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A new categorization of release models using a semi-analytic solution

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ABSTRACT

The spread of cryogenic liquid due to a limited period of release is investigated for the first time to clarify the unclear conventional concept regarding two release types: continuous and instantaneous release. The physical phenomenon is described by equations involving the volume, radius and height of the liquid pool, and there are three governing parameters: the evaporation rate per unit area, a release time, and a spill volume. As a result of the perturbation solutions, the combined model, which consists of the continuous model and the subsequent instantaneous model, is necessary for a large spill source rate, whereas the continuous model is only required for a small spill source rate. This combined release model is more realistic than the instantaneous release model, and it is shown that the combined model and the continuous model are clearly distinguished in the coordinate system of the release time and the spill volume using the analytical feature of the perturbation solution.

1. Introduction

Because the release of flammable materials in a petro-chemical plant likely leads to a fire or an explosion, a study of the release and spread of such materials is essential for the quantitative risk assessment and risk-based inspection of these plants. The release of materials can be classified into vapor phase or liquid phase according to the phase of the material, and the spread of a released liquid is more complicated than that of a released gas because evaporation occurs during the spread of a liquid. The present work focuses on the release and spread of a cryogenic liquid, such as LNG and LH_2, which is continued work from the previous results (Kim et al., 2011, 2012) of the authors.

Release can be defined as a loss of containment (American Petroleum Institute, 2008) within the components or equipment of several plants; therefore, release corresponds to the case that some materials contained in the equipment escape and spread into atmosphere. Spurted liquids can spread via vaporization from the ground or water, and various models have been developed to treat the spread. There are three-dimensional models using the full Navier–Stokes equation (Venetsanos and Bartzis, 2005), a shallow-layer model (Stein and Ermak, 1980; Verfondern and Dienhart, 1997, 2007; Brandeis and Kansa, 1983; Brandeis and Ermak, 1983), and a simple physical model (Kim et al., 2011, 2012; Briscoe and Shaw, 1980). The simple physical model describes pool spread in terms of how the pool radius and height evolve in time. In the simple physical model, the shape of the spreading liquid has been assumed to be a circular cylinder; however, in other models this assumption is not necessary. Therefore it can be said that the simple physical model is not as realistic as the other models.

The corresponding equations consist of two ordinary differential equations with respect to time and one algebraic equation. Vaporization can be modeled based on the thermal energy conservation or heat conduction from the surface on which the liquid expands and by neglecting heat radiation; however, the concept of constant evaporation rate per unit area has been used to simplify the evaporation process in most cases.

The aforementioned differential equations used in the spread model require initial conditions that depend on the type of release. Release has been generally categorized as instantaneous release and continuous release. According to API RP 581 (American Petroleum Institute, 2008), instantaneous release occurs so rapidly that the fluid disperses as a single cloud or pool, whereas continuous release occurs over a longer period of time. Therefore, it can be said that instantaneous release occurs due to an abrupt destruction of vessels or a similar situation. The case in which the fluid flows continuously from a small hole in damaged equipment can be modeled as a continuous release. Mathematically, in the

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spread model of instantaneous release, the parameters regarding the initial shape of the released liquid are given when the time is zero; however, all of the parameters are zero at that time in the case of a continuous release. The spread model of continuously-released-fluid requires a period of release time that is not necessary in the spread model of an instantaneously-released- fluid. The continuous model approaches the instantaneous one as the period of release time becomes infinitesimal with a fixed amount of spilled volume, similar to the delta function in mathematics; however, such a definition is unrealistic because there exists a finite period of release time no matter how rapid the instantaneous release is. In API RP 581, the instantaneous release corresponds to the case where a total released mass of liquid is greater than 4536 kg, or a release time is less than 180 s. When a hole size is less than or equal to 6.35 mm, the continuous release is unconditionally assumed.

To apply the above concept to engineering design, we require a clear distinction between the two categories because the release models affect the next procedures in the quantitative risk assessment, such as the dispersion analysis that treats the movement of a vapor cloud. The conventional classification for the release types is unrealistic, and the above quantitative criterion also seems arbitrary. In the present work, the spread of cryogenic liquid due to a limited period of release is investigated for the first time to clarify the unclear conventional concept regarding the two release types.

2. Governing equations

There are several forces during the spread of liquid. Gravity is only important for the spread of cryogenic liquid because cryogenic liquid vaporizes extremely quickly. The governing equations can be obtained with a slight modification of the previous work (Kim et al., 2012) of the authors.

$$\frac{dR}{dT} = \sqrt{\alpha H} \tag{1}$$

where R – pool radius, m; T – time, s; α – 2gΔ, m/s^2; g – gravity, m/s^2; Δ – 1 for spills on the ground or $1-\rho/\rho_w$ for spills on water; ρ – density of liquid, kg/m^3; ρ_w – density of water, kg/m^3; H – pool height, m.

$$\frac{dV}{dT} = -E\pi R^2 + \beta; \quad \beta = \frac{Q}{T_d} \; for \; 0 \le T \le T_d, \quad \beta = 0 \; for \; T > T_d \tag{2}$$

where V – pool volume, m^3; E – evaporation rate per unit area, m/s; β – spill source rate, m^3/s; Q – spill volume, m^3; T_d – period of release time, s. To complete the model, the following algebraic equation is required:

$$H = \frac{V}{\pi R^2} \tag{3}$$

In the present work, because the liquid is continuously released from storage, the following initial conditions can be used:

$$V(0) = 0, \quad R(0) = 0, \quad H(0) = 0 \tag{4}$$

Only the spill source rate in Equation (2) is modified to represent the limited period of release compared to the previous work (Kim et al., 2012) of the authors.

From Equations (1)–(3), it is understood that the evaporation rate per unit area, E, the spill volume, Q, and the period of release time, T_d, govern the model equations for spread on the ground. For simplicity, the spread on the ground is considered in the present study. To make the governing equations dimensionless, the following variables are introduced:

$$v = \frac{V}{\pi L^3}, \quad r = \frac{R}{L}, \quad h = \frac{H}{L} \quad t = \frac{T}{\tau} \tag{5}$$

where v – dimensionless volume; r – dimensionless radius; h – dimensionless height; t – dimensionless time; and τ and L are the characteristic time and length scales, respectively, defined as

$$\tau = T_d, \quad L = \alpha T_d^2 \tag{6}$$

Using the dimensionless variables in Equation (5), the following non-dimensional governing equations are derived:

$$\frac{dv}{dt} = -\varepsilon r^2 + \beta_*; \quad \beta_* = \frac{Q}{\pi\alpha^3 T_d^6} = \frac{Q}{\pi L^3} \; for \; 0 \le t \le 1, \quad \beta_* = 0 \; for \; t > 1 \tag{7}$$

where ε – dimensionless evaporation rate, E/α T$_d$.

$$\frac{dr}{dt} = \sqrt{h} \tag{8}$$

$$h = \frac{v}{r^2} \tag{9}$$

The initial conditions become

$$v(0) = 0, \quad r(0) = 0, \quad h(0) = 0 \tag{10}$$

From Equations (7)–(10), it can be seen that the dimensionless number,ε, corresponding to the dimensionless evaporation rate and the dimensionless spill source rate, β_*, are the parameters that can control the non-dimensional governing equations.

Using Equation (9), Equation (8) is rewritten as follows:

$$\frac{dr^2}{dt} = 2\sqrt{v} \tag{11}$$

Using Equation (11), Equation (7) is decoupled into

$$\frac{d^2 v}{dt^2} + 2\varepsilon\sqrt{v} = 0 \tag{12}$$

The initial conditions become

$$v(0) = 0, \quad v'(0) = \beta_* \tag{13}$$

Solving the decoupled governing equation is quite simple compared to the previous results (Kim et al., 2012).

3. Perturbation solutions

The evaporation rate per unit area of LH_2 on a paraffin wax surface (Verfondern and Dienhart, 2007) varies from approximately 4.23×10^{-4} m/s to approximately 12.7×10^{-4} m/s. Therefore, the dimensionless evaporation rate, ε, can be naturally chosen as the perturbation parameter. The perturbation solutions can then be expressed in the following forms:

$$v = v_0 + \varepsilon v_1 + \varepsilon^2 v_2 + \ldots \tag{14}$$

where v_0 – zeroth order term, v_1 – 1st order term, v_2 – 2nd order term.

Substituting Equation (14) into Equation (12) and equating the coefficients of up to O(ε^4) on both sides, we obtain