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Modeling and Analysis of Effect of Various Tank Geometries and Relief Pressure on Liquid Hydrogen (LH_2) Boil-Off Losses

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ABSTRACT

This research investigates the effect of various storage tank geometries and relief pressure on boil-off losses for liquid hydrogen (LH_2). The effect of storage volume of LH_2 in the tanks for the various geometries is analyzed as well. The model takes into consideration the heat transfer between the liquid and vapor phases, integrates actual heat transfer mechanisms, and employs variety equations of state to estimate evaporative losses. For this, a software package BoilFAST has been used to investigate the boil-off losses. The model was validated against experimental data available in open literature from NASA. Results showed that the effect of relief pressure on the evaporation of LH_2 is very high. The LH_2 volume is reduced by 34% in the case of cuboid shape and 22% the for spherical shape of the tank from relief pressure of 111 to 10 kPa. However, the effect of the filled volume of LH_2 in the storage tank on the evaporation of LH_2 is minimal as the volume is reduced only by less than 5% for all tank shapes. Overall, for various tank geometries, spherical shape showed minimum evaporation losses compared to other tank geometries.

Keywords: Liquid hydrogen; boil-off losses; tank geometries; relief pressure; simulation

NONMENCLATURE

Abbreviations	
BOG	Boil-off gas
EOS	Equation of state
LH_2	Liquid hydrogen
LNG	Liquified natural gas
LN_2	Liquid nitrogen
MLI	Multi-layer insulation
NASA	National Aeronautics and Space Administration
SHV	Superheated vapor

1. INTRODUCTION

The swift advancement in global energy consumption has presented significant challenges in the realms of worldwide energy security and ecological sustainability in terms of reduction in carbon emissions [1]. Therefore, to minimize the impact of carbon emissions on climate change, there is presently a shift underway, moving from energy sources dominated by fossil fuels to carbon-free energy, commonly referred to as green energy and hydrogen is one of these shifts [2]. Hydrogen is a well-considered energy source that can be relied upon to meet future energy needs. Hydrogen as energy storage is a promising green energy storage in future and there is a high attention to investigate the global advances and prospects of the different hydrogen storage options. Although, production of hydrogen through numerous methods is already being carried out, but storage of the hydrogen is still a challenge [3]. Although significant amount of work has been done in the storage of hydrogen is still and emerging field due to the evaporation losses. Since hydrogen is a gas at room temperature, it requires a considerable amount of storage space. Consequently, to get around this, cooling to about -253°C at atmospheric pressure will liquefy hydrogen [4, 5].

Due to its increased energy density and purity, liquid hydrogen is a better option to the present energy storage technologies and energy carriers [6-8]. LH_2 which burns cleanly and can serve as a storage of energy produced from carbon-free or low-carbon sources, will be crucial to this transition [9, 10]. But because of the difference in temperature between the volume the surrounding air and LH_2, heat will inevitably enter the LH_2, which could cause the LH_2 to evaporate [11, 12]. The evaporated vapor is known as boil-off gas (BOG) [13] and in a process known as self-pressurization, its creation causes the

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pressure in the appropriate storage tank to rise, forcing the venting of the tank into the atmosphere and the loss of valuable hydrogen. BOG generation can range from 0.06% per day for a 20,000 m^3 LH_2 tank to 0.4% per day for a 50 m^3 cryogenic tank, depending on the insulation quality and surface-to-volume ratio of the tank [14]. The storage of LH_2 results in the inevitable formation of boil-off gas (BOG) [4, 15]. Depending on elements like the wall material of the tank, insulation level of the tank, and surface-to-volume ratio, a certain proportion of liquid hydrogen will eventually be converted into the gas phase. Although there are comparisons with the storage of other crucial cryogenic liquids for industry, such as liquified natural gas (LNG) and liquid nitrogen (LN_2), BOG is much more severe for LH_2 because it is stored at very lower temperatures [16-18]. There are various additional factors that contribute to BOG formation at LH_2 facilities and exporting terminals. These include the production of BOG as a result of flashing (depressurization), heat influx into transfer pipes, heat contributed by machinery like pumps, and cooling of LH_2 carrying vessels. From an economic and safety perspective, the control of such BOG is crucial for future large-scale LH_2 storage and transit applications involving land-based tanks and sea-borne boats. One of the most significant sources of hydrogen loss was discovered to be boil-off from the storage tank occurring when LH_2 during the transfer from a trailer to the LH_2 tank.

In the literature, the model simulated for investigation for the BOG loss of LH_2 is investigated by Petitpas [15, 19] and Ghafari et al. [13]. Petitpas altered a MATLAB code formerly established by the National Aeronautics and Space Administration (NASA) to calculate the BOG losses of the LH_2. Whereas, Ghafari et al., developed and implemented the model in the BoilFAST software that allows for reliable calculations of the BOG losses of LH_2. Here, we present an effect of relief pressure and storage volume in tank on the superheated vapor (SHV) model developed previously for simulating liquid hydrogen storage in various tank geometries.

2. MODELING AND SIMULATION

The modeling and simulation in this research study is done using the BoilFAST, which is an open source software developed Fluid Sciences and Resources Division, University of West Australia [13]. This software's user interface enables users to effortlessly configure simulations by choosing from various tank geometries, thermodynamic models, boundary conditions, and compositions. Users can then execute the simulation, and they also have the option to observe and export the results. Various tank geometries taken in this research along with the specifications are shown in Figure 1. Within this software, users have the flexibility to choose from a variety of fluid components encompassing different isomers of hydrogen, as well as equilibrium and standard hydrogen. Here we have selected the parahydrogen as 99.8% and remaining 0.2% as orthohydrogen which is normally preferred, however, the effect of this composition can also be considered in future. The model can simulate a variety of scenarios due to its flexibility in terms of the spin isomer composition of the hydrogen in each phase, tank design, and related heat transport.

Figure 2 and Equations (1) to (9) elucidate the fundamental principles and mathematical expressions that underlie the Superheated Vapor (SHV) model. These references are made within the context of a vertically oriented cylindrical storage tank. They encapsulate the interrelated equations governing heat transfer in each phase, collectively representing the comprehensive influence of all heat transfer mechanisms between the tank contents and the surrounding environment [13].

The heat transfer coefficients U_L and U_V in Equations (1) and (2) are calculated by taking into consideration the convection, conduction and the radiant heat transfer [20]. The overall heat transfer (Q_{VL}) is calculated by Equation (3), which considers the overall heat transfer by taking into consideration the effects of evaporation and condensation [2].

$$Q_L = \left(U_L A_L\left(T_{boundary} - T_L\right) + Q_{floow}\right)\Delta t \tag{1}$$

$$Q_V = \left(U_V A_V\left(T_{boundary} - T_V\right) + Q_{floow}\right)\Delta t \tag{2}$$

$$Q_{VL} = U_{VL} A_{VL}\left(T_V - T_L\right)\Delta t \tag{3}$$

Where, A_L and A_V are phase contact area with the tank walls, Δt is specified time step interval, T_L is a saturated liquid temperature and T_V is a vapor temperature.

The $\dot{n}_{boil}$ and n_{boil} are the boil off rate and quantity of boil off and can be determined by Equations (4) and (5), respectively with respect to change in the liquid quantity between Δt. Similarly, the $\dot{n}_{relief}$ and n_{relief} are the relief rate and quantity of relief volume and can be determined by Equations (6) and (7), respectively with respect to change in the total molar quantity between Δt. The standard EOS models of Leachman et al. have been used [21].

$$\dot{n}_{boil} = -\frac{d(n_L)}{dt} \tag{4}$$

$$n_{boil} = n_{L,j-1} - n_L - n_{L,j} \tag{5}$$

$$\dot{n}_{relief} = -\frac{d(n_F)}{dt} \tag{6}$$

$$n_{relief} = n_{F,j-1} - n_L - n_V \tag{7}$$

Therefore, the amounts of liquid $(n_{L)}$, vapor (n_V), total amount of fluid within the system (n_F), and the fraction of the system contents in the liquid phase (L_f), can be calculated via Equations (8) and (9), respectively.

$$n_{boil} = n_L + n_V \tag{8}$$

$$L_f = \frac{n_L}{n_V} \tag{9}$$

In this research, we have taken the initial values of vacuum jacketed tank of 125 m^3 storage tank capacity as per the experimental values at NASA, equipped with 80-layer multi-layer insulation (MLI) system. Various geometries of the tanks are considered such as Horizontal, Vertical, Spherical and Cuboid as shown in Figure 1. Other parameters used in this research study are inner diameter as 2.896m, insulation thickness as 0.021m and initial pressure of 111 kPa. Various fill levels of the LH_2 are considered from 10% to 90%. Ambient temperature is assumed as 300K.

3. RESULTS AND DISCUSSION

3.1 Effect of relief pressure on liquid volume reduction for various tank geometries

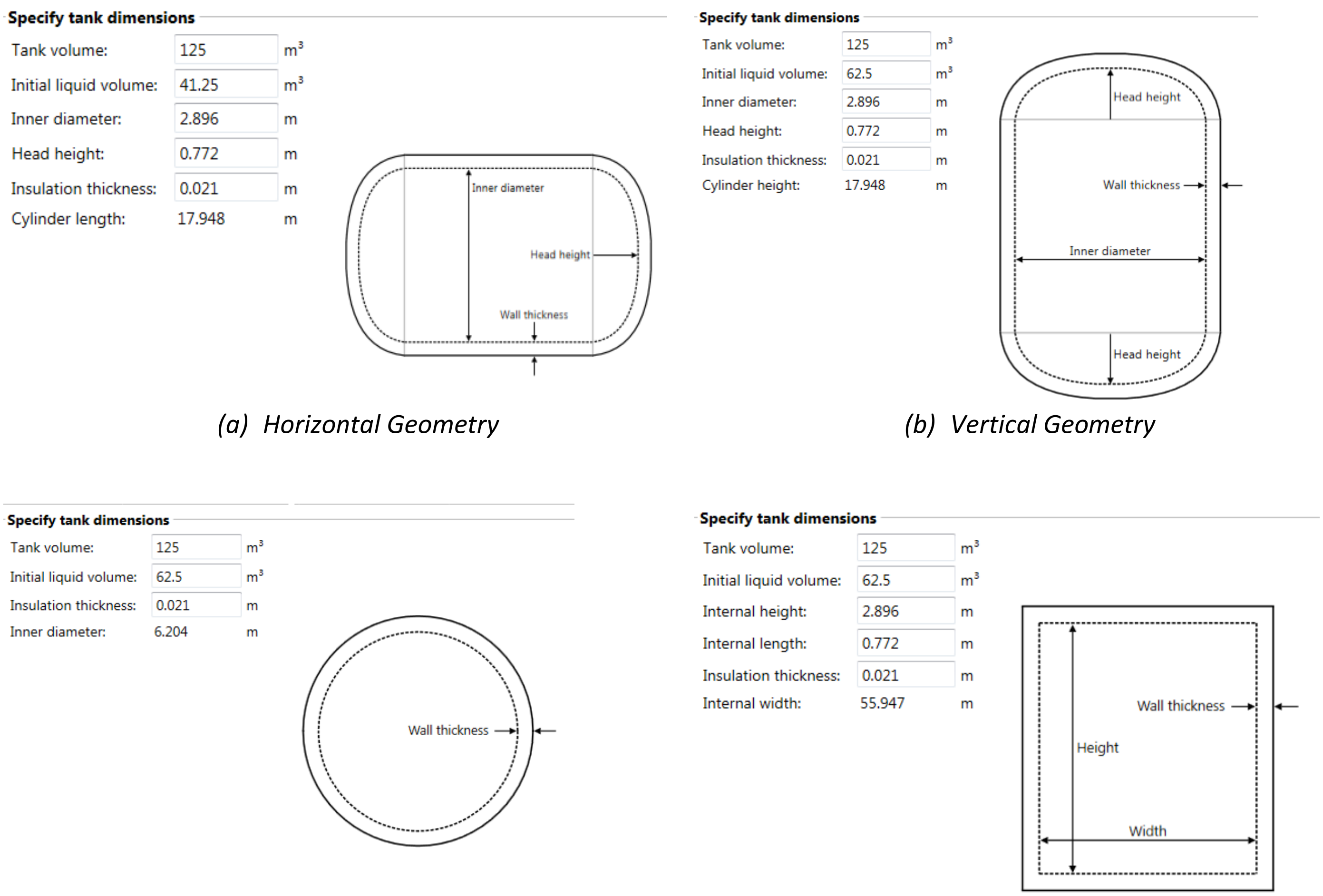
In this work, a 125 m^3 LH_2 tank with was subjected to various relief pressure to calculate the change in volume of LH_2 over time. For this investigation, the relief pressure was initially set to 111 kPa at 50% of the filled volume of LH_2 as shown in Figure 3. This model doesn't consider the insulation in the energy balance [22]. The heat transfer coefficient between vapor and liquid was selected because it best matched the vapor temperature information provided by Petitpas [19]. It can be observed from the Figure 3 that as the pressure was reduced from 111 kPa to 10 kPa, the loss in the reduction of the LH_2 is significant. For the 111 kPa volume is reduced from 62.5 m^3 to 45.5 m^3 for the Horizontal shape of tank. For the vertical this loss was observed from 62.5 m^3 to 47 m^3. For the spherical this loss was observed from 62.5 m^3 to 46 m^3. Last, for the cuboid this loss was observed from 62.5 m^3 to 40.6 m^3. Therefore, it can be observed from the Figure 3 that the loss in the LH_2 is higher around 34% for the cuboid and lower around 22% for the spherical shape of the tank. Therefore, the spherical shape of the tank is more suitable for the LH_2 storage in comparison to the Horizontal, Vertical and Cuboid. The resulting simulation is in good agreement with the literature [13].

3.2 Effect of storage volume on liquid volume reduction for various tank geometries

Similarly, a 125 m^3 LH_2 tank with was subjected to various volume of LH_2 in tank to measure the loss in LH_2 volume over time at same relief pressure. For this parametric study, the relief pressure was set to 111 kPa at 50% of the filled volume of LH_2 as shown in Figure 4. It can be observed from the Figure 4 that as the storage volume capacity was increased from 50% to 90%, the loss in the reduction of the LH_2 is minimal. For the horizontal tank by increasing volume from 62.5 m^3 to 112.5 m^3, reduction is volume is 5.73 m^3 and 5.42 m^3. Similarly, For the vertical tank by increasing volume from 62.5 m^3 to 112.5 m^3, reduction in volume is 4.30 m^3 and 6.20 m^3. For the spherical tank by increasing volume from 62.5 m^3 to 112.5 m^3, reduction in volume is 3.70 m^3 and 4.20 m^3. Lastly, For the cuboid tank by increasing volume from 62.5 m^3 to 112.5 m^3, reduction in volume is 11.60 m^3 and 14.01 m^3. Hence, it can be observed from the Figure 4 that thought the loss is minimal but the loss in the LH_2 is higher for the cuboid and lower for the spherical shape of the tank. Therefore, the spherical shape of the tank is more suitable also in this perspective than Horizontal, Vertical and Cuboid.

4. CONCLUSION

A validated simulation tool, BoilFAST, has been used in this research to estimate the boil-off loss from LH_2 storage tanks. The effect of various tank geometries and relief pressure on boil-off losses for liquid hydrogen were analyzed and also the effect of storage volume of LH_2 in the tanks was taken into consideration. Results showed that the effect of relief pressure on the evaporation of LH_2 is very high. However, the effect of the filled volume of LH_2 in the storage tank on the evaporation of LH_2 is minimal as the volume is reduced only by less than 5% for all tank shapes. Overall, for various tank geometries, spherical shape showed minimum evaporation losses compared to other tank geometries. The results presented herein can serve as a reference for future design and analysis of hydrogen storage and transportation.



(a) Horizontal Geometry *(b) Vertical Geometry*

(c) Spherical Geometry *(d) Cuboid Geometry*

Fig. 1 Model development with various geometries

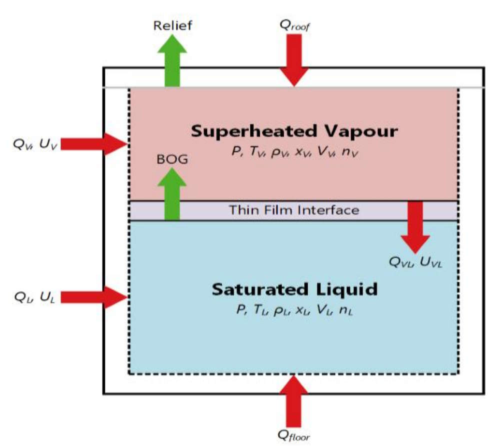


Fig. 2 Graphical representation of the SHV model [9]

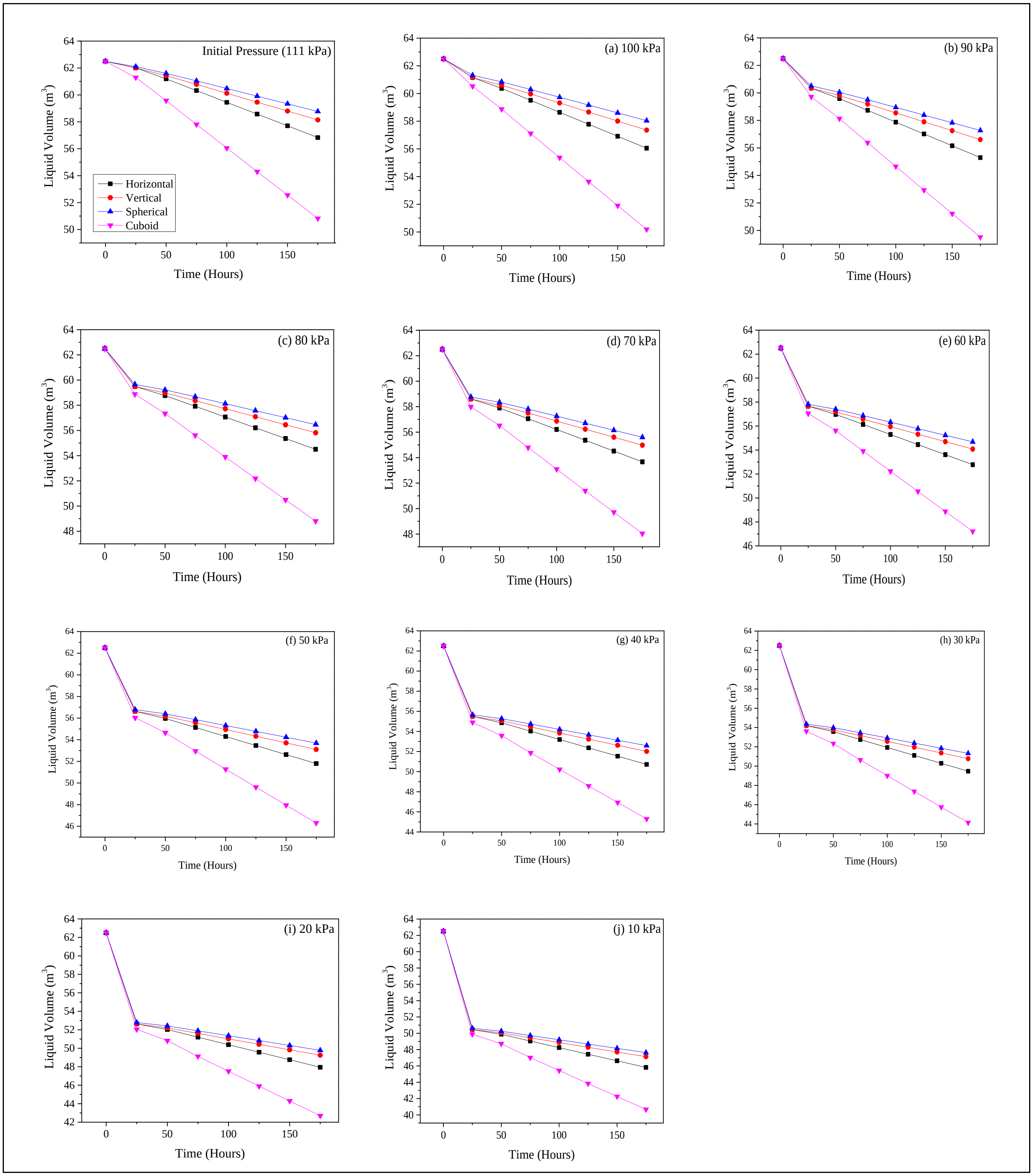


Fig. 3 Effect of relief pressure on LH_2 volume reduction for various tank geometries

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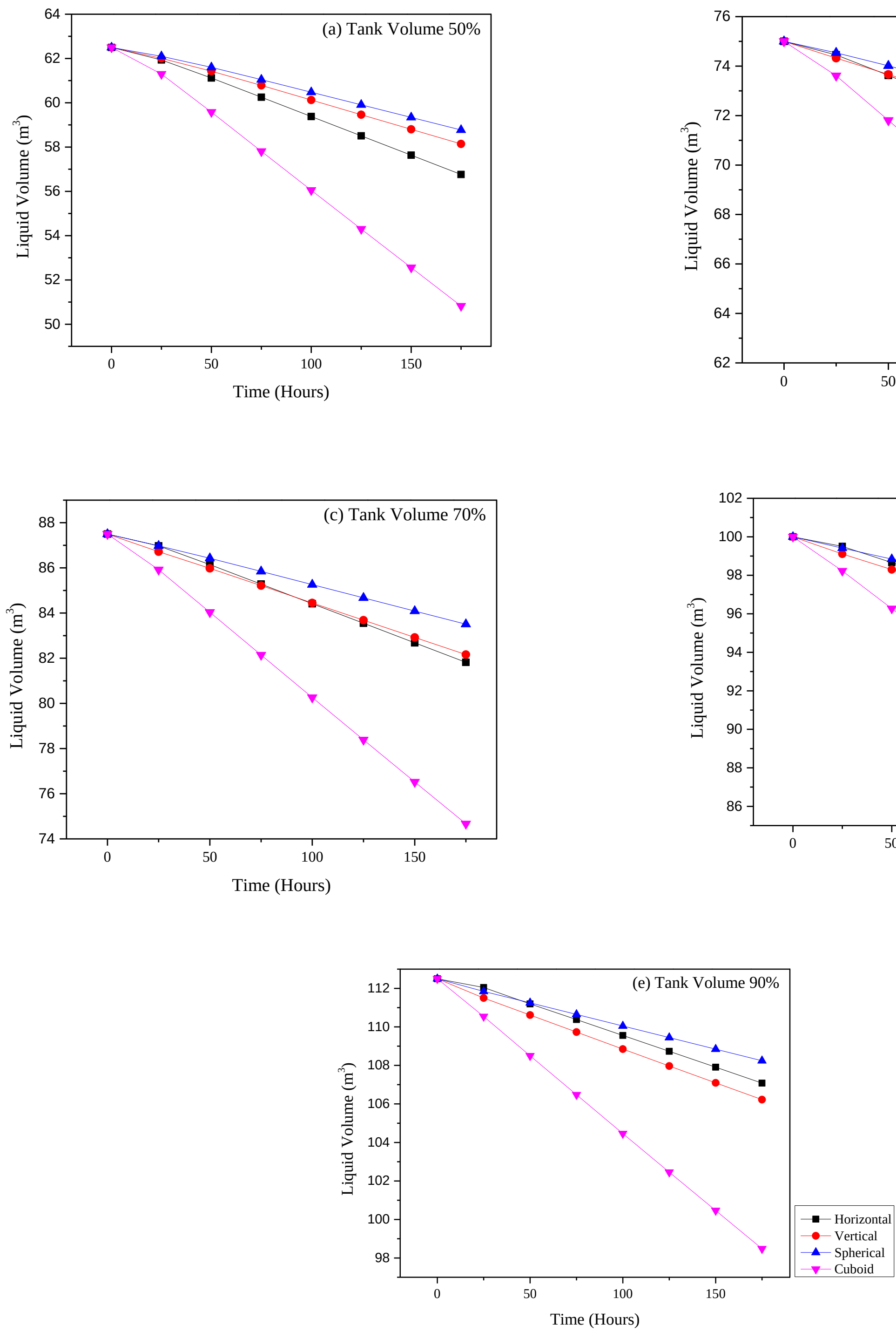

Fig. 4 Effect of storage volume of tank on liquid volume reduction for various tank geometries

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