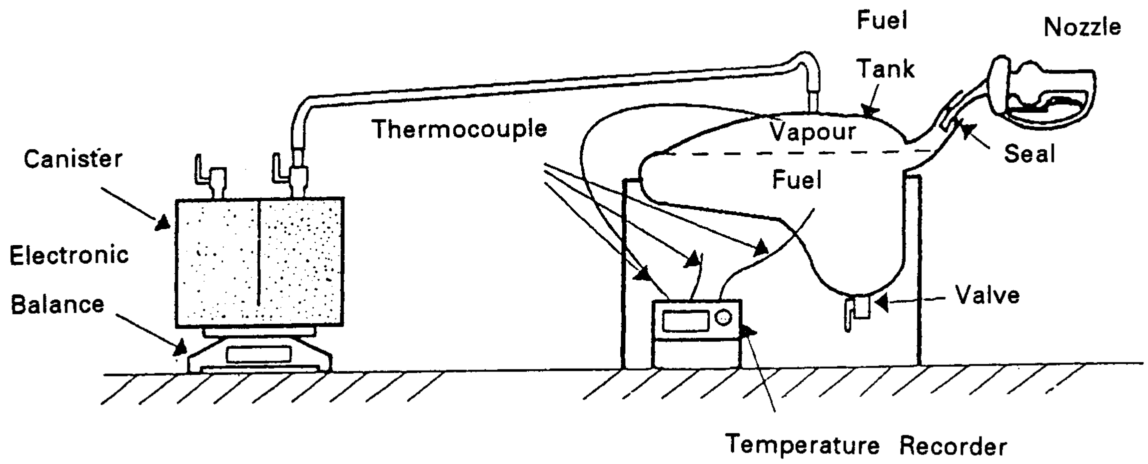
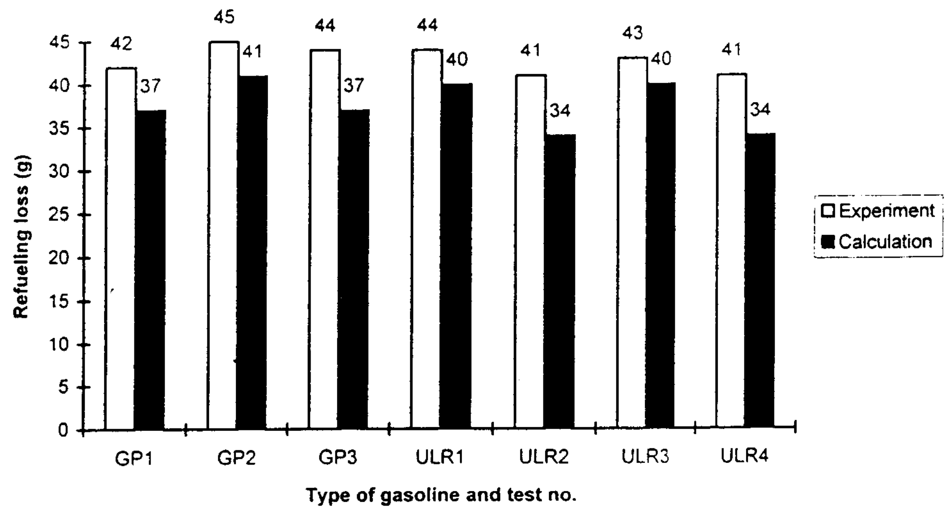


Figure 4 Schematic diagram of experimental apparatus



GP : Premium motor gasoline
ULR : Unleaded regular gasoline

Figure 5 Comparison of measured displacement loss with calculated losses.

4. Results and Discussion

Figure 5 shows the results of the refueling tests. Both unleaded and leaded gasoline were used. The experimental data were compared with the results from the calculation. The theoretical model has consistently underpredicted the displacement loss. The losses from experiment were generally greater than the calculations by about 12 %. This makes sense because the total real losses during refueling operation may not include only the displaced fuel tank vapor but also the entrained fuel droplets in the displaced vapor, and the liquid spills. The model approximates evaporative vapor loss only. However the model may be used to predict the losses. The same calculation is used to estimate the total amount of gasoline vapor emitted as displacement losses at service stations in Thailand when gasoline is transferred from the storage tank to the gasoline tanks of the customers' vehicles.

Assuming Rvp = 8 psi, T=30 °C and S=3. Vapor pressure and molecular weight can be estimated as 44.78 kN/m^2 and 64.52 respectively. The concentration of gasoline in the displaced vapor is calculated by Eq. (6) as 1.15 kg gasoline / m^3 vapor. Multiplying this concentration by 6300×10^6 litres which was the total amount of gasoline used in 1995 in Thailand, the total displacement loss is estimated at 7300 tons/year or about 90×10^6 baht/year.

5. Method to Reduce the Emissions

The above example considers only the losses from the transfer of gasoline from the underground storage at the service station to the customer. This is the final operation. In reality, there are many transfers of gasoline everyday; from the refinery or depot to the tank truck, and from the tank truck to the tank at the service station. Because the loss mechanism is the same, we can use the same method to calculate the total losses.

To reduce the losses incurred when transfering gasoline from the underground storage tank to the customer's vehicle at the service stations, a scheme such as shown in (Figure 6) can be used. The vapor from the customer's tank is forced back into the underground tank by the positive pressure caused by pumping gasoline into the customer's tank or by a blower which is added to the system. In this system a special design of hose and nozzle must be used.

The same kind of technology can be used for the transfer of gasoline from tank trucks to underground storage tanks at service stations (Figure 6)or the storage tank at the depot to the tank trucks (Figure 7). The vapor displaced from the tank is returned to the tank being emptied. Additionally the return vapor can be sent to a vapor recovery unit which can restore the vapor to liquid which then flows to a bulk gasoline storage tank (Figure 7).

6. Recommendation for Further Studies

The loss of the entrained fuel droplets in the displaced vapor and liquid spill losses which result from fuel spillage from the fuel tank or nozzle should be studied.

The breathing losses from the fuel tank which are associated with the thermal expansion and contraction of the vapor space resulting from the daily temperature cycle should be studied.

The technical and economic feasibility of using the vapor recovery system should be determined.

7. Conclusion

This paper presents new data for displacement losses from a vehicle gasoline tank during refueling. The work was undertaken to investigate the displaced hydrocarbon losses obtained during the refueling of passenger cars. A calculation method was developed based on thermodynamic theory. An experimental study was conducted to verify the results from calculations. Calculated losses were compared with measured losses. Factors influencing losses are the temperature of the vapor and liquid, vapor pressure and molecular weight. The magnitude of the average observed loss was about 40 g for filling 30 litres of gasoline.

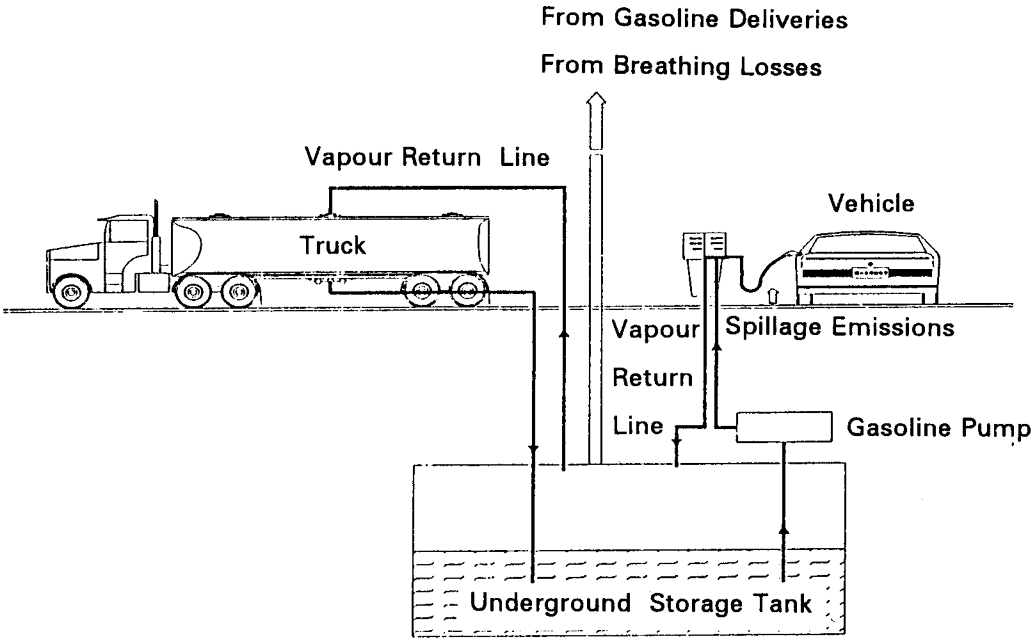


Figure 6 Vapor return system in service station [4]

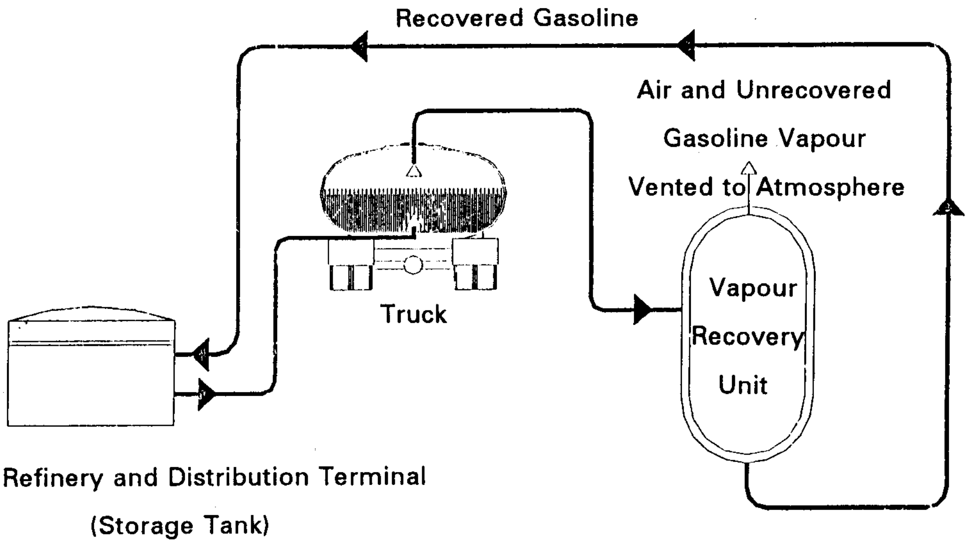


Figure 7 Vapor recovery system

The results can be used to predict the total displacement losses in Thailand when gasoline is transferred from the underground storage tanks at service stations to the gasoline tanks of the passenger cars. Total national displacement losses from the refueling operation of passenger cars in 1995 are estimated as 7300 ton/year or about 90×10^6 baht/year.The results should be of concern to vehicle manufacturers, the petroleum industry and also to government agencies with a view to promote regulations in Thailand.

8. Acknowledgement

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9. References

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