COMPARISON OF SOLUTIONS FOR A LIQUID POOL SPREADING MODEL WITH CONTINUOUS AND INSTANTANEOUS SPILLS

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ABSTRACT

In this study, a solution for a liquid pool spreading model with a continuous spill is compared with that for a liquid pool spreading model with an instantaneous spill under the same total release volume. As reducing spill time in completely releasing liquid from a tank, it is evaluated whether the solution for a continuous spill approaches to that for an instantaneous spill or not. Also, effects of the viscous term in the liquid pool spreading model with continuous and instantaneous spills on the liquid pool spreading behavior are investigated.

1.0 INTRODUCTION

Liquefied gaseous fuels as energy sources play an important role in the world energy economy. Since the 1970s, liquefied natural gas (LNG) and liquefied petroleum gas (LPG) are being transported in large amounts around the world. Still on a much smaller scale is the use of liquid hydrogen (LH_2) at present, but this may change in the future with the increasing application of hydrogen as a clean fuel in the energy market. With the wide use of cryogenic liquids, however, questions arise concerning their safe storage, transportation, and application. Probabilistic risk analysis helps to identify and classify conceivable accident scenarios covering the whole path from the release of cryogenic liquids via propagation of the evolving gas cloud and its potential explosion, to an assessment of the consequences for the environment [1]. For this, the study of liquid pool spreading has an essential role in risk assessment to quantify the risks of cryogenic liquids, such as LNG and liquefied hydrogen because the spread of such liquids is the first step in the development of many accident sequences that result in a major hazard [2]. Many numerical simulations have been performed for several model equations that govern pool spread. Various types of governing equations are available and range from a simple physical model to the full Navier-Stokes equation [3]. One such model is the model of shallow layer equations [4-7]. The simplest mathematical model, which can be called as the simple physical model [8] considers pool spread as the change in the pool radius and height with time. In 2004, the Federal Energy Regulatory Commission (FERC) contracted with ABS consulting to identify appropriate consequence analysis methods for estimating flammable vapor and thermal radiation hazard distances for potential releases of LNG from tank ships during transit and while at berth [9]. In this study, solutions for a liquid pool spreading model with continuous and instantaneous spills are discussed based on the model used in the FERC's report. The effects of the spill time on the liquid pool volume and radius are investigated for the continuous spill. In addition, as reducing spill time in completely releasing liquid from a tank, it is evaluated whether the solution for a continuous spill approaches to that for an instantaneous spill or not. Also, effects of the viscous term in the liquid pool spreading model with continuous and instantaneous spills on the liquid pool spreading behavior are investigated.

2.0 MODEL DESCRIPTION

The FERC consequence analysis models compute the rate of release from a hole in a containment vessel, the subsequent spreading of the released liquid and the evaporation of the liquid.

2.1 Mass Balance in the Spreading Pool

First of all, let us consider mass balance in the spreading pool. Liquid is supplied from a tank to the pool and liquid is also removed from the pool to the environment due to vaporization by conduction heat transfer from the substrate surface to the pool, convection heat transfer from the environment to the pool, and/or heat transfer from the flame to the pool if the pool is ignited. In this paper, it is assumed that there exists the only heat transfer from the flame to the pool. For a burning LNG Pool, a constant heat flux of 143 KW/m^2 ($m_b = 0.282$ kg/m^{2}s) is used. Eq. (1) is an equation for mass balance in the spreading pool.

$$\frac{dV}{dt} = Q - \frac{(\pi r^2) m_b}{\rho_l} \tag{1}$$

where V is the pool volume (m^3), Q is release rate from a tank (m^3/s), r is the pool radius (m) and m_b is the burning rate (kg/m^{2}s), respectively. The first term of the right hand side in Eq. (1) means supplied liquid from a tank and the second term of the right hand side in Eq. (1) means vaporization rate from the pool to the environment. In this paper, the cross-section of the pool is assumed as a circle. Therefore, the cross-sectional area of the pool is determined as πr^2.

2.2 Liquid Pool Spreading Model

The spreading of LNG on a water surface follows the technique developed by van den Bosch and Weterings [10]. The governing equation is

$$\frac{d^2 r}{dt^2} = \frac{du}{dt} = \frac{4 g_r \Phi h}{r} - C_f \tag{2}$$

where r is the pool radius (m), u is the spreading velocity (m/s), t is the time (s), g_r is $g(\rho_w - \rho_l)/\rho_w$ (m/s^2), ρ_w is the density of liquid substrate (kg/m^3), Φ is the coefficient that is a function of h_f/h, h_f is the pool height at leading edge (m), h is the mean pool height (m) and C_f is the frictional resistance force (m/s^2). The first term of the right hand side in Eq. (2) is the gravity driving term and the second term of the right hand side in Eq. (2) is the friction resistance term. Φ is called as the shape factor because it is related to the pool shape. The shape factor is defined as follows.

$$\Phi(s) = \begin{cases} 1 - s & \text{if } s < 2 \\ -s^2/4 & \text{if } s > 2 \end{cases} \tag{3}$$

where s is defined as h_f/h. The frictional resistance (C_f) models ground resistance and can be presented as appropriate forms for both laminar and turbulent flow. The details for the frictional resistance are described in [10]. If we assume that the viscous effect is negligible, the frictional resistance can be deleted in Eq. (2).

3.0 RESULTS AND DISCUSSION

Eqs. (1) and (2) can be numerically solved. Total released volume is assumed to be constant at π m^3 in this paper. We can consider two kinds of spills: continuous and instantaneous spills. The continuous spill means that an LNG is discharged in a continuous manner over a period of time. On the contrary, a spill in which the time required for the liquid to leave the tank is much smaller than the time for complete vaporization is referred to as instantaneous spills. In this paper, liquid pool spreading phenomena with continuous and instantaneous spills are compared numerically. In addition, effects of frictional resistance (C_f) on the liquid pool spreading are discussed.

3.1 Continuous Spill

In this paper, four cases which have different spill time (τ) are discussed at the same released volume as shown in Fig. 1.

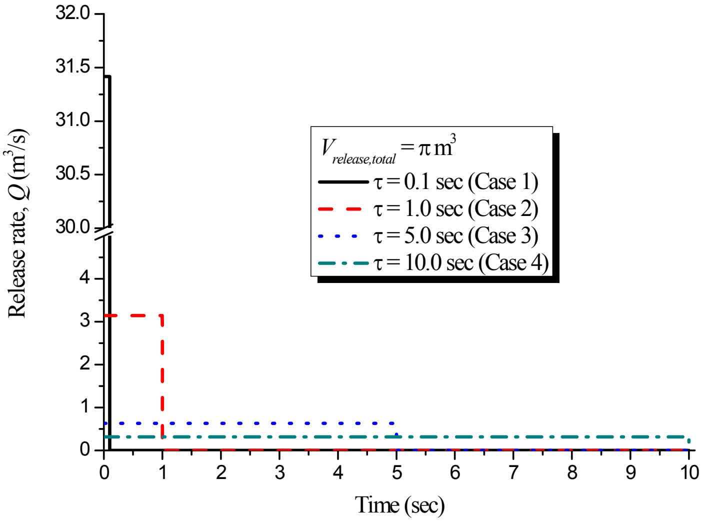

Figure 1. Release rates for continuous spill

As varying spill time for continuous spill, liquid pool volume is changed with time as shown in Fig. 2. During the liquid discharges from the tank, liquid pool volume increases. For case 1, it is hard to see increasing pool volume because of very short spill time. After the end of the spill from the tank, however, the liquid pool volume decreases because of no more liquid spill from the tank. There exists the only vaporization from the liquid pool. So, the liquid volume decreases.

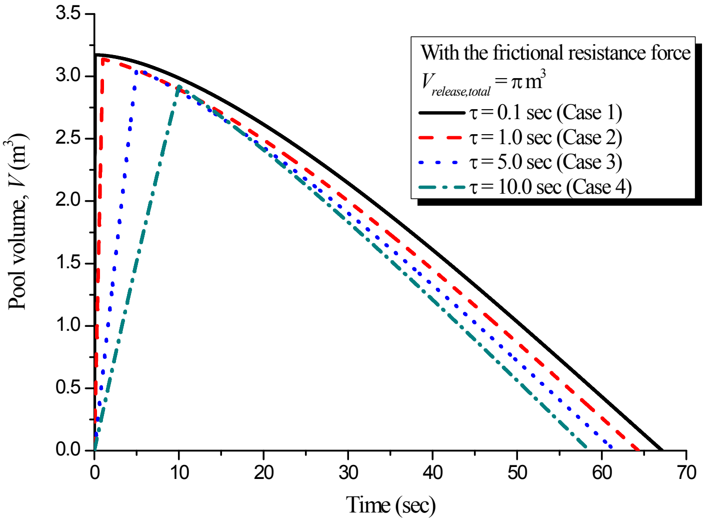

Figure 2. Pool volume for continuous spill in liquid pool spreading model
with the frictional resistance term

Fig. 3 shows the liquid pool radius trend according to the spill time. During the liquid discharges from the tank, the pool radius increases rapidly. After the end of the spill from the tank, the pool radius increases slowly. At the end of liquid discharge from the tank, the pool radius for case 4 (the largest spill time) is largest. Table 1 shows the vaporization time for the continuous spill in liquid pool spreading model with the frictional resistance term. As shown in Table 1, the vaporization time decreases as the spill time increases. The reason for this tendency can be explained by using the pool radius tendency. As shown in Eq. (1), the vaporization is related to the surface area of the liquid pool. So, as the pool radius increases, the vaporization increases. Therefore, the vaporization time decreases as the pool radius increases.

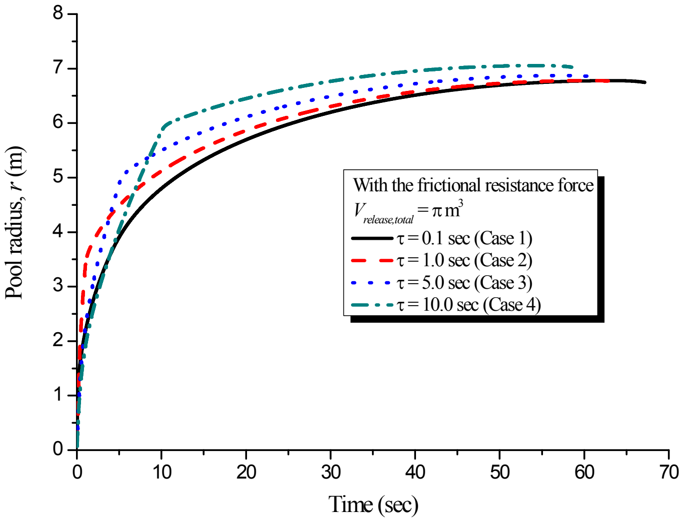

Figure 3. Pool radius for continuous spill in liquid pool spreading model with the frictional resistance term

Table 1. Vaporization time for continuous spill in liquid pool spreading model

Spill time	Vaporization time	
	with the frictional force	without the frictional force
0.1 sec (Case 1)	67.1 sec	3.4 sec
1.0 sec (Case 2)	64.3 sec	4.6 sec
5.0 sec (Case 3)	61.6 sec	5.4 sec
10.0 sec (Case 4)	58.6 sec	5.9 sec

Figs. 4 and 5 show the pool volume and radius for continuous spill in liquid pool spreading model without the frictional term. Table 1 shows the comparison of the vaporization time with and without the frictional force. The pool volume trend for continuous spill in liquid pool without the frictional term is different from that for continuous spill in liquid pool with the frictional term. The vaporization time for the cases with the frictional term is almost 1 min. However, the vaporization time for the cases without the frictional term is the order of 1 sec. For the case 4, the vaporization time is smaller than the spill time. This means that the vaporization is complete before the liquid is totally discharged from the tank. In addition, although the vaporization time decreases as the spill time increases in the cases with friction, the vaporization time increases as the spill time increases in the cases without friction. This can be explained by using the pool radius trend. In Fig. 5, the pool radius for the cases without the frictional term is larger than that for the cases with the frictional term. This is because it is easy for liquid pool to spread due to no friction. So, the pool radius is large. As mentioned before, the vaporization rate increases as the pool radius increases. Therefore, the vaporization time for the cases without the frictional term is smaller than that for the cases with the frictional term.

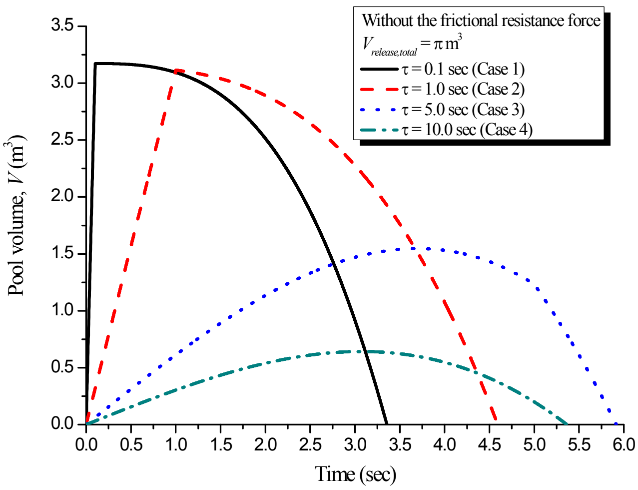

Figure 4. Pool volume for continuous spill in liquid pool spreading model without the frictional resistance term

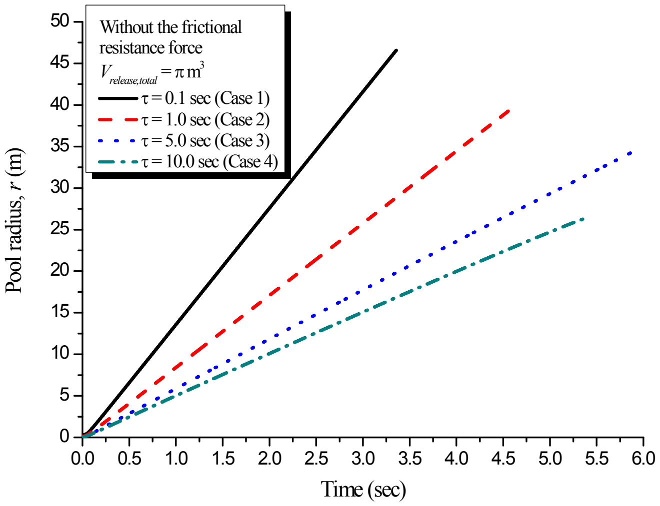

Figure 5. Pool radius for continuous spill in liquid pool spreading model without the frictional resistance term

3.2 Instantaneous Spill

In this paper, the instantaneous spill configuration is determined as shown in Fig. 6. When a liquid tank is suddenly ruptured, it can be assumed that the liquid starts to spread out from the cylindrical liquid pool as shown in Fig. 6. Therefore, the initial conditions for the instantaneous spill can be expressed as

$$V(0) = \pi\, m^3,\ r(0) = r_i,\ h(0) = \frac{V(0)}{\pi\left[r(0)\right]^2} = \frac{1}{r_i^2} \qquad (4)$$

In this paper, the effect of the initial pool radius on the liquid pool spreading is discussed. Also, the liquid pool spreading phenomena for the instantaneous spill is compared to that for the continuous spill. Figs. 7 and 8 show the pool volume and radius for the liquid pool spreading model with the frictional force term for continuous and instantaneous spills. The initial pool radius for the instantaneous spill does not affect the pool spreading phenomena as shown in Figs. 7 and 8.

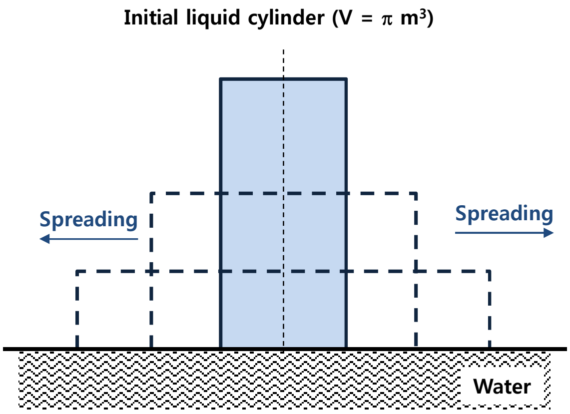

Figure 6. The description of the instantaneous spill

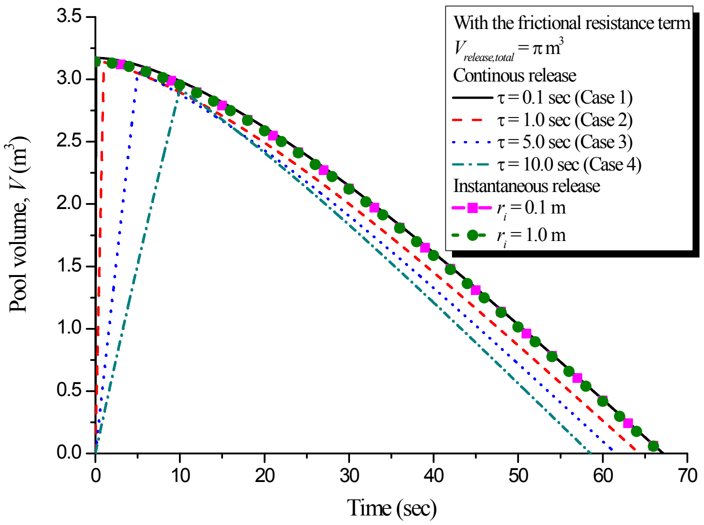

Figure 7. Pool volume for instantaneous spill in liquid pool spreading model with the frictional resistance term

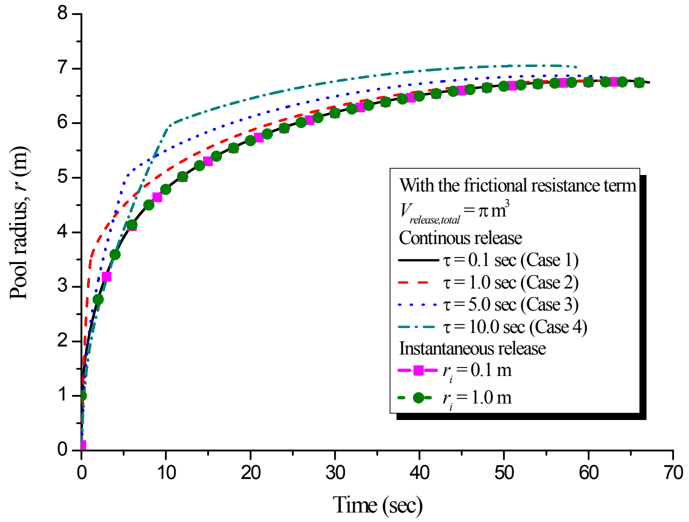

Figure 8. Pool radius for instantaneous spill in liquid pool spreading model with the frictional resistance term

In addition, as the spill time decreases, the pool volume and radius graphs according to time for the liquid pool spreading model with the frictional force for the instantaneous spill approaches to those for the liquid pool spreading model with the frictional force for the continuous spill. In other words, as reducing spill time in the model with the frictional force for the continuous spill, the solution for a continuous spill approaches to that for an instantaneous spill.

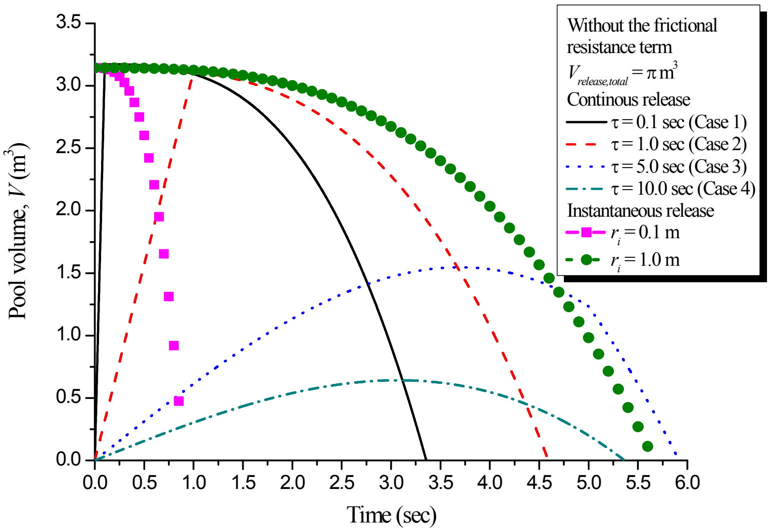

Figure 9. Pool volume for instantaneous spill in liquid pool spreading model without the frictional resistance term

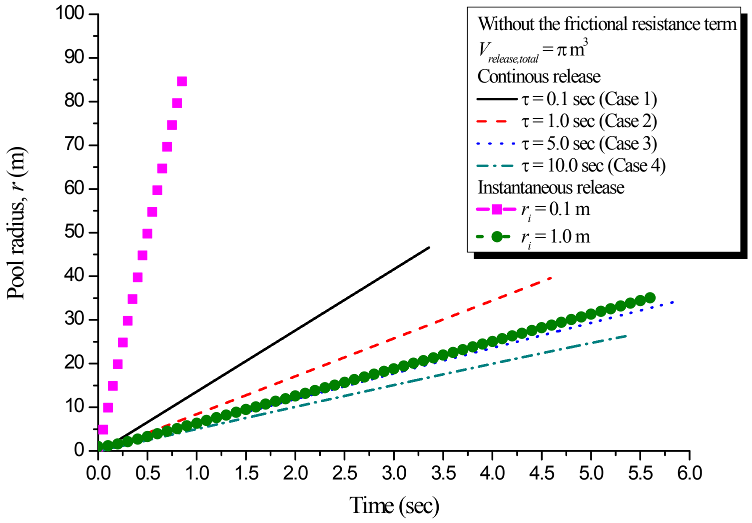

Figure 10. Pool radius for instantaneous spill in liquid pool spreading model without the frictional resistance term

Figs. 9 and 10 show the pool volume and radius for the liquid pool spreading model without the frictional force term for continuous and instantaneous spills. Contrary to the instantaneous spill cases with the frictional force, the pool volume and radius for the instantaneous spill are totally different from those for the continuous spill. When the initial pool radius for the instantaneous spill is small, the liquid from the pool is rapidly spread and vaporized. When the initial pool radius for the instantaneous spill is large, the liquid from the pool is slowly spread and vaporized. This means that the initial pool radius is dominant in the gravitational driving term in the liquid spreading equations without the frictional resistance force.

4.0 CONCLUSION

In this study, solutions for a liquid pool spreading model with continuous and instantaneous spills are discussed based on the model used in the FERC's report. The effects of the spill time on the liquid pool volume and radius are investigated for the continuous spill. For the continuous spill with the frictional resistance force in the liquid pool spreading model, the vaporization time decreases as the spill time increases. On the other hand, for the continuous spill without the frictional resistance force in the liquid pool spreading model, the vaporization time increases as the spill time increases. These phenomena are deeply related to the pool radius. In addition, the effects of the initial pool radius for the instantaneous spill in the liquid pool spreading model are discussed. For the case with the frictional resistance force in the liquid pool spreading model, as reducing spill time in the model with the frictional force for the continuous spill, the solution for a continuous spill approaches to that for an instantaneous spill. Contrary to the instantaneous spill cases with the frictional force, the pool volume and radius for the instantaneous spill without the frictional force are totally different from those for the continuous spill without the frictional force.

ACKNOWLEDGEMENT

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