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Research Paper

# Transient modeling of cryogenic two-phase flow boiling during chill-down process

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## HIGHLIGHTS

- An accurate chill-down model which can be applied to actual fueling is proposed.
- The performances and characteristics of cryogenic pipeline chill-down are obtained.
- A sudden increased disturbance possibly causes safety hazard to the filling transfer.
- The sensible heat of cryogenic gas can be used to reduce propellant consumption.

## ARTICLE INFO

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## ABSTRACT

Accurate predictions of chill-down time and propellant consumption as well as a clear understanding of the performance and characteristics of cryogenic pipeline chill-down are significant for achieving the safe and high-efficiency cryogenic propellants fueling. On the basis of available nitrogen experimental data, detailed mechanism analysis and comprehensive verification are carried out for three characteristic points and four heat transfer regimes respectively, and a group of correlations for cryogenic pipeline chill-down are proposed. Besides, an accurate chill-down model involving intricate interaction of phase change, heat transfer and fluid dynamics is established with quasi-steady state method. To further reveal the unknown mechanism and phenomena of chill-down boiling, flow regime and heat transfer performance at typical moments and wall temperature drop characteristics at typical locations are studied respectively, which provide feasibility for more efficient refueling and arouse concern for potential safety hazard.

## 1. Introduction

Cryogenic fluids, such as liquid hydrogen ($LH_2$), liquid oxygen (LOX), and liquid methane ($CH_4$), have been regarded as the preferred propellants for space launch vehicles around the world because of their advantages of high specific impulse, large thrust and environmentally friendly properties. However, due to the low boiling point characteristics of cryogenic fluids, two-phase flow boiling phenomenon could be easily encountered during the transportation of cryogenic propellants. Hence, accurate and high-efficiency control of the fueling process is indispensable for cryogenic operating systems, such as in-space cryogenic engines, in-space fuel storage depots and ground fueling systems. The process of cooling down pipelines and components below the saturation temperature is defined as cryogenic chill-down. The cryogenic chill-down process is characterized by the violent phase change caused under large temperature difference, the transient heat transfer regimes accompanied by decreasing wall temperature, and the instabilities of pressure and mass flow rate. Thus, unsteady and complicated phenomena make it difficult to grasp the mechanism of two-phase flow and boiling in the cryogenic pipeline chill-down.

A lot of experiments have been carried out to explore the phenomena and performances in the cryogenic chill-down, and some of the experimental details are rigorously reviewed in the assessment paper by Hartwig et al. [1]. According to the influencing factors, cryogenic chill-down experiments could be divided into different categories, namely mass flow rates [2–5], flow directions [6,7], physical properties of cryogens [8,9], chill-down strategies [10,11], pipeline structures [12,13], and so forth. Meanwhile, visual experiments conducted by Velat et al. [2], Jackson et al. [14], Yuan et al. [15], Kawanami et al. [16], Rame et al. [8], and Hartwig et al. [9] showed much valuable information about the two-phase flow patterns. Besides, Jin et al. [17] investigated chill-down process in a 7 m long pipeline and provided

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**Nomenclature**

| | |
|---|---|
| $Bo$ | Boiling number |
| $c_p$ | Specific heat, J/(kg·K) |
| $d$ | Diameter, m |
| $g$ | Acceleration due to gravity, m/s$^2$ |
| $G$ | Mass flux, kg/(m$^2$·s) |
| $h$ | heat transfer coefficient, W/(m$^2$·K) |
| $h_{fg}$ | latent heat of vaporization, J/kg |
| $Ja$ | Jakob number, $c_p(T_{w\text{–}i}$ - $T_{f,sat})/h_{fg}$ |
| $k$ | Thermal conductivity, W/(m·K) |
| $L$ | Length, m |
| $Nu$ | Nusselt number |
| $P$ | Pressure, Pa |
| $Pr$ | Prandtl number |
| $q$ | Heat flux, W/m$^2$ |
| $r$ | Radius, m |
| $Re$ | Reynolds number |
| $t$ | Time, s |
| $T$ | Temperature, K |
| $We$ | Weber number, $G^2d/(\rho\cdot\sigma)$ |
| $x$ | Equilibrium quality |
| $X_{tt}$ | Martinelli parameter |
| $\Delta T_W$ | Wall superheat, $T_W$-$T_{sat}$ |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | Mass quality |
| $\beta$ | Dimensionless property parameter |
| $\rho$ | Density, kg/m$^3$ |
| $\mu$ | Viscosity, Pa·s |
| $\gamma$ | Enthalpy, J/kg |
| $\sigma$ | Surface tension, N/m |
| $\sigma_{SB}$ | Stefan-Boltzmann cocstant |
| $\varepsilon$ | Emissivity |

*Subscripts*

| | |
|---|---|
| $b$ | Buoyancy |
| $cr$ | Critical property |
| $dw$ | Droplet-to-wall |
| $f$ | Fluid |
| $fb$ | Film boiling |
| $g$ | Gas |
| $i$ | Node number in axial direction |
| $in$ | Inner side |
| $j$ | Node number in radial direction |
| $l$ | Liquid |
| $m$ | Time step |
| $NB$ | Nucleate boiling |
| $out$ | Outside |
| $s$ | Solid |
| $sat$ | Saturation property |
| $sub$ | Subcooled property |
| $sp$ | Single phase |
| $tb$ | Transition boiling |
| $tc$ | Turbulent convection |
| $vac$ | Vacuum |
| $W$ | Wall |
| $CHF$ | Critical heat flux |
| $MFB$ | Minimum film boiling |
| $ONB$ | Onset of nucleate boiling |

abundant chill-down data. Driven by the development of aerospace technology, the cryogenic chill-down under microgravity has become the focus of attention in recent years. Westbye et al. [18] found that the heat flux under microgravity reduced to 20–50% of the heat flux in ground environment. Visual results from experiments reported by Antar and Collins [19,20] showed that the continuous liquid column was surrounded by a thicker annular gas film in low gravity conditions, which agreed with the results from Yuan et al. [21]. However, Kawanami et al. [22], whose conclusions were opposite to others, pointed out that the chill-down heat flux increased by 20% in microgravity and the microgravity condition was obtained through a drop tower. Experiments by Celata et al. [23] identified that mass flow rates had a great influence on flow pattern and droplet morphology under microgravity conditions. Verthier et al. [24] discovered that the minimum film boiling temperature increased and the film boiling heat transfer efficiency decreased under microgravity conditions. In addition, Darr et al. [25] carried out an experiment using LN2 onboard an aircraft and found that film boiling heat transfer was lessened by up to 25% and longer time and more liquid consumption for chill-down were required.

Theoretical studies and calculation predictions for cryogenic chill-down are also conducted by researchers. The most direct approach to predicting two-phase flow boiling is use of empirical or semi-empirical correlations. However, Hartwig et al. [1] compared correlations used in Generalized Fluid System Simulation Program (GFSSP) and SINDA/FLUINT, as well as existing correlations with seven sets of quenching data and drew a conclusion that the correlations based on steady state, heated tube tests for critical heat flux and two-phase heat transfer coefficient for room temperature fluids did not match well with the cryogenic chill-down data. Besides, few cryogenic correlations were reported, and no universal correlation was proposed. Based on chill-down results of a flexible metal hose using liquid nitrogen, Hu et al. [12] developed a set of chill-down correlations in which the critical heat flux model was modified by correlations applying to pool boiling, and the film boiling model was developed based on flow over a flat plate. Darr et al. [6] produced new chill-down correlations for film boiling and nucleate boiling by means of investigating the effect of mass flux, equilibrium quality, inlet sub-cooling as well as flow direction, but ignored the predictions for critical heat flux and Leiden-frost point temperature. Moreover, Darr et al. [26] developed a one-dimensional numerical simulation of chill-down of a vertical stainless steel tube and the predicted results agreed well with the experimental data. On the basis of chill-down experiments from a 7 m long stainless steel horizontal pipe with liquid nitrogen, Jin et al. [27] investigated the correlations for characteristic points as well as film boiling, and the results fitted wall temperature well in the mass flux range from 26.0 kg/m$^2$ s to 73.6 kg/m$^2$ s. Another approach to predicting two-phase behavior is the use of two-fluid models. Liao et al. [28] established a two-fluid model to represent cryogenic stratified flow, and the results fitted the data in horizontal pipe chill-down experiments by Yuan et al. [29] and Chung [30]. Moreover, Yuan et al. [29] produced a simplified model of film boiling carrying liquid droplets, and this model also predicted the wall temperature history well. Liao et al. [31] conducted the numerical stability study of two-fluid model and found that the central difference was the most accurate and stable discrete format when dealing with two-fluid problems.

Although a lot of experiments have been carried out to reveal the cryogenic chill-down characteristics, the critical details of hydrodynamic and heat transfer performance during chill-down process are still poorly understood, involving the intricate interaction of phase change, heat transfer and fluid dynamics. As for theoretical studies, only a few two-fluid models are available, which are limited to some specific flow regimes such as annular flow boiling, inverse annular flowing, and falling films. Moreover, the application ranges of correlations for cryogenic chill-down are narrow, which lack detailed