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Validation of numerical models for cryogenic-liquid pool spreading and vaporization on solid ground

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ABSTRACT

Accidental spills of cryogenic liquids create vaporizing pools spreading over the ground that can result in pool fires, explosions, or hazardous vapor clouds. Various integral models have been developed for simulating the spread and vaporization of cryogenic liquid pools. The spreading law of a constant Froude number (CFN[1]), which was originally derived for floating pools on water, has been assumed to be accurate for pools spreading on land in some models. This assumption is controversial and has not been validated. In addition, although the gas accumulation over spreading pools (GASP[2]) model has been well developed, further validation is required. An attempt was made to fill these gaps. This study aimed to propose and validate numerical models, *i.e.*, a model incorporating the spreading law of a constant Froude number (CFN model) and simplified GASP models for indoor spills. The results were compared to the experimental data of cryogenic liquid pools spreading on solid ground. A good agreement between the predictions obtained from the simplified GASP models and the measured data was shown. Conversely, the CFN model yielded unrealistic results. Then, a modified CFN model was proposed and validated. The validations suggested that the modified CFN and simplified GASP models successfully simulated the behavior of cryogenic liquid pools spreading on solid ground.

1. Introduction

The prediction of possible hazards associated with accidental spills of cryogenic liquids is required because the liquids are commonly used and most are flammable or toxic. Thus, the spreading and vaporization of cryogenic liquid pools should be thoroughly investigated. The liquid pool vigorously boils during spreading in response to the large difference between the ground temperature and the boiling point of the liquid. Therefore, a vapor cloud forms quickly and disperses, which may cause an explosion or a pool fire [1].

Researchers have attempted to experimentally and numerically investigate the spread and vaporization of cryogenic liquids spilled on both water [2–4] and solid surfaces [5–10]. However, there is a shortage of suitable experimental data for validating the models [11]. Batt [11] broadly categorized the spill models into three approaches, such as integral, shallow layer, and computational fluid dynamics (CFD). The integral models [12–15], which are the simplest models, consider the depth of the pool to be an average value calculated over the pool area and assume the pool is circular. Because these models describe the pool by ordinary differential equations, they require less calculation effort than the other models. For shallow-layer models [16,17], the spill is described by a system of two-dimensional partial differential equations. The CFD approach [4,18,19] involves the solution of three-dimensional turbulent flow equations. In safety studies and hazard assessments, integral models are employed to provide source information, and the CFD approach is then used to model the subsequent gas dispersion [11]. To evaluate the accuracy of the models, validations of the proposed models against the experimental data are required. Thyer [20] reviewed the availability and utility of the experimental data on spreading and vaporization of cryogenic liquid spills for validating computer software.

The governing equation for pools spreading in a gravity-front-resistance regime is described as the law of spreading at a constant Froude number [21]. Although the spreading law was originally derived for floating pools spreading on water, it was assumed to be true for pools spreading on land [22]. Webber [22] mentioned

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[1] Constant Froude number.
[2] Gas accumulation over spreading pools.

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Nomenclature

A_{top}	liquid pool area, m^2
C_F	frictional resistance term, m/s^2
$C_{p,L}$	specific heat of the liquid, J/(kg K)
E	vaporization velocity, m/s
$E_{empirical}$	empirical vaporization velocity, m/s
$E_{theoretical}$	theoretical vaporization velocity, m/s
g	acceleration owing to gravity, m/s^2
g'	$= g(\rho_w - \rho)/\rho_w$, m/s^2
$G(e^{\chi Sc})$	function given in Ref. [25]
h	heat transfer coefficient, $W/(m^2 K)$
H	pool depth, m
H_{min}	minimum pool depth, m
k	thermal conductivity of the ground, W/(m K)
K	Froude number
L	latent heat of vaporization of the liquid, J/kg
m	pool mass, kg
$m_{m,V}$	mole fraction of vapor above liquid pool surface
n	wind profile index
$P_V(T)$	vapor pressure above the pool, N/m^2
q	heat flux to the pool, W/m^2
q_{cond}	heat flux into the pool owing to heat conduction from the ground, W/m^2
q_{conv}	heat flux into the pool owing to heat convection from the air, W/m^2
r	pool radius, m
r'	pool radius, m
R	gas constant, J/(mol K)
s	depth profile shape factor
Sc_t	turbulent Schmidt number
t	time from release, s
t'	arrival time at pool radius r', s
T	liquid pool temperature, K
T_a	ambient temperature, K
T_B	boiling point of the liquid, K
T_{q_s}	liquid source temperature, K
u	radial liquid velocity at the edge, m/s
u_{*p}	atmospheric friction velocity above the pool, m/s
α	thermal diffusivity of the ground, m^2/s
β	mass spill rate, kg/s
κ	von Karman constant
μ_i	molecular weight liquid, kg/mol
ν	kinematic viscosity of the liquid, m^2/s
ρ	cryogenic liquid density, kg/m^3
ρ_w	water density, kg/m^3
$\Phi(s)$	function of s

a recent study employing this assumption and emphasized that the assumption was not accurate for pools spreading on land because different physical mechanisms control the spread of pools on the two different surfaces. However, no experimental confirmation was presented in the study. In this study, an attempt was made to address this gap.

The gas accumulation over spreading pools (GASP) is an accurate integral model for modeling the spread and vaporization of liquid hydrogen and liquefied natural gas. Although the model has been well developed, it is complicated, not easy to solve, and unable to consider no-wind conditions. Moreover, further validation is required in the area of heat transfer, pool spreading, and vaporization to better understand its capabilities. In the latest model validation for liquid hydrogen spills, there were significant discrepancies between the experiment results and model predictions [11]. Generally, the experimental data for a spreading and vaporizing pool are rare. Most of the validation tests for vaporization were performed on non-spreading pools. For spreading pools, the measurement of pool mass has not been performed, and the pool radius was the only validation parameter [11].

In this study, the spread and vaporization of cryogenic liquid pools were numerically investigated based on integral models, *i.e.*, a model incorporating the constant Froude number law (CFN model) and two simplified GASP models for indoor spills. Based on the experimental data obtained from a previous study, the predictions provided by the models were validated to examine whether the CFN model for pool spreading on a flat, solid surface was accurate and whether the simplified GASP models accurately predicted the pool behaviors. In previous studies [1,23], the authors conducted laboratory-scale experiments involving spreading pools of liquid nitrogen on concrete to measure the time-dependent pool mass and pool radius and to evaluate the vaporization velocity, *i.e.*, the vaporization mass flux divided by density. In addition, an empirical formula of the vaporization velocity owing to pool boiling for the spreading pool was derived.

2. Materials and methods

2.1. Model details

2.1.1. CFN model

The relationship between gravity and front resistance drives pool spreading on water. It is conventionally known as the CFN law for pool spreading. The spreading law was derived based on an assumption that the hydrostatic pressure difference across the pool front is balanced by a resistance from pushing water out of the way. In addition, this is not justified for pool spreading on solid ground [22]. The model of the CFN for continuous spills is as follows.

The equation of mass conservation is written as

$$\frac{dm}{dt} = \beta - \rho E \pi r^2 \quad (1)$$

where m is the pool mass, and t is the time from the start of the spill. The parameter β is the mass spill rate, and ρ is the liquid density. The parameter E denotes the vaporization velocity, and r is the radius of the pool.

The spreading law of the CFN is written as

$$\frac{dr}{dt} = K\sqrt{g'H} \quad (2)$$

where K is the Froude number, and $g' = g(\rho_w - \rho)/\rho_w$. The parameter g denotes acceleration owing to gravity, and ρ_w is the water density. The parameter H is the pool depth.

Raj and Kalelkar [12] derived a model for spreading pools on water with the regime of pool spread being described as a gravity–inertia regime. The model assumed the positive gravity force to be equal to the negative inertia force. This model was proven to be inaccurate [24]. Briscoe and Shaw [13] adopted this model to describe cryogenic liquid pools vaporizing and spreading on land and water for instantaneous and continuous spills. The same