Research Article

Fill-In and Boiling Transition Characteristics during the Liquid Oxygen Chill-Down Process in a Vertical Exit-Contracted Pipe

Jiaqi Zhang©, Ke Wang, and Lanwei Chen

Science and Technology on Scramjet Laboratory, College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

Correspondence should be addressed to Jiaqi Zhang; amatyer_a@hotmail.com

Received 2 July 2022; Accepted 27 July 2022; Published 23 August 2022

Academic Editor: Yiheng Tong

Copyright © 2022 Jiaqi Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Liquid oxygen chill-down in a vertical exit-contracted pipe was investigated experimentally. The wall temperatures were recorded in detail to describe the fill-in and chill-down process of the experimental section. Two quenching fronts, the exit one and the inlet one, were detected, and their propagations were found. Results show that the chill-down process is controlled mainly by the formation and propagation of quenching front, which are determined by the pressure level. With the increase of pressure, the roles of both propagation of quenching front and inlet quenching front undergo decreasing. On the vertical section, the effect of circumferential position was discussed in detail and the dominant point was identified, which determines the boiling transition time of the dominated points on the current cross-section. Based on the experimental data, two correlations were suggested for dominant point and dominated points, respectively, to predict heat flux on Leidenfrost, heat transfer coefficient on Leidenfrost, and critical heat flux. One equation was approved to predict heat transfer coefficient on critical heat flux point for both sorts of points. All of these correlations could produce reliable predictions.

1. Introduction

Liquid oxygen (LO₂) and liquid methane (LCH₄) are characterized by low-cost, nontoxic, high performance compared to hypergolic propellants, and both of them could be produced on Mars [1, 2]. In this way, a number of projects have been put forward to support future exploration missions using this cryogenic propellant combination [3]. Systematical demonstrations indicated that for space propulsion using this combination, the primary technical risks included the cryogenic fluid management (CFM) and the low-pressure engine technology [4–6].

A number of studies have been put forward to improve the technology readiness level (TRL) for CFM system [3]. For this system, cryogenic fluid could be the liquid phase when the container or pipe are cooled to the liquid temperature. In this way, cryogenic chill-down in the transportation pipe is one of the basic processes here, especially for refueling and transportation of the cryogenic propellants [7]. With the cryogenic fluid first flowing into the pipe with room temperature, flash vaporization would happen in the pipe. Figure 1 gives a typical process of cryogenic chill-down. With the pipe temperature decreasing, fluid pattern in the pipe undergoes film boiling, transition boiling, nucleate boiling, and single phase in sequence. These 4 flow patterns are divided by 3 boiling transition points, Leidenfrost (LFP), critical heat flux (CHF), and onset of nucleate boiling (ONB) [8].

A number of studies have been put forward to investigate the cryogenic chill-down in the transport pipeline. A series of visual studies have been put forward [9, 10], and based on them, a series of phenomenological models have been set up to model the cryogenic chill-down process [11, 12]. For setting up more reliable model, recently, a number of experimental studies have been performed [13–21] to correlate the heat transfer coefficients for various boiling patterns and boiling transition points (LFP, CHF). It is believed that in the current stage, correlations approved by Darr et al. [15, 16] could obtain general
applications for transport pipe. Based on the improvement on models, a couple of reliable numerical results have been obtained [22, 23].

For low-pressure cryogenic engine, the primary technical difficulty is the unstable combustion associate with the two-phase injection produced by cryogenic chill-down [24]. As Figure 2 [25] shows, taking LO₂ for example, before start-up, components upstream of point G would be chilled completely by LO₂ out, components upstream of point G would be chilled. During the start-up process, liquid propellant flows into the components downstream of point G in ambient temperature, which produces two-phase injection and unstable combustion in the combustion chamber of the engine [24]. Basically, this phenomenon could be avoided by chilling the components downstream point G before start-up [26]. However, in most cases, the feasibility of this process is determined mainly by the engine procedure. Furthermore, it has been found that two-phase injection could not be avoided even after start-up process [27].

Cryogenic chill-down in low-pressure engine is characterized by the components downstream point G, with a flow contraction on the exit, known as injector, which could be reduced to an exit-contracted pipeline as Figure 3 shows [8, 28]. This is much different from that in transportation pipe taking CFM system as the investigation background, without any flow contraction on the exit.

In the previous studies, cryogenic chill-down in exit-contracted pipe has not been distinguished from cryogenic chill-down in transport pipe. A series of pioneered experimental studies on cryogenic chill-down in the horizontal exit-contracted pipe have been performed by the present authors [8, 28, 29]. Chill-down process was discussed, and boiling transition points were correlated. It has been found that boiling transition points could be well correlated by formats from pool boiling for the exit-contracted pipe, rather than formats from flow boiling from transport pipe [8]. However, the latest study showed that the quenching front seems to be formed in the center length in the horizontal exit-contracted pipe, then propagates to the both ends of the pipe during the chill-down process. In addition, gravity or the circumferential position (bottom, top, or side) plays significant role [29]. This induces extra difficulty to model the heat transfer and transition boiling points in exit-contracted pipe, which is much different from that in transport pipe [16].

It has been concerned that the effects of both gravity and propagation of the quenching front play significant roles in the previous study that [29]. In the present study, for excluding the effect of gravity, vertical pipe would be applied instead of horizontal pipe. In this way, experimental study would be performed to investigate the chill-down process by a constant flow rate of LO₂ in a vertical exit-contracted pipe. A series of tests with the same flow rate and various pressure in the pipe would be performed. Chill-down process would be tracked, by which the propagation of quenching front would be investigated. Based on these data, boiling transition points would be discussed, and \( q_i \) and \( h_l \) on these points would be correlated for vertical pipe section.

2. Experimental Methodology

2.1. Experimental Platform. Figure 4 gives the experimental platform applied in the present study. It is the LO₂ branch of a typical test platform for cryogenic engine. Compared to the previous one applied in the previous studies [8, 28], the present platform has been upgraded, where the previous 100 L/5.5 MPa LO₂ tank is replaced by a 500 L/10 MPa one. Other parts of the present platform are the same with the previous ones. As shown in the figure, flow rate of the fluid is controlled by the Venturi nozzle.

2.2. Experimental Section and Measurement Approach. Figure 5 gives the experimental section in detail. The shape of experimental section applied could be drawn in Figure 5(a), which also indicates the necessary sensors measuring the pressure and temperature of the fluid. As shown in the figure, a pressure sensor (PT301) and a temperature sensor (PT100) are set up on the experimental section to measure the pressure and temperature of the fluid.

![Figure 1: Typical boiling curve and flow patterns for chill-down process.](image-url)
respectively, in the section. 13 $T_o$ sensors (T-type thermocouples) were welded on the outer surface of the experimental section, and they were distributed on 5 cross-sections (various $L_{sec}$) as Figure 5(a) shows. Figure 5(b) gives the cross-section (vertical) on $L_{sec} = 1.55$ m, where the 2 sensors, denoted by 1.55-1 and 1.55-2, were welded on the bottom and south-side of the pipe, respectively. The cross-section (horizontal) for other $L_{sec}$ could be shown in Figure 5(c), which shows for every section, 3 sensors were set up on the west, south, and east of the pipe in turn (2 sensors on the west and south for $L_{sec} = 0.3$ m, denoted by 0.3-1 and 0.3-2). $T_o$ data were recorded by temperature scanner (EX32A). All of the above sensors are with the scan rate of 1000 Hz.

2.3. Other Conditions. For minimizing the potential deviations including nitrogen solution in LO$_2$ and flow rate oscillations, the test process were well designed and illustrated as shown in reference [1], which would not be repeated here.
3. Experimental Results

3.1. Basic Results. Four tests were performed, and related conditions and results could be listed in Table 1. It shows that the present series of tests are all with the similar flow rate and various $A_{inj}$. With the decrease of $A_{inj}$ (Exp. 1~4), pressure in the experimental section shows the increasing manner. This indicates that the $P_{ss}$ range is from 0.328 to 1.325 MPa.

3.2. Data Processing and Boiling Transition Points. Parameters in the pipe as well as $T_o$ data were measured for all of the four tests. By processing $T_o$ data, $T_i$ and $q_i$ were obtained because most discussions next would be based on these 2 parameters. Here, $T_i$ would be determined according to reference [30], and $q_i$ would be obtained by numerical methods introduced in the previous studies [28], which would not be repeated here anymore.

Based on $T_i$ and $q_i$ data, boiling curves could be drawn. In this way, boiling transition points, LFP, and CHF could be determined as well. These two points could be identified in the boiling curve easily, which indicate the minimum $q_i$ point and maximum $q_i$ point, respectively.

3.3. Uncertainty. The present study focuses on the comparison between experimental values and predicted values for $T_{LFP}$, $q_{LFP}$, $T_{CHF}$, and $q_{CHF}$. The experimental values depend mainly on the $T_o$ measurement, physical properties as well as the geometric parameter of the pipe. On the other hand, as shown in the correlations, the predicted values depend mainly on the measured pressure and geometric parameter of the pipe. These factors could be shown in Table 2. Furthermore, the respective mean absolute errors (MAE) can be defined as Equation (1) shows [31].

$$\text{MAE} = \frac{1}{N} \sum \frac{|V_{exp} - V_{pre}|}{V_{exp}} \times 100\%.$$  

3.4. Basic Chill-Down Process. Figure 6 shows all of the $T_i$ curves as well as $T_p$, $T_{sat}$, and $P_p$ curves to show the chill-down process for Exp. 1. As shown in the figure, during the chill-down process, $T_p$, $T_{sat}$, and $P_p$ curves show the similar manner with the curves recorded in the previous studies [8, 28]. It also shows that a typical $T_i$ curve is composed by three sequent phases as follows.

1. Phase I: the initial linear decrease phase. In this phase, $T_i$ increases in a linear manner, which indicates the inner flow is on the film boiling. LFP, the transition point between film boiling and transition boiling, could be seen as the transition point between phases I and II as well

2. Phase II: the sudden decrease followed by phase I. This phase is with the shortest period, in which $T_i$ decreases dramatically. This phase involves both transition boiling section and nucleate boiling section, and CHF, the transition point between transition boiling and nucleate boiling, sometimes would be seen as the central point of it

3. Phase III: the gradual decrease followed by phase II. In this phase, $T_i$ decreases gradually, which indicates the inner flow is the single-phase flow. As shown in Figure 1, the transition point between phase II and phase III is denoted as ONB, which always indicates the end of chill-down
As shown in Figure 6, for Exp. 1, $T_i$ on $L_{se}$ = 1.55 m decreases at first, followed by $L_{se}$ = 0.75 m, 1 m, and 0.5 m in turn. Similarly, LFP happens in $L_{se}$ = 1.55 m at first, followed by $L_{se}$ = 0.75 m, 1 m, and 0.5 m in turn. This indicates that two quenching fronts (QF) are formed on the exit and inlet of the experimental section independently. In the current stage, the exact positions of them could not be decided yet. However, based on the current information, the characteristics of QF formation and propagation could be approved.

It is evident that the QF formed near the exit propagates backward, from somewhere downstream of $L_{se}$ = 1.55 m to the inlet section. It gets to $L_{se}$ = 1.55 m, 1 m, 0.75 m, and 0.5 m in turn and produces boiling transitions on these points. On the other hand, the inlet QF propagates forward from the inlet section to the exit, and it gets to $L_{se}$ = 0.3 m.
and produces boiling transition here. It has to be noted that QFs get to \( L_{se} = 1.55 \) m and \( L_{se} = 0.3 \) m almost simultaneously at 10 s. However, after that, it seems like that the inlet QF does not propagate forward, and the vertical section is chilled by the exit QF.

As shown in Figure 7, for Exp. 2, \( T_{1} \) on \( L_{se} = 1.55 \) m decreases at first, followed by \( L_{se} = 1 \) m, 0.75 m, 0.3 m, and 0.5 m in turn, and LFP shows the similar manner. However, as shown in Figure 8 and Table 3, for Exp. 3, \( T_{1} \) on \( L_{se} = 1.55 \) m decreases at first, followed by \( L_{se} = 1 \) m, 0.75 m, 0.3 m in turn, and LFP shows the similar manner. However, as shown in Figure 9 and Table 3, for Exp. 4, \( T_{1} \) on \( L_{se} = 1.55 \) m decreases at first. After that, \( T_{1} \) values on \( L_{se} = 1 \) m, 0.75 m, and 0.5 m decrease with the similar slope, which are obvious prior to \( L_{se} = 0.3 \) m. This indicates that QF on \( L_{se} = 0.3 \) m happens at first for Exp. 1, at the fourth place for Exp. 2, and at last for Exp. 3 and Exp. 4.

### 4. Film Boiling Heat Transfer and the Leidenfrost Point

In the present section, film boiling heat transfer, liquid rewetting, and LFP would be discussed for \( L_{se} = 0.5 \) m and 1 m. This is primary because these cross-sections are set on the vertical section, and the LFPs of them are primary controlled by the exit QF, at least for lower and medium pressure cases.

---

**Table 1: Experimental conditions and results.**

| Parameters | Exp. 1 | Exp. 2 | Exp. 3 | Exp. 4 |
|------------|--------|--------|--------|--------|
| Injector type | Orifice | Pintle | Pintle | Orifice |
| \( A_{inj} \) (mm) | 110.6 | 67.2 | 33 | 12 |
| \( n \) (kg/s, start) | 0.44 | 0.435 | 0.429 | 0.417 |
| \( m \) (kg/s, end) | 0.45 | 0.444 | 0.438 | 0.426 |
| \( G \) (kg/(m²·s), end) | 2546 | 2513 | 2478 | 2411 |
| Re (end) | 259192 | 270824 | 319074 | 329295 |
| \( T_{p} \) (K, end) | 101.5 | 104.0 | 112.0 | 115.0 |
| \( T_{sat} - T_{p} \) (K, subcooling, end) | 1.65 | 2.06 | 3.3 | 9.64 |
| \( P_{peak} \) (MPa, start) | 0.586 | 0.843 | 1.678 | 3.049 |
| \( P_{inj} \) (MPa, end) | 0.328 | 0.41 | 0.77 | 1.325 |

**Table 2: Summary of the uncertainties.**

| Parameters | Uncertainty |
|------------|-------------|
| Fluid pressure (%) | 0.5 |
| Fluid temperature (K) | 1 |
| Outer wall temperature (K) | 1 |
| Pipe \( D_{o} \) and \( D_{s} \) (mm) | 0.01 |
| Mass flow rate (%) | 1 |
| \( T_{o} \) (K) | 1 |
| \( T_{i} \) (K) | 2 |
| \( q_{e} \) (%) | 5 |
4.1. Basic Effect of $A_{\text{inj}}$. The experimental $\Delta T_{\text{LFP}}$, $q_{\text{LFP}}$, and $\theta_{\text{LFP}}$ versus $A_{\text{inj}}$ could be shown in Figure 10–12, respectively. It shows that, basically, with the decrease of $A_{\text{inj}}$, both $q_{\text{LFP}}$ and $\theta_{\text{LFP}}$ show the increasing manner (except some individual cases). On the other hand, with the decrease of $A_{\text{inj}}$, approximately, $\Delta T_{\text{LFP}}$ shows the increase manner for $L_{\text{se}} = 0.5$ m, the decrease manner for $L_{\text{se}} = 0.75$ m, and increase-decrease manner for $L_{\text{se}} = 1$ m. This is similar with those indicated in reference [29].

4.2. Evaluation of the Previous Correlations. Leidenfrost point (LFP), on which the liquid rewets the pipe wall, is known as the transition point from film boiling to transition boiling. This point is always identified as the point with the minimum heat flux. Historically, based on the flow instability theories, Zuber et al. [32] improved the basic correlation on $q_{\text{LFP}}$ as shown in Equation (2) ($C_1 = 0.09$). After that, Berenson [33] approved Equation (3) ($C_2 = 0.425$) to evaluate $h_{\text{FB}}$, the heat transfer coefficient on film boiling, and suggested Equation (4) ($C_{\text{LFP}} = 0.127$) on LFP to evaluate $\Delta T_{\text{LFP}}$ based on basic heat transfer equation, Equation (6). After that, most correlations on $q_{\text{LFP}}$ and $\Delta T_{\text{LFP}}$ for both pool boiling and flow boiling were based on these 2 equations. In the previous studies, $\Delta T_{\text{LFP}}$ and $q_{\text{LFP}}$ were tried to be correlated. In this way, Equation (4) and Equation (2) were applied to predict $\Delta T_{\text{LFP}}$ and $q_{\text{LFP}}$, respectively, for horizontal exit-contracted pipe [8, 29].

\[
q_{\text{LFP}} = C_1 \rho_v H_{\text{vL}} \left( \frac{\sigma_{\text{vL}} g (\rho_1 - \rho_v)}{\rho_v} \right)^{0.25},
\]

(2)

\[
h_{\text{FB}} = C_2 \left[ \frac{k_v H_{\text{vL}} \sigma_{\text{vL}} g (\rho_1 - \rho_v)}{\mu_v \Delta T_i \sqrt{\sigma_{\text{vL}} g (\rho_1 - \rho_v)}} \right]^{0.25},
\]

(3)

\[
\Delta T_{\text{LFP}} = T_{\text{LFP}} - T_{\text{sat}} = C_{\text{LFP}} \cdot E_{\text{LFP}},
\]

(4)

\[
E_{\text{LFP}} = \frac{\rho_v H_{\text{vL}}}{k_v} \left( \frac{g (\rho_1 - \rho_v)}{\rho_1 + \rho_v} \right)^{2/3} \left( \frac{\sigma_{\text{vL}}}{g (\rho_1 - \rho_v)} \right)^{1/2} \left( \frac{\mu_v}{g (\rho_1 - \rho_v)} \right)^{1/3},
\]

(5)

\[
q_i = h_i \Delta T_i,
\]

(6)

According to Equation (4), in the present study, for vertical experimental section, $\Delta T_{\text{LFP}}$ could be plotted versus $E_{\text{LFP}}$ in Figure 13, where $C_{\text{LFP}}$ could be correlated to be 0.0576 and produces the MAE of 16.62%. As shown in the

![Figure 6: Tested data curves for Exp. 1 (0.45 kg/s, $P_{\text{ss}} = 0.328$ MPa).](image-url)
figure, the point distribution and constant $C_{\text{LFP}}$ do not show significant differences from the previous studies [29]. It shows that with the increase of $A_{\text{inj}}$, $\Delta T_{\text{LFP}}$ shows the overall increasing manner for $L_{se} = 0.5$ and overall decreasing manner for other $L_{se}$. This indicates the similar difficulties on correlation, which has been discussed in the previous studies in horizontal pipes [29].

On the other hand, Zuber’s correlation, Equation (2), indicates that on LFP, vapor was not produced rapidly enough to lift the interface as rapidly as it would normally collapse [34]. In this way, $q_{\text{LFP}}$ in the present study could be correlated by this equation as shown in Figure 14, where the constant $C_1$ and MAE could be listed in Table 4. Generally speaking, as shown in Equation (2), the effects of fluid properties could be represented by the items in the absissa of Figure 14, and the effects of circumferential position and $L_{se}$ could be represented by the variable parameter $C_1$, which has been correlated for every point. Obviously, it is not a general correlation. However, in the current stage, this equation is important to set up the basic outline for the following investigations.

As shown in Figure 14, basically, Equation (2) could produce reliable predictions on $q_{\text{LFP}}$ for $L_{se} = 0.5$ and $0.75$ m relatively. However, for $L_{se} = 1$ m, with the increase of $\rho_v H_l \sigma \sqrt{g (\rho_l - \rho_v)/(\rho_l + \rho_v)}^{2/5}$, $q_{\text{LFP}}$ shows the decreasing-increasing manner. Thus, from the view of point of correlation, Equation (2) could be used to produce $q_{\text{LFP}}$ for $L_{se} = 1$ m only on higher pressure (e.g., $P_{ss} \geq 0.4$ MPa). In this way, $C_1$ items listed in Table 4 for $L_{se} = 1$ m were correlated for Exp. 2~4.

4.3. Correlations on $h_{\text{LFP}}$. By the present set of data, $h_{\text{LFP}}$ could be correlated by Equation (3) as shown in Figure 15, where the constant $C_2$ could be listed in Table 4. Basically, with the increase of pressure, the 2nd item of the right side of Equation (3) keeps increasing constantly, which is consistent to the experimental $h_{\text{LFP}}$ data.

4.4. Primary Effect Factors. According to Carbajo [35], liquid rewetting involves the effects of pressure, liquid subcooling, liquid and solid properties, surface conditions, and flow rate. However, in the present study, throughout all of the tests, only pressure shows the obvious variations. On the other
hand, \( L_{se} \) and circumferential positions are obviously different for these points. In this way, the effects of pressure, \( L_{se} \), and circumferential positions would be discussed in the present section.

4.4.1. The Effects of \( A_{inj} \) or Pressure. The present series of tests are with the same flow rate. Thus, the effects of \( A_{inj} \) in the present study indicates the effects of pressure only. On the film boiling section, with the decrease of \( A_{inj} \) (increase of pressure), \( h_{FB} \) keeps increasing because \( \delta_{FB} \) keeps almost constant and \( k_v \) keeps increasing as shown in Equation (7) [29].

\[
h_{FB} = \frac{k_v}{\delta_{FB}}.
\] (7)

In this way, with the increase of \( A_{inj} \), the slope of \( T_i \) decreasing increases for every point, and chill-down period \( (t_{LFP}) \) would be shortened as well. As a result, both heat flux and heat transfer coefficient would be enhanced on film boiling section, which produces the overall increasing \( q_{LFP} \) and \( h_{LFP} \) for every point.

These principles are very similar with those tendencies in horizontal exit-contracted pipe [29].

4.4.2. The Effects of \( L_{se} \). Traditionally, \( h_{LFP} \) decreases with the increase of \( L_{se} \) according to the existing correlations [7]. However, in the present study, experimental data do not
show the similar tendency. Comparison between Figures 14 and 15 shows that, for a certain test, both $q_{LFP}$ and $h_{LFP}$ increase with the increase of $L_{se}$, which is contrary to that in transport pipe [7]. Comparison among transport pipe [7], horizontal exit-contracted pipe [29], and vertical exit-contracted pipe indicates that the effects of $L_{se}$ traditionally concerned are essentially more like the effects of $L_{qf}$, distance from the present point to the QF formation point. In this way, experimental results in reference [29] and in the present study could be explained well. Thus, it is necessary to denote that from the view of point of pipe length, $L_{qf}$ plays the significant role on LFP instead of $L_{se}$.

In general, for a certain test, along the directions of QF propagation, $t_{LFP}$ shows the increasing manner, compared to that $q_{LFP}$ and $h_{LFP}$ show the decreasing manner. This characteristic plays significant roles on the LFP. This indicates the basic principle, longer $L_{qf}$ is corresponding to greater $t_{LFP}$, lower $q_{LFP}$ and $h_{LFP}$. This principle is always the case independent on $L_{se}$ and the dominant QF, even for $L_{se} = 0.3$ m, on which even the LFP is controlled by various QF.

For a certain $L_{se}$ with the increase of $A_{inj}$, $t_{LFP}$ shows the decreasing manner, and $q_{LFP}$ and $h_{LFP}$ show the increasing manner. This indicates that with the increase of pressure, both $h_{FB}$ and $M$ (magnitude of instable waves) undergo corresponding increase. According to results in horizontal exit-contracted pipe [29], LFP is controlled by the competition between heat transfer and the increase of $M$. However, according to the present study, QF propagation also plays a significant role on. In the present study, for Exp. 1–3, QF propagation could be well tracked according to the experimental data, which indicates that the latter one is the dominant factor. However, for Exp. 4, LFP happens almost simultaneously on $L_{se} = 0.5$, 0.75, and 1 m, which indicates that the former is the dominant factor in this case.

Another key point is where is the QFs formed. In the present study, both inlet QF and exit QF are identified. Analysis indicates that QF formation is controlled by the fill process of the cryogenic fluid in the exit-contracted pipe.

### 4.4.3. The Effects of Circumferential Position

As shown in Table 3, for every $L_{se}$, $t_{LFP}$ values for circumferential position (1, West; 2, South; 3, East) are quite similar to each other. This indicates the propagation of QF circumferentially also plays significant role. This is similar with those in horizontal exit-contracted pipe [29]. However, traditionally,
circumferential position plays ignorable role in the vertical transport pipe [7]. In the present study, vertical section \(L_{se} = 1\), 0.75, and 0.5 m, as shown in Table 4, could produce around 50% variation on \(h_{LFP}\) and \(q_{LFP}\) and \(q_{CHF}\) for \(L_{se} = 1\) and 0.75 m and 30% for \(L_{se} = 0.5\) m.

In this way, for a certain \(L_{se}\), \(h_{FB}\) always dominates the decrease of \(T_i\) on points 1–3. After that, once one of them gets to LFP, boiling transitions would happen immediately on other two points, which produces the \(h_{FB}\) at that time as \(h_{LFP}\). In another word, on the same \(L_{se}\) cross-section, various points are with the similar \(t_{LFP}\).

In this way, for a certain \(L_{se}\), \(h_{FB}\) always dominates the decrease of \(T_i\) on points 1–3. After that, once one of them gets to LFP, boiling transitions would happen immediately on other two points, which produces the \(h_{FB}\) at that time as \(h_{LFP}\). In another word, on the same \(L_{se}\) cross-section, various points are with the similar \(t_{LFP}\).

In this way, three points, 0.5-2, 0.75-2, and 1-3 are the dominant points for \(L_{se} = 0.5\), 0.75, and 1 m, respectively, and determines the \(t_{LFP}\) point on the present section in the present study. For other points (dominated points), during the chill-down process, \(q_i\) and \(T_i\) keep decreasing, and \(h_{FB}\) keeps increasing. Once LFP happens at \(t_{LFP}\) on the dominant point on the same section, liquid rewetting would happen on the dominated points. Thus, \(q_i\), \(T_i\), and \(h_{FB}\) at that time would be identified as \(q_{LFP}\), \(T_{LFP}\), and \(h_{LFP}\).

This implies that on a certain \(L_{se}\) cross-section, the liquid rewetting mechanism for the dominant point is different from that for the dominated points. For the dominant point, liquid rewetting is more likely to be controlled by flow instability, which is similar with that on pool boiling or flow boiling. According to the series of data, this process is dominated by the QF propagation axially. However, for the dominated points, liquid rewetting is controlled by both the dominant point and the local heat transfer. This process is dominated by the QF propagation circumferentially.

The difference between the dominant point and dominated points could be also found in the horizontal exit-contracted pipe. Obviously, because of the gravity, the dominant point is the bottom point for horizontal pipe [29]. However, for the vertical pipe, the effect of gravity could be ignored. According to Carbajo [35], liquid rewetting involves the effects of pressure, liquid subcooling, liquid and solid properties, surface conditions, and flow rate. In this way, on the same \(L_{se}\) cross-section, this sort of difference between the dominant point and dominated points is probably caused by the inner surface conditions.

### 4.4.4. Summary on the Basic Effect Factors

As discussed above, the effects of pressure, \(L_{se}\), and circumferential position could be summarized and concluded as follows.

1. For a certain point, the increase of \(A_{inj}\) produces overall increasing \(q_{LFP}\) and \(h_{LFP}\) and deceasing \(t_{LFP}\).
2. With the increase of \(L_{se}\), overall decreasing \(q_{LFP}\) and \(h_{LFP}\) and increasing \(t_{LFP}\) could be obtained.
3. Because of the propagation of QF circumferentially, on a certain \(L_{se}\) (cross-section), there are both dominant point and dominated points, which are

![Figure 10: Experimental \(\Delta T_{LFP}\) versus \(A_{inj}\).](image-url)
controlled by flow instability and both dominant point and \( h_{FB} \) and, respectively. In the present study, 0.5-2, 0.75-2, and 1-3 are the dominant points for these sections, respectively.

4.5. Discussions

4.5.1. Correlations on the Dominant Points. From the view of point of correlation, all of these factors should be involved. For three dominant points, 0.5-2, 0.75-2, and 1-3, on which liquid rewetting is controlled by flow instability. According to Equation (2) and Table 4, \( C_1 \) for them are correlated to be 0.0643, 0.0748, and 0.086, respectively. It shows that \( C_1 \) increases linearly with the increase of \( L_{se} \) (decrease of \( L_{qf} \)). In this way, based on Equation (2), \( q_{LFP} \) on the dominant points for \( L_{se} = 0.5, 0.75, \) and 1 m could be correlated by Equation (8). This correlation could be approved for dominant points in vertical section.

\[
q_{LFP} = (0.0425 + 0.0434 L_{se}) \rho_v h_{st} \left( \frac{\sigma_{st} g (\rho_l - \rho_v)}{\rho_l + \rho_v} \right)^{0.25}. \tag{8}
\]

As discussed above, in the present study, \( q_{LFP} \) decreases with the decrease of \( L_{se} \) for \( L_{se} = 0.5 \) m and its downstream. In addition, on 1.55-2, the dominant point on \( L_{se} = 1.55 \) m, and the horizontal section, \( C_1 \) was correlated to be 0.1335, which has not been given above. This indicates the \( C_1 \) values along the QF propagation, from 0.1335 (\( L_{se} = 1.55 \) m) to 0.086 (\( L_{se} = 1 \) m), 0.0748 (\( L_{se} = 0.75 \) m), and finally, 0.0643 (\( L_{se} = 0.5 \) m). These series of values are consistent to the literature data, in which \( C_1 \) was correlated to be 0.09 [32] for room-temperature fluid in pool boiling. At first, the deviation of \( C_1 \) between the present study and reference [32] is mainly caused by the variations between the fill-in flow in the exit-contracted pipe and pool boiling. On the other hand, the decrease of \( C_1 \) along the reverse direction of the flow in the experimental section pipe indicates the special characteristics of flow in the exit-contracted pipe.

Similarly, according to Equation (3), \( C_2 \) for 0.5-2, 0.75-2, and 1-3 are correlated to be 0.573, 0.7139, and 0.8264, respectively. Similar with \( q_{LFP} \), \( h_{LFP} \) on the dominant points for \( L_{se} = 0.5, 0.75, \) and 1 m could be correlated by Equation (9). This series of data is consistent to the literature data, in which \( C_2 \) was correlated to be 0.425 [33] for room-temperature fluid in pool boiling.

\[
h_{FB} = \left( 0.324 + 0.5068 L_{se} \right) \left( \frac{k^2 h_{st} \rho_v g (\rho_l - \rho_v)}{\mu_i \Delta T_1 \sqrt{\sigma_{st} g (\rho_l - \rho_v)}} \right)^{0.25}. \tag{9}
\]

![Figure 11: Experimental \( q_{LFP} \) versus \( A_{inj} \).](image-url)
Compared to the literature data from room-temperature fluid in pool boiling, dominant points in the vertical section are with lower $q_{\text{LFP}}$, lower $\Delta T_{\text{LFP}}$, and higher $h_{\text{LFP}}$. Basically, this sort of differences is mainly caused by the variations on the system pressure and flow condition. On the other hand, the similarity on $C_1$ and $C_2$ between for exit-contracted pipe and pool boiling indicates that flow instability is the primary dominant factor, and $L_{se}$ also plays a certain role for the dominant points on the present vertical pipe.

4.5.2. Correlations on the Dominated Points. For the dominated points, Equations (2) and (3) with constants listed in Table 4 could be suggested in the current stage. It has to be denoted that on this sort of points, liquid rewetting is not caused by local flow instability on this sort of points. On the contrary, the local instable wave has not been developed adequately. Result indicates that at $t_{\text{LFP}}$, liquid rewetting happens on the dominant point on the current cross-section. Almost simultaneously, all of this cross-section is rewetted by the liquid as a result of QF propagation circumferentially from the dominant point. In this way, on the dominated points, as a result of being rewetted, $q_i$, $h_i$, and $T_i$ at $t_{\text{LFP}}$ have to be denoted as parameters on LFP.

4.5.3. Correlation Approach and Correlation Formats. In the previous studies, $q_{\text{LFP}}$ and $\Delta T_{\text{LFP}}$ were tried to be correlated, and $h_{\text{LFP}}$ has not been tried to be correlated before [8]. In the present study, $q_{\text{LFP}}$ and $h_{\text{LFP}}$ (instead of $\Delta T_{\text{LFP}}$) are correlated. This is the new correlation approach. In the recent studies, correlation formats for Equations (2)–(4) were approved to correlate $q_{\text{LFP}}$, $h_{\text{LFP}}$, and $\Delta T_{\text{LFP}}$, respectively. The primary items in these equations could be plotted versus pressure as shown in Figure 16.

For $\Delta T_{\text{LFP}}$, as discussed above, there are two difficulties on reliable correlation, which determines it would not be considered to be correlated in the current stage. The first one is, as shown in Figures 13 and 16, parameter combination, with the increase of pressure from ambient to around 2.5 MPa, $E_{\text{LFP}}$ in Equation (4) shows the increasing-decreasing manner, which indicates that it could not represent the effects of pressure. On the other hand, with the increase of pressure, the variations of $\Delta T_{\text{LFP}}$ show different manners for various $L_{se}$. The primary reason is $E_{\text{LFP}}$ and Equation (4) are approved for pool boiling in ambient-pressure, which could not be applied in high pressure cases.

For both dominant point and dominated points, $q_{\text{LFP}}$ and $h_{\text{LFP}}$ are well correlated on the vertical section. This is primarily because the basic effects including pressure, $L_{se}$, and circumferential position are well involved. At first, for dealing with the effect of circumferential position, dominant points were identified from dominated points, and they were correlated apart from each other. On the other hand, the effects of pressure and $L_{se}$ are involved well in Equations
(2)–(3) and Equations (8)–(9). Especially, as shown in Figure 16, in the effective LFP pressure range from ambient to around 2.5 MPa [8], the primary items in both Equations (2) and (3) (as well as (8) and (9)) increase consistently with the increase of pressure, which indicates that these equations could represent the effect of pressure well.

5. New Correlation on \( q_{\text{CHF}} \) and Discussions on the Critical Heat Flux Point

5.1. Basic Effect of \( A_{\text{inj}} \). Figure 17–19 shows the basic experimental data, where \( \Delta T_{\text{CHF}}, q_{\text{CHF}}, \) and \( h_{\text{CHF}} \) are plotted versus \( A_{\text{inj}}, \) respectively. With the decrease of \( A_{\text{inj}}, \Delta T_{\text{CHF}} \) shows the overall decreasing manner, and both \( q_{\text{CHF}} \) and \( h_{\text{CHF}} \) show the overall increasing-decreasing manner, primarily. This is similar with the results in the previous study for horizontal exit-contracted pipe [29].

5.2. Evaluations on the Previous Correlations. In the previous studies, Equation (10) from transport pipe was recommended by the present authors to predict \( \Delta T_{\text{CHF}} \) for horizontal exit-contracted pipe [8, 28]. However, this equation was demonstrated to produce great deviations when predicting the previous set of data, where more detailed \( T_{\circ} \) was measured [29].

\[
\Delta T_{\text{CHF}} = T_{\text{CHF}} - T_{\text{sat}} = 1.345 \times 10^{-5} B, \quad (10)
\]

\[
B = H_{\text{ct}} \rho_{v} \left[ \frac{g \sigma_{d}(\rho_{l} - \rho_{v})}{\rho_{v}^2} \right]^{0.25}. \quad (11)
\]

Figure 20 plots the experimental \( \Delta T_{\text{CHF}} \) versus parameter \( B \) in the present study. These figures show very similar with Figure 13. In this way, similar difficulties on correlations with LFP could be found, which could be discussed next.

In the previous study, new correlations on \( q_{\text{CHF}} \) have been approved for horizontal exit-contraction pipe [29] as shown in Equation (12) (Equation (13) is another version). This equation involves the effects of \( L_{\text{sc}} \) and circumferential by constant \( C_{3}, \) the effects of \( u_{l} \) by \( u_{l}^{-0.7149}, \) and the effects of fluid properties by other items. In the present study, \( q_{\text{CHF}} \) values could be correlated by Equation (13) as shown in Figure 21, where the constant \( C_{3} \) could be listed in Table 4, which indicates correlation equation approved from the horizontal exit-contraction pipe would be used in the present vertical exit-contraction pipe.

\[
q_{\text{CHF}} = C_{3} u_{l}^{0.1149} \rho_{v}^{0.1262} H_{\text{ct}} (\rho_{l} - \rho_{v})^{0.1667} \rho_{v}^{0.5405} \sigma_{d}^{0.25}. \quad (12)
\]

\[
q_{\text{CHF}} \rho_{v} H_{\text{ct}} u_{l} = C_{3} \left( \frac{\rho_{l}}{\rho_{v} u_{l}^{2.25}} \right)^{0.8738} \left( \frac{\sigma_{d}}{\rho_{v} u_{l} D_{\text{ba}}} \right)^{0.3333}. \quad (13)
\]

5.3. New Correlation on \( h_{\text{CHF}} \). For LFP, both \( q_{\text{LFP}} \) and \( h_{\text{LFP}} \) could be correlated by the existing correlation format. In this

\[
\text{Figure 13: Experimental } \Delta T_{\text{LFP}} \text{ versus } E_{\text{LFP}}.
\]
way, \( \Delta T_{\text{LFP}} \) could be obtained correspondingly. This approach could be adopted when discussing CHF point. In this way, the possibility of correlating \( h_{\text{CHF}} \) should be evaluated well. Basically, a number of correlations on heat transfer coefficient for nucleate boiling were approved in the previous studies.

Forster-Zuber correlation was applied widely to predict heat transfer for nucleate boiling in pool [36]. In this correlation, the variation between saturation pressure on \( T_i \) (temperature inner wall), \( P_{\text{si}} \), and \( P_{\text{p}} \) (pressure in the pipe) was assumed to vary linearly versus subcooling \( \Delta T_i \), \((T_i - T_{\text{sat}})\), as Equation (14) shows. In this way, heat transfer coefficient could be predicted by Equation (15), where constant \( C_4 \) indicates \( C \cdot k_{\text{FZ}}^{0.75} \). Experimental results show that in the present study, most \( T_{\text{CHF}} \) values are higher than the critical temperature, which gives the constant \( P_{\text{si}} \) values. Of course, another possibility is this series of equations were approved for low-pressure cases. Nevertheless, this reduces the role of \( k_{\text{FZ}} \) as shown in Equation (14), and the effects of \( k_{\text{FZ}} \) could be just represented by \( C_4 \) in Equation (15).

\[
\rho_{\text{si}}H_i \left( \frac{\sigma g (\rho_{\text{v}} - \rho_{\text{i}})}{(\rho_{\text{v}} + \rho_{\text{i}})^2} \right)^{0.25} \]  

\[
P_{\text{si}} - P_{\text{p}} = k_{\text{FZ}} \Delta T_i, \tag{14}
\]

\[
h_{\text{NB}} = C_4 \left( \frac{0.5 \rho_{\text{pl}} \delta_{125} \delta_{125}^{0.333} \rho_{\text{pl}}^{0.25}}{\rho_{\text{v}}^{0.25} \rho_{\text{pl}}^{0.25} \delta_{125}^{0.25} \sigma_{\text{v}}^{0.5}} \right) \Delta T_i. \tag{15}
\]

Comparison shows that, as shown in Equation (15), for CHF, with the increase of pressure, \( P_i^{0.5} \rho_{\text{pl}}^{0.125} \delta_{125}^{1.125} \rho_{\text{pl}}^{0.333} / \rho_{\text{v}}^{0.25} \rho_{\text{pl}}^{0.25} \delta_{125}^{0.25} \sigma_{\text{v}}^{0.5} \) shows the overall increasing manner;

### Table 4: Constants for every point in Equations (2), (3) and (11), respectively.

| Point | Constant \( C_1 \) | MAE (%) | Constant \( C_2 \) | MAE (%) | Constant \( C_3 \) | MAE (%) |
|-------|------------------|--------|------------------|--------|------------------|--------|
| 0.5-1 | 0.0555           | 14.28  | 0.4828           | 10.16  | 0.00703          | 11.24  |
| 0.5-2 | 0.0643           | 7.12   | 0.573            | 6.29   | 0.00982          | 4.06   |
| 0.5-3 | 0.0607           | 11.20  | 0.5236           | 6.26   | 0.00828          | 4.06   |
| 0.75-1| 0.0597           | 14.05  | 0.5281           | 6.40   | 0.00769          | 4.00   |
| 0.75-2| 0.0748           | 5.45   | 0.7139           | 13.60  | 0.00835          | 4.19   |
| 0.75-3| 0.0502           | 12.26  | 0.4121           | 5.72   | 0.00428          | 13.65  |
| 1-1   | 0.0572*          | 10.49  | 0.4967*          | 7.09   | 0.00683          | 1.53   |
| 1-2   | 0.0749*          | 6.05   | 0.7384*          | 8.74   | 0.00725          | 1.63   |
| 1-3   | 0.086*           | 8.02   | 0.8264           | 4.47   | 0.00994          | 5.57   |

* except Exp. 1.
However, $\Delta T_{CHF}$ shows the contrary manner, which produces extra difficulties on correlation. In this way, the parameter combination could be revised as Equation (16) shows, and the present set of data could be plotted as shown in Figure 22. It shows that $h_{CHF}$ could be correlated by Equation (17), which produces the overall MAE of 2.3% and the max deviation 13.4%. The deviation bar has been plotted in the figure, where the red lines show the $\pm 2\%$ deviation on the present figure, and $\pm 17.9\%$ for the $h_{CHF}$ data.

$$h_{CHF} = C_4 \left( \frac{\rho_v^{0.25} H_{vl}^{0.25} \mu_{vl}^{0.5} \sigma_{vl}^{0.5}}{\rho_1^{0.5} \mu_1^{1.25} \kappa_1^{125} \Delta T_{CHF}} \right)^N, \quad (16)$$

$$h_{CHF} = 19511.9 \left( \frac{\rho_v^{0.25} H_{vl}^{0.25} \mu_{vl}^{0.5} \sigma_{vl}^{0.5}}{\rho_1^{0.5} \mu_1^{1.25} \kappa_1^{125} \Delta T_{CHF}} \right)^{0.6588} \quad (17)$$

### 5.4. Primary Effect Factors

Similar with LFP, the effects of pressure, $L_{se}$, and circumferential positions would be discussed in the present section.

#### 5.4.1. The Effect of $A_{inj}$ or Pressure

CHF point could be recorded in a wide range from the ambient-pressure to around 4.0 MPa. Basically, as shown in Section 5.1, in this pressure range, with the decrease of $A_{inj}$ (increase of pressure), primarily, $q_{CHF}$, $\Delta T_{CHF}$, and $h_{CHF}$ show the overall constant or increase-decrease manner. These factors are consistent to those approved in the previous studies [8, 29].

#### 5.4.2. The Effects of $L_{se}$

For LFP, at least $q_{LFP}$ shows the obviously decreasing manner with the increase of $L_{qf}$. However, for the experimental data on $q_{CHF}$, $\Delta T_{CHF}$, and $h_{CHF}$, the effects of $L_{se}$ do not show the obvious regulations. In this way, correlations on these parameters do not involve $L_{se}$. At least, this indicates $L_{se}$ plays ignorable roles on bubble separation.

#### 5.4.3. The Effects of Circumferential Position

The effect of circumferential position on CHF is similar to that of LFP. As shown in Table 3, for every $L_{se}$, $l_{CHF}$ values for various circumferential positions (1, West; 2, South; 3, East) are quite similar to others. This indicates that the propagation of bubble separation “front” circumferentially plays significant roles on the CHF for a certain $L_{se}$ cross-section. In
Figure 16: Parameter combinations in Equations (2)–(4) versus pressure.

Figure 17: Experimental $\Delta T_{\text{CHF}}$ versus $A_{\text{inj}}$. 
addition, for a certain \( L_{se} \), various circumferential positions are with various \( q_{CHF} \), \( h_{CHF} \), \( T_{CHF} \). This indicates that, similar with LFP, for a certain \( L_{se} \), there are both dominant point and dominated points. As shown in Table 3, dominant points for bubble separation (CHF), 0.5-2, 0.75-2, and 1-3 are same with those for liquid rewetting (LFP). This is because on the current cross-section, \( T_i \) on the dominant point decreases prior to other points, not only on film boiling section but also on transition boiling section. In this way, \( T_i \) on the dominant point is always the lowest on the current cross-section and dominates the boiling transitions on the current cross-section.

5.4.4. Summaries on the Basic Factors. As discussed above, the effects of pressure, \( L_{se} \), and circumferential position could be summarized and concluded as follows.

1. For a certain point, the increase of pressure produces overall decreasing \( q_{CHF} \), \( h_{CHF} \), and deceasing \( t_{CHF} \)
2. The effect of \( L_{se} \) plays ignorable roles on CHF, including \( q_{CHF} \) and \( h_{CHF} \)
3. Similar with LFP, because of the propagation of bubble separation front circumferentially, on a certain \( L_{se} \) (cross-section), there are both dominant point and dominated points, which are controlled by flow instability and both heat transfer and the dominant points. In the present study, 0.5-2, 0.75-2, and 1-3 are the dominant points for these sections, respectively

5.5. Discussions

5.5.1. Correlation on the Dominant Points. From the view of point of correlation, the effects of both pressure and
The circumferential position should be involved. The related strategy is similar with that for LFP, by which the dominant points and dominated points would be discussed, respectively.

As shown in Equation (12) and Table 4, in the present correlation on $\dot{q}_{\text{CHF}}$, $C_3$ is correlated to be 0.00982, 0.00835, and 0.00994 for dominant points, 0.5–2, 0.75–2, and 1–3, respectively. This shows that $C_3$ for 0.5–2 is well consistent to that for 1–3, which shows around 16% greater than that for 0.75–2. Of course, there is also another possibility that 0.75–2 is not the exactly dominant point. Nevertheless, for the dominant points in the vertical section, $\dot{q}_{\text{CHF}}$ could be correlated by Equation (12), in which $C_3$ could be suggested to be 0.00935, which produces the deviation within $\pm 12\%$, referring Figure 21.

Correlation format as Equation (12) shows for $\dot{q}_{\text{CHF}}$ is much different from that in the pool boiling, in which $\dot{q}_{\text{CHF}}$ was correlated to be linear versus parameter $B$ as shown in Equation (11) [37]. Equation (12) was approved by the present authors, which represents the effects of bubble size and fluid properties by parameter combination and the effects of $L_{se}$ and circumferential position by $C_3$ [29]. Figure 21 shows that on the dominant points of the vertical section, $\dot{q}_{\text{CHF}}$ is primarily controlled by bubble size and fluid properties, which are determined primarily by system pressure. In this way, on the vertical section of the present study, $\dot{q}_{\text{CHF}}$ could be well correlated by Equation (12) with the $C_3$ of 0.00935. Here, previous flow instability theories could not be used here, which has been discussed before [29].

On the other hand, Equation (17) gives good correlations on $h_{\text{CHF}}$ for both dominant points and dominated points. With the increase of pressure, all of the parameters including $\dot{q}_{\text{CHF}}, \Delta T_{\text{CHF}},$ and $h_{\text{CHF}}$ show the overall decreasing manner. In this way, a new parameter combination has been set up referring F-Z equation, as shown in Equation (16), and reliable correlations have been obtained by Equation (17).

5.5.2. Correlation on the Dominated Points. In the current stage, Equation (12) and $C_3$ listed in Table 4 could be suggested to predict $\dot{q}_{\text{CHF}}$ values for the dominated points. Similar with LFP, on this sort of points, bubble separation is not caused by local flow instability. Result indicates that at $t_{\text{CHF}}$, bubble separation happens on the dominant point of the current cross-section. Almost simultaneously, bubbles are
separated from the inner wall on all of this cross-section as a result of bubble separation front propagation circumferentially. In this way, on the dominated points, as a result of bubble separation front propagation circumferentially, on the dominated points, as a result of bubble separation front propagation circumferentially, when LFP or CHF happened on the dominant point, LFP or CHF would happen on the same cross-section (dominated points) in a short period.

5.5.3. Correlation Formats and Analyses. In the previous studies, \( q_{\text{LFP}} \) and \( \Delta T_{\text{CHF}} \) were always correlated [8]. However, in the present study, \( q_{\text{CHF}} \) and \( h_{\text{CHF}} \) were tried to be correlated instead of \( \Delta T_{\text{CHF}} \). This is the new correlation approach, similar with LFP. The primary parameter combinations in Equation (11), (12), and (17), used to predict \( q_{\text{CHF}} \) and \( h_{\text{CHF}} \), respectively, could be plotted versus pressure in Figure 23.

As shown in Figure 23, for \( \Delta T_{\text{CHF}} \), the correlation difficulties are more or less similar to those for \( \Delta T_{\text{LFP}} \). The key point is the primary parameter combination \( B \) in Equation (11) could not represent the effect of pressure.

For \( q_{\text{CHF}} \) analysis shows that the effects of pressure and circumferential position should be involved. In the present study, the strategies are similar with those for LFP. For involving the effect of circumferential position, dominant points and dominated points are identified. Results show that \( q_{\text{CHF}} \) could be well correlated by Equation (12). For three dominant points, \( C_3 \) in Equation (12) is approved to be 0.00935, and for dominated points, \( C_3 \) in Equation (12) is listed in Table 4. On the other hand, parameter combination in Equation (12) decreases linearly with the increase of pressure as shown in Figure 23. This indicates the effect of pressure, determining bubble size, and fluid properties could be represented well by this correlation.

For \( h_{\text{CHF}} \), Equation (17) could be suggested for both dominant points and dominated points. It shows that on the vertical section, it is determined by \( \Delta T_{\text{CHF}} \) and fluid properties, which are dominated by pressure.

6. Conclusion

LO_2 chill-down in a vertical exit-contracted pipe was studied experimentally. Wall temperature was detected in detail (various \( L_{\infty} \) and circumferential position, 1-east, 2-south, and 3-west) to investigate the filling and chill-down process. The filling and chill-down process was described in detail, on which the propagation of quenching front (QF) was detected. Two QFs were found, one for the exit QF and another for the inlet QF. It has been found that the chill-down process is controlled mainly by the formation and propagation of QFs, which are determined by the pressure level. Based on the experimental data, \( q_{\text{LFP}}, h_{\text{LFP}}, q_{\text{CHF}}, \) and \( h_{\text{CHF}} \) were correlated, respectively, for the vertical section. Primary conclusions could be listed as follows.

1. During LO_2 chill-down process in the vertical exit-contracted pipe, both exit QF and inlet QF are detected. Results show that on most cases, the propagation of the exit QF dominates the liquid rewetting for \( L_{\infty} = 0.5 \text{ m} \) and its downstreams.

2. For both LFP and CHF, circumferential position plays significant roles. On the vertical section, because of the proportions of QF or bubble separation front circumferentially, when LFP or CHF happens on the dominant point, LFP or CHF would happen on the same cross-section (dominated points) in a short period. On the dominant points, LFP is controlled by the flow instability, and CHF is controlled by the bubble size and fluid properties.
However, on the dominated points, both LFP and CHF are determined by the dominant points and heat transfer themselves.

(3) Both $\Delta T_{\text{LFP}}$ and $\Delta T_{\text{CHF}}$ have not been tried to be correlated. A series of difficulties have been discussed. At first, these two parameters are not independent themselves, and they are both determined by other parameters. On the other hand, the current parameter combinations could not represent the effects of pressure in such a wide range of pressure.

(4) Equations (8) and (9), involving the effects of pressure and $L_{\text{se}}$, could be suggested to predict $q_{\text{LFP}}$ and $h_{\text{LFP}}$ on the dominant points. Equations (2) and (3), with the similar formats with Equations (8) and (9) could be suggested to predict $q_{\text{CHF}}$ and $h_{\text{CHF}}$ on the dominated points by constant in Table 4.

(5) For $q_{\text{CHF}}$, Equation (12) would be suggested, with $C_3$ of 0.00935 for dominant points and $C_3$ listed in Table 4 for dominated points. Equation (17) could be strongly suggested to predict $h_{\text{CHF}}$ for both sorts of points.

### Nomenclature

|       | Description                                      |
|-------|--------------------------------------------------|
| $A$   | Area, m²                                         |
| $B$   | Parameter combination in correlations           |
| $C$   | Constant in correlations                        |
| $c$   | Specific heat, J·kg⁻¹·K⁻¹                       |
| $D$   | Diameter, m                                      |
| $E$   | Parameter combination in correlations           |
| $G$   | Mass flux in the experimental section, kg·m⁻²·s⁻¹|
| $g$   | Gravity acceleration, m·s⁻²                       |
| $H$   | Latent heat or enthalpy, J·kg⁻¹                 |
| $h$   | Heat transfer coefficient, W·m⁻²·K⁻¹             |
| $k$   | Heat conductivity, W·m⁻¹·K⁻¹, or constant in $k_{\text{FZ}}$ |
| $L$   | Distance, m                                      |
| $m$   | Mass flow rate, kg·s⁻¹                          |
| $N$   | Number of data                                  |
| $P$   | Pressure, Pa                                     |
| $Pr$  | Prandtl number, $c_p \cdot \mu \cdot k^{-1}$   |
| $q$   | Heat flux, W·m⁻²                                 |
| $Re$  | Reynolds number, $D_iG \cdot \mu_i^{-1}$        |
| $T$   | Temperature, K                                   |
| $t$   | Time, s                                          |
| $u$   | Velocity, m/s                                   |
| $V$   | Variables mainly represent $T_{\text{LFP}}$, $q_{\text{LFP}}$, $T_{\text{CHF}}$, and $q_{\text{CHF}}$ data. |

### Subscripts

- **bu**: The bubble
- **CHF**: Critical heat flux point
- **cr**: Critical properties
- **exp**: Experimental data
- **FZ**: Forster-Zuber parameter
- **FB**: Film boiling
- **i**: The inner wall of the pipe
- **inj**: Injector on the pipe exit
- **LFP**: Inner wall data of the Leidenfrost point
- **l**: Liquid phase
- **NB**: Nuclear boiling
- **o**: The outer wall of the pipe
- **p**: Fluid in the experimental section, or constant pressure in $c_p$
- **peak**: Value of the pressure peak
- **pre**: Predicted data by correlations
- **s**: The solid material
- **sat**: Saturation condition
- **se**: Saturation parameter on inner wall temperature
- **ss**: Steady-state condition, the chill-down finishes
- **v**: Vapor phase
- **vl**: From vapor phase to liquid phase

### Greek Symbols

- $\mu$: Viscosity, Pa·s
- $\rho$: Density, kg·m⁻³
- $\sigma$: Surface tension, N·m⁻¹
- $\delta$: Thickness of film, m.

### Data Availability

Data have been uploaded by “supplemental files” with manuscript file.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Supplementary Materials

In the “Supplementary files” section, a file named “Data_B,” including the LFP and CHF data in the format of table has been uploaded with the manuscript. Related description has been given in the previous section “Data Availability.” (Supplementary Materials)

### References

[1] D. Conte, D. Budzyń, H. Burgoyne et al., “Innovative Mars Global International Exploration (IMaGlInE) mission,” in AIAA Space 2016, Long Beach, California, 2016.

[2] E. A. Hurbert, R. Whittley, M. D. Kelm et al., “International space exploration coordination group assessment of technology gaps for LOx/methane propulsion systems for the global exploration roadmap,” in AIAA Space 2016, Long Beach, California, 2016.

[3] H. C. Hansen, W. L. Johnson, M. L. Meyer, A. H. Werkheiser, and J. R. Stephens, “Cryogenic fluid management technologies enabling for the Artemis program and beyond,” in ASCEND 2020, Virtual Event and Cincinnati, Ohio, 2020.

[4] T. D. Smith, M. D. Kelm, and K. L. Fisher, “Propulsion risk reduction activities for non-toxic cryogenic propulsion,” in AIAA SPACE 2010 Conference & Exposition,Anaheim, California, 2010.

[5] T. Polsgrove, D. Thomas, S. Sutherlin, W. Stephens, and M. Rucker, “Mars ascent vehicle design for human exploration,” in AIAA SPACE 2015 Conference and Exposition, Pasadena, California, 2015.
[6] J. Collins, E. Hurlbert, K. Romig, J. Melcher, A. Hobson, and P. Eaton, "Sea-level flight demonstration and altitude character-
ization of a LO2/LCH4 based ascent propulsion lander," in 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibi-
t, Denver, Colorado, 2009.

[7] S. R. Darr, J. W. Hartwig, J. Dong et al., "Two-phase pipe quenching correlations for liquid nitrogen and liquid hydro-
gen," Journal of Heat Transfer, vol. 141, no. 4, 2019.

[8] J. Zhang, K. Wang, and L. Chen, "Characteristics of boiling transitions during liquid oxygen chill-down in a horizontal pipe with an injector on the exit," Applied Thermal Engineering, vol. 182, article 116068, 2021.

[9] J. N. Chung, "Cryogenic two-phase flow and boiling heat transfer during pipe chilldown (invited)," in 37th AIAA Thermophysics Conference, Portland, Oregon, AIAA, 2004.

[10] K. Yuan, Y. Ji, and J. N. Chung, "Cryogenic boiling and two-
phase flow during pipe chilldown in earth and reduced gravity," Journal of Low Temperature Physics, vol. 150, no. 1-2, pp. 101–122, 2008.

[11] K. Yuan, Y. Ji, and J. N. Chung, "Cryogenic chilldown process under low flow rates," International Journal of Heat and Mass Transfer, vol. 50, no. 19-20, pp. 4011–4022, 2007.

[12] J. Chen, R. Zeng, X. Zhang, L. Qiu, and J. Xie, "Numerical modeling of flow film boiling in cryogenic chilldown process using the AIAD framework," International Journal of Heat and Mass Transfer, vol. 124, pp. 269–278, 2018.

[13] H. Hu, T. K. Wijeratne, and J. N. Chung, "Two-phase flow and heat transfer during chilldown of a simulated flexible metal hose using liquid nitrogen," Journal of Low Temperature Physics, vol. 174, no. 5-6, pp. 247–268, 2014.

[14] R. Shaheffer, H. Hu, and J. N. Chung, "An experimental study on liquid nitrogen pipe chilldown and heat transfer with pulse flows," International Journal of Heat and Mass Transfer, vol. 67, pp. 955–966, 2013.

[15] S. R. Darr, H. Hu, N. G. Glikin et al., "An experimental study on terrestrial cryogenic transfer line chilldown I. Effect of mass flux, equilibrium quality, and inlet subcooling," International Journal of Heat and Mass Transfer, vol. 103, pp. 1225–1242, 2016.

[16] S. R. Darr, H. Hu, N. G. Glikin et al., "An experimental study on terrestrial cryogenic tube chilldown II. Effect of flow direction with respect to gravity and new correlation set," International Journal of Heat and Mass Transfer, vol. 103, pp. 1243–1260, 2016.

[17] L. Jin, C. Park, H. Cho, C. Lee, and S. Jeong, "Experimental investigation on chill-down process of cryogenic flow line," Cryogenics, vol. 79, pp. 96–105, 2016.

[18] L. Jin, H. Cho, C. Lee, and S. Jeong, "Experimental research and numerical simulation on cryogenic line chill-down pro-
cess," Cryogenics, vol. 89, pp. 42–52, 2018.

[19] L. Jin, H. Cho, and S. Jeong, "Experimental investigation on line chill-down process by liquid argon," Cryogenics, vol. 97, pp. 31–39, 2019.

[20] L. Jin, J. Lee, and S. Jeong, "Investigation on heat transfer in line chill-down process with various cryogenic fluids," International Journal of Heat and Mass Transfer, vol. 150, article 119204, 2020.

[21] J. Johnson and S. R. Shine, "Transient cryogenic chill down process in horizontal and inclined pipes," Cryogenics, vol. 71, pp. 7–17, 2015.

[22] J. Wang, Y. Li, L. Wang, K. Zhu, F. Xie, and C. Li, "Transient modeling of cryogenic two-phase flow boiling during chill-
down process," Applied Thermal Engineering, vol. 143, pp. 461–471, 2018.

[23] A. C. LeClair, J. W. Hartwig, D. M. Hauser, M. Kassemi, P. G. Diaz-Hyland, and T. R. Going, "Modeling cryogenic chilldown of a transfer line with the generalized fluid system simulation program," in 2018 Joint propulsion conference, p. 4756, Virtual Event and Cincinnati, Ohio, 2018.

[24] J. C. Melcher and R. L. Morehead, "Combustion stability character-
istics of the project morpheus liquid oxygen/liquid methane main engine," in 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, 2014.

[25] P. Cui, Q. Li, P. Cheng, and L. Chen, "System scheme design for LOX/LCH4 variable thrust liquid rocket engines using motor pump," Acta Astronautica, vol. 171, pp. 139–150, 2020.

[26] R. L. Morehead, J. C. Melcher, M. J. Atwell, E. A. Hurlbert, and P. Desai, "Vehicle-level oxygen/methane propulsion system hotfire demonstration at thermal vacuum conditions," in 53rd AIAA/ASME/ASEE Joint Propulsion Conference, Atlanta, GA, 2017.

[27] N. Cho, S. Kim, Y. Kim, and S. J. Jung, "Two-phase flow characteristics of liquid oxygen flow in low pressure liquid rocket engine," Cryogenics, vol. 44, no. 6-8, pp. 493–500, 2004.

[28] J. Zhang, K. Wang, and L. Chen, "Experimental study on liquid oxygen chilldown in the horizontal pipe with an injector on the exit," Applied Thermal Engineering, vol. 173, article 115212, 2020.

[29] J. Zhang, K. Wang, and L. Chen, "Experimental study on liquid oxygen chill-down in a horizontal exit-contracted pipe," Cryogenics, vol. 120, article 103387, 2021.

[30] H. Hong, N. Jacob, A. Chung, and S. H. Amber, "An experimental study on flow patterns and heat transfer characteristics during cryogenic chilldown in a vertical pipe," Cryogenics, vol. 52, no. 4-6, pp. 268–277, 2012.

[31] J. Hartwig, S. Darr, and A. Asencio, "Assessment of existing two phase heat transfer coefficient and critical heat flux corre-
lations for cryogenic flow boiling in pipe quenching experiments," International Journal of Heat and Mass Transfer, vol. 93, pp. 441–463, 2016.

[32] N. Zuber, M. Tribus, and J. W. West, "The hydrodynamic cri-
is in pool boiling of saturated and subcooled liquid," Interna-
tional Development in HEAT Transfer, pp. 230–236, 1961.

[33] P. J. Berenson, "Film-boiling heat transfer from a horizontal surface," Journal of Heat Transfer, vol. 83, no. 3, pp. 351–356, 1961.

[34] Y. Katto and C. Kurata, "Critical heat flux of saturated convect-
ive boiling on uniformly heated plates in a parallel flow," International Journal of Multiphase Flow, vol. 6, no. 6, pp. 575–582, 1980.

[35] J. J. Carbajo, "A study on the rewetting temperature," Nuclear Engineering and Design, vol. 84, no. 1, pp. 21–52, 1985.

[36] H. K. Forster and N. Zuber, "Dynamics of vapor bubbles and boiling heat transfer," AIChE Journal, vol. 1, no. 4, pp. 531–535, 1955.

[37] N. Zuber, "Nucleate boiling. The region of isolated bubbles and the similarity with natural convection," International Journal of Heat and Mass Transfer, vol. 6, no. 1, pp. 53–78, 1963.