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Review article

Pool boiling in liquid hydrogen, liquid methane and liquid oxygen: A review of available data and predictive tools

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A B S T R A C T

The experimental data accessible in the open literature related to pool boiling of liquid hydrogen (LH2), liquid methane (LCH4), and liquid oxygen (LO2) were compiled. Pool nucleate boiling of LH2 data were compiled from 17 sources, and pool film boiling of LH2 data were compiled from six sources. Pool nucleate boiling of LCH4 data were collected from eight sources, and useful data for pool film boiling of LCH4 were found from only three sources, all representing boiling on the outside surface of horizontal cylinders. For LO2, pool nucleate boiling data from 11 sources were compiled, and useful pool film boiling data could be found from only four sources, three for horizontal cylinders and one for vertical cylinders. The predictions of 19 pool nucleate and 10 pool film boiling correlations were compared with experimental data for the three cryogens. The film boiling data were only compared with appropriate models and correlations based on surface geometry and orientation.

Overall, pool nucleate boiling data for all three fluids display considerable scatter, and existing correlations are unable to effectively narrow the scatter to better than an order of magnitude. The correlations of Stephan and Abdelsalam (1980) and Forster and Zuber (1955) perform best for LH2, and can predict the bulk of the existing heat flux data within an order of magnitude. They can predict respectively, 38% and 27% of the data within a factor of two. The correlations of Bier and Lambert (1990) and Forster and Zuber (1955) perform best for nucleate boiling of LCH4 and can predict the bulk of the existing heat flux data within an order of magnitude. They can predict respectively, 58% and 49% of the data within a factor of two. For LO2, the correlations of Forster and Zuber (1955) and Bier and Lambert (1990) provide the best agreement with experimental data for nucleate pool boiling, and can predict the heat flux data within an order of magnitude. They could predict respectively, 50% and 47% of the data within a factor of two.

The film boiling data show smaller scatter in comparison with nucleate boiling, and can be predicted by existing correlations with reasonable accuracy.

1. Introduction

Liquid hydrogen (LH2), liquid methane, (LCH4) and liquid oxygen (LO2) are among the most important cryogenic propellants, and their applications in space systems are expected to expand in the future. Transport, storage, and delivery of these and other liquefied cryogens often involve boiling and two-phase flow. Models with good fidelity are thus required for boiling and two-phase flow processes for these cryogens for reliable design of their transport and delivery systems. The most widely-encountered pool boiling regimes are nucleate boiling (NB) and film boiling. These boiling/heat transfer regimes have been studied in the past rather extensively. However, boiling regimes and thresholds in their entirety, including critical heat flux (CHF), transition boiling (TB), and minimum film boiling (MFB), occur in transient processes and need to be investigated. An example of such processes is the chill-down of transfer passages for liquid cryogens.

The literature dealing with pool and flow boiling is vast. Monographs and textbooks that present a summary of the well-established models and correlations include [1] and [2]. Most of the existing data and predictive methods are for water and refrigerants, however. The applicability of well-established predictive methods to cryogenic fluids, except for a few correlations for which the data bases include cryogens [often liquid nitrogen (LN2)], is at best uncertain.

In this paper we report on the results of an investigation aimed at the compilation and review of the existing experimental data and predictive methods for pool and flow boiling in LH2, LCH4, and LO2. The objectives of the investigation are to:

(1) Compile the existing data dealing with pool and flow boiling of key cryogens that are of interest as cryogenic propellants, including LH2, LCH4 and LO2

(2) Assess the applicability or otherwise of well-established boiling heat transfer correlations for these cryogens

(3) Develop a roadmap for remedial experimental studies aimed at filling the important gaps in the experimental data

In this paper pool nucleate and film boiling are discussed. Pool boiling regime thresholds including critical heat flux, minimum film billing. Flow boiling will be presented in follow-up papers in the future.

Abbreviations: CHF, critical heat flux; DNB, departure of nucleate boiling; HTC, heat transfer coefficient; ID, inner diameter; LCH4, liquid methane; LH2, liquid hydrogen; LO2, liquid oxygen; MFB, minimum film boiling; ONB, onset of nucleate boiling; OD, outer diameter; PN, pool nucleate; PF, pool film.

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Notation

C_p	specific heat
D	diameter of disk or pipe
d_B	diameter of bubble
f	Darcy friction factor
G	mass flux
g	gravitational constant
H	height of plate
h	heat transfer coefficient
$h_{fg} h_g - h_f$	latent heat of vaporization
k	thermal conductivity
L	length
M	molar mass
Nu	Nusselt number
P	pressure
p_{heat}	heated perimeter
R_p	roughness parameter
q''	heat flux
t	thickness of plate or tube
T	temperature
ΔT	Wall superheat (T_w -T_{sat})
W	width of plate
x	thermodynamic quality

Greek letters

α	thermal diffusivity
$\Delta\rho$	$\rho_f - \rho_g$
θ	angle of channel with respect to the horizontal, contact angle
λ	laplace length scale $\sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}$
μ	dynamic viscosity
ν	kinematic viscosity
ν_{fg}	$\nu_g - \nu_f$
ρ	density
σ	surface tension

Subscripts

cr	critical
e	equilibrium
f	liquid phase
g	vapor phase
H	hydraulic
r	reduced
s	solid phase
w	wall

2. Methodology and rationale

A thorough search of the open literature has been performed with the purpose of compiling experimental data dealing with boiling of LH2, LCH4 and LO2. The sources of data can generally be divided into two groups, primary and secondary. Primary sources are publications that directly report on data generated by the authors of a publication or the institution where the experiments have been performed. Secondary sources either depict or report on data generated by others, or use such data for model validation or other purposes. Primary sources are evidently more reliable and easier to process, nevertheless secondary sources are also important when dealing with data for which the primary source is difficult to find or even fully understand. The data collected in this study have been reported in a variety of document types, including journal and conference papers as well as reports, and cover several decades, some dating back to the 1940s. Furthermore, data available in tabular form are few, and most of the available data are in graphical form. These graphs were digitized and their data extracted. The secondary sources virtually all depict experimental data in graphs where the data are used for model comparison and validation, and occasionally for displaying data trends. The data extracted in this way often need extra calculations and are therefore more prone to uncertainty.

3. Summary of boiling correlations and models used for comparison with data

Some of the most widely referenced correlations with respect to the boiling of cryogenic fluids are reviewed below. The selected correlations are either of known and proven general applicability, or have in the past been applied to cryogens, and they are presented below in Tables 1 and 2 in chronological order of development. The correlations of Clark [3], Gilmour [4], Borishanki [5],Nishikawa et al. [6], and Jung et al. [7] were analyzed but are not discussed here due to their poor performance against the pool of experimental data for all fluids.

4. Pool boiling of liquid hydrogen

Fig. 1 displays the ranges of the available experimental data for pool boiling of LH2. As noted, with the exception of TB and MFB, virtually all pool boiling regimes have been investigated, and there is extensive experimental data, in particular for the pool nucleate and film boiling regimes. However, investigations that have addressed the entire boiling regime are few and are generally relatively old. The more recent studies, dating back to the start of the 21st century, are often focused on pool and flow nucleate boiling, and in a few cases on pool and flow film boiling. These data cover a wide range of pressures. Counter to the nucleate and film boiling studies, TB and MFB have received literally no attention, and CHF has only been addressed by two investigations.

Table 3 is a summary of the compiled past studies dealing with pool boiling of LH2. A few old investigations which were not accessible are not depicted in Fig. 1. However, in view of the relative abundance of more recent data dealing with boiling of LH2, the exclusion of the experimental data of these documents are not considered to be a serious loss. The majority of the listed studies are experimental; however, some modeling and simulation studies that compare the boiling LH2 data with models and correlations are also mentioned. The data include both flat surfaces and cylindrical heated elements, incorporating a large variety of surface materials.

4.1. Comparison of LH2 nucleate pool boiling data with correlations

The existing data represent different test parameters, including different heated surface materials and conditions. These differences can be the cause of at least some of the scatter in the data. In what follows, however, the available data are compared with some of the most widely-referenced correlations for pool nucleate boiling, without an attempt to consider the aforementioned parametric effects. The objective is to examine the overall reliability of these correlations for scoping analysis and design calculations when pool nucleate boiling of LH2 is considered.

Table 1
Correlations for pool nucleate boiling.

Source	Correlation	Comments
Kruzhilin (1947), applied in [5]	$\frac{h\lambda}{k_f} = 0.082\left\{\left[\frac{h_{fg}q_w^{"}}{gT_{sat}k_f}\right]\left[\frac{\rho_g}{\rho_f-\rho_g}\right]\right\}^{0.7}\left[\frac{T_{sat}C_{p_f}\sigma\rho_f}{h_{fg}^2\rho_g^2\lambda}\right]^{0.33}Pr_f^{-0.45}$ (1)	
Kutateladze (1952) [8], applied in [3]	$q_w^{"} = 5.66\times10^{-10}\frac{k_fC_{p_f}^{1.5}\rho_f^{1.28}p^{1.75}}{\mu_f^{0.625}\sigma^{0.9}h_{fg}^{1.5}\rho_g^{1.5}}(T_w-T_{sat})^{2.5}$ (2)	This version of the correlation requires SI units
Rohsenow (1952) [9]	$C_{p_f}\frac{T_w-T_{sat}}{h_{fg}} = 0.013\left(\frac{q_w^{"}}{h_{fg}\mu_f}\sqrt{\frac{\sigma}{g\Delta\rho}}\right)^{0.33}\left(\frac{C_{p_f}\mu_f}{k_f}\right)^{1.7}$ (3)	Applicable to various fluids. This version is used for cryogens
McNelley (1953), applied in [4]	$\frac{hD_H}{k_f} = 0.225\left(\frac{D_Hq_w^{"}}{h_{fg}\mu_f}\right)^{0.69}\left(\frac{PD_H}{\sigma}\right)^{0.31}\left(\frac{\rho_f}{\rho_g}-1\right)^{0.33}\left(\frac{C_{p_f}\mu_f}{k_f}\right)^{0.69}$ (4)	
Kichigin and Tobilevich (1955) [10]	$\frac{h\lambda}{k_f} = 3.25\times10^{-4}\left(\frac{q_w^{"}\lambda}{h_{fg}\nu_f\rho_g}\right)^{0.6}Pr_f^{0.6}\left(\frac{g\lambda^3}{\nu_f^2}\right)^{0.125}\left[\frac{P_{sat}}{\sqrt{\sigma g(\rho_f-\rho_g)}}\right]^{0.7}$ (5)	
Forster and Zuber (1955) [11]	$\frac{q_w^{"}}{\rho_gh_{fg}}\sqrt{\frac{\pi}{\alpha_f}}\left(\frac{\rho_fR^{*3}}{2\sigma}\right)^{0.25} = 0.0015\left\{\frac{\rho_f}{\mu_f}\left[\frac{(T_w-T_{sat})k_f}{\rho_gh_{fg}}\right]^2\frac{\pi}{\alpha_f}\right\}^{\frac{5}{8}}\left(\frac{\mu_fC_{p_f}}{k_f}\right)^{\frac{1}{3}}$ (6)	
	$R^* = \frac{2\sigma}{P_{sat}(T_w)-P}$ (7)	
Borishanski and Minchenko (1961), applied in [4]	$\frac{h\lambda}{k_f} = 8.7\times10^{-4}\left(\frac{q_w^{"}\lambda}{\alpha_f\rho_gh_{fg}}\right)^{0.7}\left(\frac{P\lambda}{\sigma}\right)^{0.7}$ (8)	
Borishanski and Zhokhov (1968) [12]	$\frac{q_w^{"}}{k_f(T_w-T_{sat})} = 5.32\times 10^{-7}\left(1+\frac{1.85k_f(T_w-T_{sat})Pr_f^3\rho_f}{h_{fg}\rho_g\mu_f}\right)\left(\frac{h_{fg}\rho_g(T_w-T_{sat})}{T_{sat}\sigma}\right)^{1.5}$ (9)	
Labuntsov (1972), applied in [5]	$h = 0.075\left[1+10\left(\frac{\rho_g}{\rho_f-\rho_g}\right)^{2/3}\right]\left(\frac{k_f^2}{\nu_f\sigma T_{sat}}\right)^{1/3}q_w^{"2/3}$ (10)	
Stephan and Abdelsalam (1980) [13]	$Nu_{d_B} = 4.82\left(\frac{q_w^{"}d_B}{k_fT_{sat}}\right)^{0.624}\left[\frac{(\rho C_pk)_s}{(\rho C_pk)_f}\right]^{0.117}\left(\frac{\rho_g}{\rho_f}\right)^{0.257}\left(\frac{C_{p_f}T_{sat}d_B^2}{\alpha_f^2}\right)^{0.374}\left(\frac{h_{fg}d_B^2}{\alpha_f^2}\right)^{-0.329}$ (11)	This correlation was developed exclusively for cryogens
	$d_B = 0.0208\theta\sqrt{\frac{\sigma}{g\Delta\rho}}$ (12) Fritz (1935) [14]	
Cooper (1984) [15]	$q_w^{"1/3} = 55\left(\frac{P}{P_{cr}}\right)^n\left(-\log_{10}\frac{P}{P_{cr}}\right)^{-0.55}M^{-0.5}(T_w-T_{sat})F_{Cu}$ (13)	This version of the correlation requires SI units. When surface roughness in unknown, $n = 0.12$
	$n = 0.12-0.21\log_{10}R_P$ (14)	
	$F_{Cu}\begin{cases}1.7, horizontal tube or copper cylinders\\ 1, otherwise\end{cases}$ (15)	
Bier and Lambert (1990) [16]	$q_w^{"} = 3072+28,546exp\left(-5.248\times10^6\frac{T_{sat}\sigma}{h_{fg}\rho_g}\right)(T_w-T_{sat})$ (16)	This version of the correlation requires SI units
Grigorev et al. (1973) [17]	$q_w^{"} = \frac{A^3h_{fg}\rho_g(T_w-T_{sat})}{T_{sat}\sigma(A+1.6K)}\left(\frac{0.8\times10^{-4}k_f(T_w-T_{sat})\rho_f}{\mu_f}+1.0\times10^{-4}h_{fg}\rho_g\right)$ (17)	This correlation was developed using cryogenic test data
	$A = -K+\sqrt{K^2+0.4545M}$ (18)	
	$K = \frac{k_f}{0.00809k_s}\sqrt{\frac{2}{3}\pi\alpha_s}$ (19)	
	$M = \frac{200k_f(T_w-T_{sat})}{h_{fg}\rho_g}$ (20)	
Gorenflo (1993) [18]	$\frac{h}{h_0} = F_{PR}\left(\frac{q_w^{"}}{q_0}\right)^n\left(\frac{R_P}{R_{P0}}\right)^{0.133}$ (21)	Values of h_0 are provided by the author for various fluids, including some cryogens. h_0 should be calculated by another trusted correlation if fluid is not listed.
	$F_{PR} = 1.2P_r^{0.27}+\left(2.5+\frac{1}{1-P_r}\right)P_r$ (22)	
	$n = 0.9-0.3P_r^{0.3}$ (23)	
	$q_0^{"} = 20,000\frac{W}{m^2}$ (24)	
	$P_r = 0.1$ (25)	

Table 2
Correlations for Pool Film Boiling.

Source	Correlation	Comments
Hsu and Westwater (1958) [19]	$h\left[\frac{\mu_v^2}{k_v^2\rho_v(\rho_f-\rho_v)g}\right]^{1/3} = 0.002Re_v^{0.6}$ (26) $Re_v = \frac{4\dot{m}_v}{\pi D\mu_v}$ (27)	Vertical tubes
Chang (1959) [20]	$h = 0.234\left[\frac{k_g^2\rho_g\Delta\rho g h_{fg}^{'}}{\mu_g(T_w-T_{sat})}\right]^{0.333}$ (28) $h = 0.72\left[\frac{k_g^3\rho_g\Delta\rho g h_{fg}^{'}}{\mu_g(T_w-T_{sat})\lambda}\right]^{0.25}$ (29) $h_{fg}^{'} = h_{fg}\left[1+0.5C_{p_g}\frac{T_w-T_{sat}}{h_{fg}}\right]$ (30)	Eq. 28 is for horizontal flat surfaces; Eq. 29 is for vertical cylinders
Sciance et al.(1967) [21]	$\frac{q_w^{''}\lambda}{k_g(T_w-T_{sat})} = 0.346\left[\frac{\lambda^3\rho_g\Delta\rho g Pr_g h_{fg}^{'}}{\mu_g^2C_{p_g}T_f^2(T_w-T_{sat})}\right]^{0.276}$ (31) $h_{fg}^{'}$ found from Eq. 30	Horizontal cylinders
Berenson (1961) [22]	$h = 0.425\left[\frac{k_g^3\rho_g\Delta\rho g h_{fg}^{'}}{\mu_g(T_w-T_{sat})\lambda}\right]^{0.25}$ (32) $h_{fg}^{'}$ found from Eq. 30	Horizontal flat surfaces
Breen and Westwater (1962) [23]	$h = (0.59+0.069C)\left[\frac{k_g^3\rho_g\Delta\rho g h_{fg}^{'}}{\mu_g(T_w-T_{sat})\lambda_{cr}}\right]^{0.25}$ (33) $\lambda_{cr} = 2\pi\lambda$ (34) $C = \min(1,\frac{\lambda_{cr}}{D})$ (35) $h_{fg}^{'}$ found from Eq. 30	Horizontal cylinders
Modified Bromley (1978) [1]	$h = 0.663\left[\frac{k_g^3\rho_g\Delta\rho g h_{fg}^{'}}{\mu_g(T_w-T_{sat})\lambda}\right]^{0.25}$ (36) $h_{fg}^{'} = h_{fg}\left[1+0.34C_{p_g}\frac{T_w-T_{sat}}{h_{fg}}\right]$ (37)	Vertical surfaces
Klimenko (1981–1982) [24,25]	For $\frac{\lambda_{cr}^3g}{\nu_g^2}\left(\frac{\rho_f}{\rho_g}-1\right) < 1\times10^8$: $\frac{h\lambda_{cr}}{k_f} = 0.19\left[\frac{\lambda_{cr}^3g}{\nu_g^2}\left(\frac{\rho_f}{\rho_g}-1\right)\right]^{0.333}Pr_g^{0.333}f_1(K)$ (38) $K = \frac{h_{fg}}{C_{p_g}(T_w-T_{sat})}$ (39) $f_1(K) = \begin{cases} 1 & K < 1.4 \\ 0.89K^{0.333} & K > 1.4 \end{cases}$ (40) For $\frac{\lambda_{cr}^3g}{\nu_g^2}\left(\frac{\rho_f}{\rho_g}-1\right) > 1\times10^8$: $\frac{h\lambda_{cr}}{k_f} = 0.0086\left[\frac{\lambda_{cr}^3g}{\nu_g^2}\left(\frac{\rho_f}{\rho_g}-1\right)\right]^{0.5}Pr_g^{0.333}f_2(K)$ (41) $f_2(K) = \begin{cases} 1 & K < 2.0 \\ 0.71K^{0.5} & K > 2.0 \end{cases}$ (42)	Horizontal flat surfaces
Sakurai et al. (1990) [26,27], applied in [28]	$\frac{Nu}{\left(1+\frac{2}{Nu}\right)} = K(D^{'})[M^{*}]^{0.25}$ (43) $K(D^{'}) = \begin{cases} 0.415D^{'0.25} & D^{'} > 6.6 \\ \frac{2.1D^{'}}{1+3.0D^{'}} & 1.25 \le D^{'} \le 6.6 \\ \frac{0.75}{1+0.28D^{'}} & 0.14 \le D^{'} \le 1.25 \end{cases}$ (44) $M^{*} = \frac{\left(\frac{Gr_g}{Sp}\right)\left[\frac{E^3}{\left(1+\frac{E}{SpPr_f}\right)}\right]}{(RPr_fSp)^2}$ (45) $E = \left(A+C\sqrt{B}\right)^{0.333}+\left(A-C\sqrt{B}\right)^{0.333}+\frac{1}{3}Sc^{*}$ (46) $A = \frac{1}{27}Sc^{*3}+\frac{1}{3}R^2SpPr_fSc^{*}+\frac{1}{4}R^2Sp^2Pr_f^2$ (47) $B = \frac{-4}{27}Sc^{*2}+\frac{2}{3}SpPr_fSc^{*}-\frac{32}{27}SpPr_fR^2+\frac{1}{4}Sp^2Pr_f^2+\frac{2}{27}\frac{Sc^{*3}}{R^2}$ (48) $C = \frac{1}{2}R^2SpPr_f$ (49) $D^{'} = D\sqrt{\frac{g\Delta\rho}{\sigma}}$ (50) $R = \sqrt{\frac{\rho_g\mu_g}{\rho_f\mu_f}}$ (51) $Sp = \frac{C_{p_g}\Delta T_{sat}}{h_{fg}^{'}Pr_g}$ (52)	Horizontal cylinders

(*continued on next page*)

Table 2 (*continued*)

Source	Correlation	Comments
	$Sc = \frac{C_{p_f}\Delta T_{sub}}{h_{fg}^{'}}$ (53) $Sc^{*} = 0.93Pr_f^{0.22}Sc$ (54) $h_{fg}^{'}$ is found from Eq. 30	

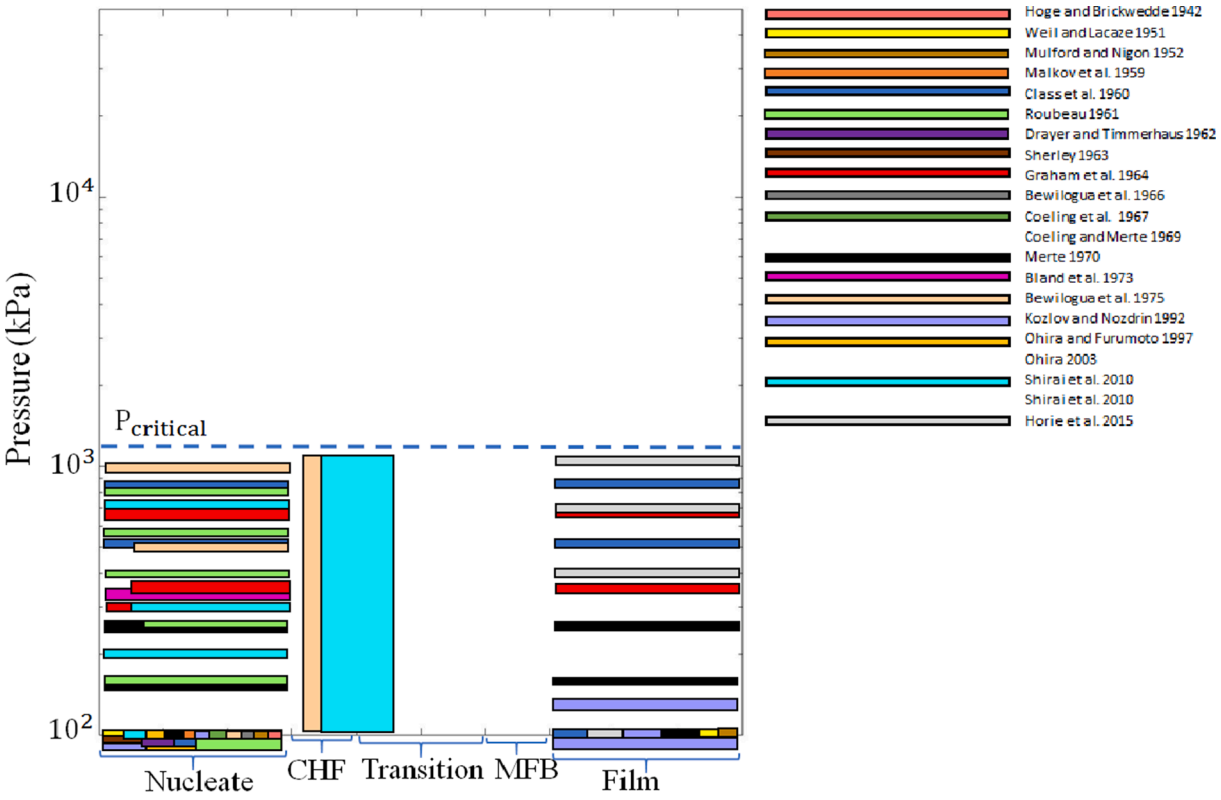

Fig. 1. The range of existing experimental data for pool boiling of LH2.

Fig. 2 displays all of the pool nucleate boiling data points on a heat flux vs. wall superheat plot. The data represent different heated surface geometries, materials, pressures, and surface conditions. The displayed data represent nucleate pool boiling on horizontal or vertical surfaces, both flat as well as cylindrical heated elements, and are limited to normal gravity. Significant scatter can be noted in the data, even among data representing similar test conditions. The profiles of the data from various authors all agree with the expected profile in the nucleate pool boiling regime and do not suggest the occurrence of CHF or film boiling even for cases where wall superheat is high. However, some of the data points represent extremely low wall superheats indicating that at least some of these data points may in fact represent free convection (see Fig. 3).

The experimental data have been compared with all the correlations that were presented earlier. Table 4 depicts a summary of the statistics related to the comparison between the entire compiled experimental data and various correlations. The table includes the percentage error, which is defined as

$$\xi = \frac{q''_{predicted} - q''_{exp}}{q''_{exp}} \tag{55}$$

Evidently, values of the percentage error closer to zero indicate better agreement. Before the statistical data analysis was performed, the 7.2 bar test case of Shirai et al. [55] and the 1 bar platinum wire test case of Merte [45] were removed due to their disagreement with every considered correlation by at least an order of magnitude. The best performing correlations considering the remaining 879 data points are provided in Table 4. The correlations of McNelly (Eq. (4)) and Cooper (Eqs. (13)–(15)), which greatly under predicted and over predicted the test data respectively, are not included.

Fig. 4 compares the LH2 pool nucleate boiling data on horizontal flat surfaces generated at near-atmospheric pressures with the predictions of three correlations. The correlations depicted in this figure in fact perform best among all the correlations, and can predict most of the

Table 3
Summary of past studies for pool boiling of LH2.

Source	Data Type	Boiling Regime	Geometry & Orientation	Material	Operating Condition	Additional Comments
Weil and Lacaze [29]	Plots	Pool nucleate Pool film	Wire (unknown orientation) D = 0.4 mm, 3 mm	Lead	Atmospheric pressure	Other fluids: LN2 Roughness unspecified
Mulford and Nigon [30]	Plots	Pool nucleate Pool film	Cylinder (horizontal) D = 12 mm	Copper	Atmospheric pressure	Other fluids: LN2 Cannot access paper; data extracted from Seader et al. [31] Roughness unspecified
Malkov et al. [32]	Plots	Pool nucleate	Coiled tube (vertical) D = 45 mm	Monel alloy	Atmospheric pressure	Other fluids: LO2 Roughness unspecified
Class et al. [33]	Plots	Pool nucleate Pool film	Rectangular plate (vertical, horizontal, 45°) L = 25.4 mm W = 558.8 mm	Karma alloy	For nucleate: P = 0.83 bar, 0.91 bar, 5.2 bar, 8.7 bar, For film: P = 1 bar, 5.2 bar, 8.8 bar	Compared with correlations: For nucleate: Forster and Zuber (1955) For film: Bromley (1950) ε= 0.15 μm, 0.69 μm
Roubeau [34]	Plots	Pool nucleate	Square plate (horizontal) L = 2.236 cm	Copper	P = 0.47 bar, 0.91 bar, 1.6 bar, 2,6 bar, 3.9 bar, 5.7 bar, 8 bar	Roughness unspecified
Drayer and Timmerhaus [35]	Plots, Tables	Pool nucleate	Cylinder (vertical) D = 15.9 mm	Brass	P = 0.84 bar	$0.4\mu m \leq \varepsilon \leq 0.8\mu m$
Sherley [36]	Plots	Pool nucleate	Rectangular plate (horizontal) L = 76.2 mm W = 25.4 mm	Copper Gold Chromium Germanium Nickel Lead	Gravity = 0g, 1g P = 0.81 bar	Plot data is unclear as to which metals constituted the heating surface Lead surface described as “fairly smooth;” surface condition for other metals is unspecified
Graham et al. [37]	Plots	Pool nucleate Pool film	Rectangular plate (vertical) Dimensions not specified but estimated to be: L = 33.53 cm W = 10.36 cm	Chromel-A heating element on a Bakelite block	Gravity = 1g-10 g $\Delta T_{sub} \leq 2.77$ K For nucleate: P = 2.9 bar, 3.4 bar , 3.6 bar, 6.3 bar, 6.7 bar For film: P = 3.5 bar, 6.7 bar	Roughness unspecified
Brentari et al. [38]	Plots	Pool nucleate Pool film				This is a secondary source containing multiple experiments conducted at atmospheric pressure; furthermore it contains an extensive literature review Compared with correlations: For nucleate: Kutateladze (1952) For film: Breen and Westwater (1962) Other fluids: LO2, LN2, LHe
Seader et al.[31]	Plots	Pool nucleate Pool film				This is a secondary source containing multiple experiments conducted at atmospheric pressure; furthermore it contains an extensive literature review Other fluids: LO2, LN2
Bewilogua et al. [39]	Plots	Pool nucleate	Coiled tube (horizontal) D = 0.6 mm	Stainless steel	Atmospheric pressure	Other fluids: Neon, LN2, LAr Surface condition describes as “smooth”
Chi [40]	Plots	Pool nucleate Pool film				New correlation proposed; no new data
Coeling et al. [41]	Plots, Tables	Pool nucleate	Disk (horizontal) D = 25.4 mm	347 Stainless steel Copper TFE Teflon Glass fiber with epoxy cement coating	Atmospheric pressure	Surface roughness: Stainless steel: 0.13 μm, 0.2 μm, 0.79 μm Copper: 0.1 μm, 0.23 μm
Bewilogua and Knöner [42]	Plots	Pool film	Cylinder (vertical) Diameter not specified	Lead with stainless steel coating	Not specified	Data from this paper was not used due to the lack of experimental conditions and geometric parameters Other fluids: LO2, LAr; LN2, LNe
Clark [43]	Plots	Pool nucleate Pool film				This is a secondary source containing multiple experiments; furthermore it contains an extensive literature review Other fluids: LO2, CH4, and other cryogenic fluids
Coeling and Merte [44]	Plots	Pool nucleate				Identical data as in source [41]
Merte [45]	Plots	Pool nucleate Pool film MFB	Sphere D = 2.54 cm Square plate (horizontal, vertical) L = 2.54 cm Wire D = 0.1346 mm	Copper (sphere, plate) Fiberglass (plate) Platinum (wire)	Gravity≤1g P = 1 bar, 1.6 bar, 2.6 bar	Other fluids: LN2 Roughness unspecified
Bland et al. [46]	Plots			Copper	P = 3.25 bar	

(*continued on next page*)

Table 3 (*continued*)

Source	Data Type	Boiling Regime	Geometry & Orientation	Material	Operating Condition	Additional Comments
		Pool nucleate	Square plate (horizontal) L = 20 mm			Other fluids: LN2 ε= 0.19 μm
Bewilogua et al. [47]	Plots	Pool nucleate	Plate (horizontal)	Not specified	P = 8.8 bar	Data from this paper was not used due to the lack of experimental conditions and geometric parameters
Bewilogua et al. [48]	Plots	Pool nucleate CHF	Disk (horizontal) D = 1.92 cm	Copper	P = 1 bar, 5 bar, 9.8 bar	Compared with correlation: Kutateladze (1952) Other fluids: LO2, LCH4, LHe, LN2, LAr, LNe ε= 0.2 μm
Kalinin et al. [49]	Plots	Pool film				This is a secondary source containing multiple experiments; furthermore it contains an extensive literature review Other fluids: LO2, LCH4
Klimenko [24]	Plots	Pool film	Plate (horizontal)			New correlation proposed; no new data Other fluids: LN2, LHe, ethanol, Freon, and others
Klimenko [25]	Plots	Pool film	Plate (horizontal)			Revision to a correlation previously published; see source [24]
Louie and Steward [50]	Plots	Pool nucleate Pool film	Rectangular plate (horizontal) L = 4.11 cm W = 6.35 cm	Carbon Platinum		Contains predominately transient experiments Extractable data available in this paper were not useful for the objectives of this study and therefore not used
Kozlov and Nozdrin [51]	Plots	Pool nucleate Pool film	Disk (horizontal) D = 30 mm	Stainless steel Aluminum alloy Copper	For nucleate: P = 0.072 bar, 0.16 bar, 0.4 bar, 1.013 bar, 1.3 bar	Roughness unspecified
Ohira and Furumoto [52]	Plots	Pool nucleate	Disk (horizontal, vertical) D = 25 mm	Copper	P = 0.07 bar, 1.013 bar	Other fluids: Slush H2, LH2, LN2, slush N2 ε= 1 μm
Ohira [53]	Plots	Pool nucleate CHF	Disk (horizontal, vertical) D = 25 mm	Copper	P = 0.07 bar, 1.013 bar	Compared with correlations: For nucleate: Rohsenow (1952), Clark (1975) For CHF: Kutateladze (1959) Identical data as in source [52]
Shirai et al. [54]	Plots	Pool nucleate	Rectangular plate (horizontal) L = 10 mm W = 100 mm	Manganin	P = 7.2 bar	See source [55] for a more comprehensive source containing this data and more
Shirai et al. [55]	Plots	Pool nucleate CHF	Rectangular plate (horizontal) L = 10 mm W = 100 mm	Manganin	P = 1.1 bar, 2 bar, 3 bar, 7 bar, 7.2 bar $\Delta T_{sub} \leq 10$ K	Compared with correlations: Kutateladze (1952), Rohsenow (1952), Labountsov (1972) Roughness unspecified
Garcia [56]	Plots	Pool nucleate Pool film	Rectangular plate (horizontal)	Copper	P = 1 bar, 2 bar Gravity = 0g, 0.1g, 1g $\Delta T_{sub} = \leq 2$ K	Compared with correlations For nucleate: Kutateladze (1952) For film: Breen and Westwater (1962) Data from this paper was not used due to the lack of labeling on the results
Shiotsu et al. [57]	Plots	Pool nucleate	Rectangular plate (horizontal) L = 5 mm W = 60 mm	SUS316	1 bar≤P≤7 bar $\Delta T_{sub} \leq 8$ K	All data is transient Extractable data available in this paper were not useful for the objectives of this study
Horie et al. [28]	Plots	Pool film	Wire (horizontal) D = 1.2 mm	PtCo alloy	P = 1 bar, 4 bar, 7 bar, 11 bar ΔT_{sub} = 0, 5, 8, 11 K	Compared with correlation: Sakurai (1990) Roughness unspecified
Wang et al. [3]	Plots	Pool nucleate Pool film CHF MFB				This is a secondary source containing multiple experiments with several correlation comparisons; furthermore it contains an extensive literature review
Wang et al. [58]	Plots	Pool nucleate Pool film	Rectangular plate (horizontal) Sphere			Compared with correlations: For nucleate: Raj (2012), Kutateladze (1952) For film: Breen and Westwater (1962) For CHF: Kutateladze (1959), Zuber (1959) No new experimental data here

existing experimental data within an order of magnitude. There is significant scatter in the existing data, as can be seen in the figure, and all of the relevant correlations over predict the test data.

The best agreements with the data are provided by the correlation of Stephan and Abdelsalam [13] (Eqs. (11) and (12)), followed by the correlations of Grigorev et al. [17] (Eqs. (17)–(20)) and Forster and Zuber [11] (Eqs. (6) and (7)). Based on the percentage error, the correlation of Stephan and Abdelsalam objectively has both the best agreement and the smallest variance and can predict about 38% of the data points within a factor of two.

Based on the 879 pool nucleate boiling data points extracted from the experiments described above, it is recommended that the correlation of Stephan and Abdelsalam be used to predict LH2 pool nucleate boiling heat transfer. The database used for the development of this correlation included close to 400 cryogenic data points from 18 independent studies and the version of the correlation depicted in Eqs. (11) and (12) was developed specifically for cryogenic fluids. The correlation considers the effect of thermal properties of the heated surface, which is known to be an important factor for the boiling of cryogens. Furthermore, its bubble diameter length scale extends the applicability of this correlation to a variety of surfaces. The correlation of Girgorev et al. [17] performed well only when the boiling surface was made from copper. The statistics

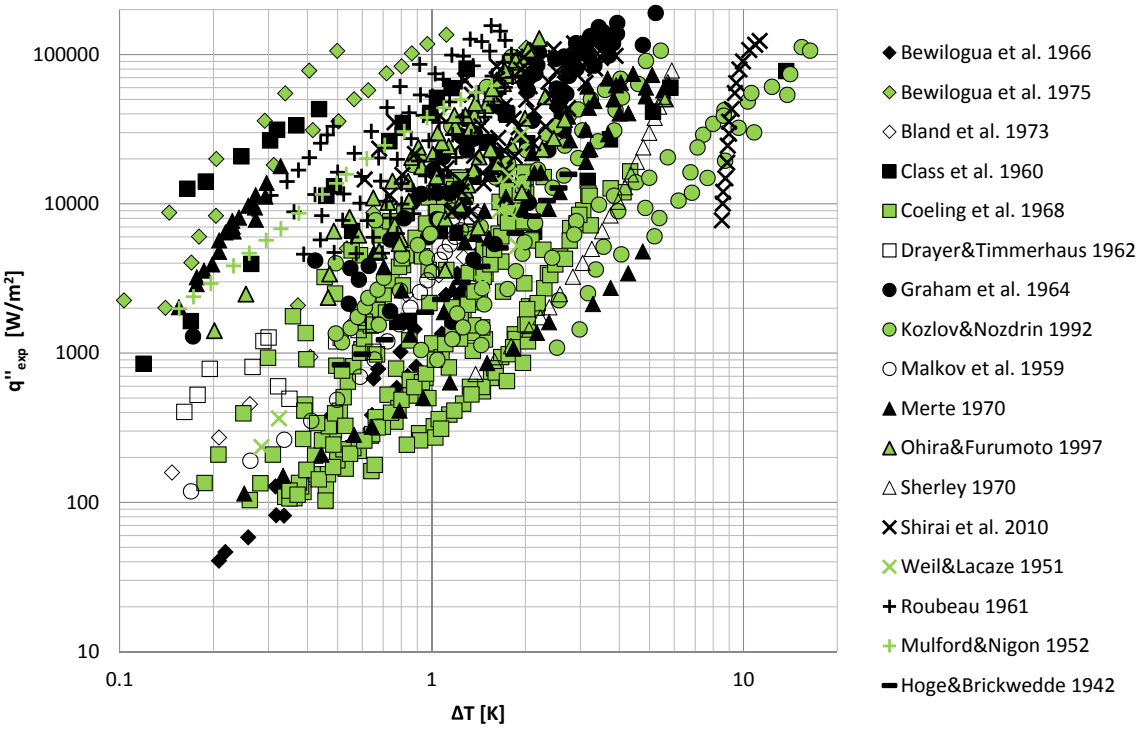

Fig. 2. Pool nucleate boiling experimental data for LH2.

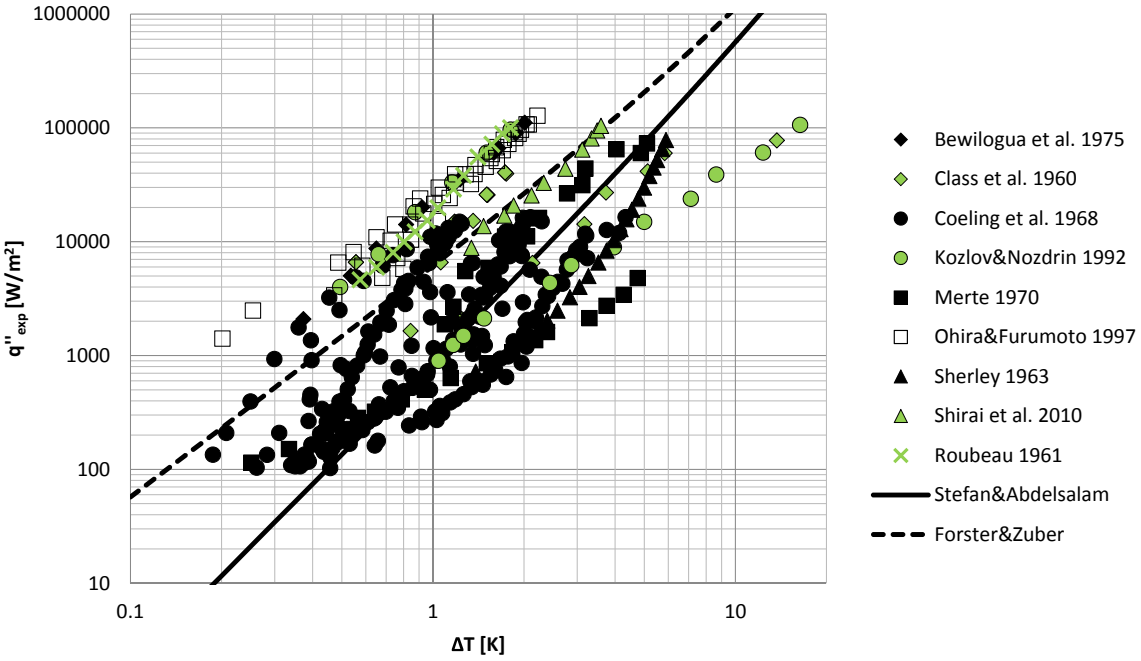

Fig 3. Comparison of the LH2 pool nucleate boiling data on horizontal flat surfaces close to atmospheric pressure with the predictions of best-performing correlations.

Table 4
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool nucleate boiling of LH2.

	Stephan and Abdelsalam [13]	Gorenflo [18]	Kutateladze [8]	Forster and Zuber [11]	Borishanski and Minchenko [4]	Kichigin and Tobilevich [10]	Labuntsov [5]	Kruzhilin [5]	Bier and Lambert [16]	Grigorev et al. [17]*	Rohsenow [9]
Mean	1.67	7.22	4.90	3.46	6.48	5.49	5.73	7.25	11.00	4.09	5.91
Standard deviation	5.37	26.52	9.25	6.47	21.72	10.35	14.96	27.18	19.60	11.47	16.98
Percentage of data for which $0.5 \leq \xi \leq 1.0$	38.11	20.82%	23.32	27.42	23.89	21.62	24.12	23.09	31.17	25.81	21.27
Percentage of data for which $0.23 \leq \xi \leq 0.3$	12.06	8.53%	8.53	10.92	6.26	7.85	8.87	9.33	12.17	5.85	6.60

*For data obtained with copper surfaces only.

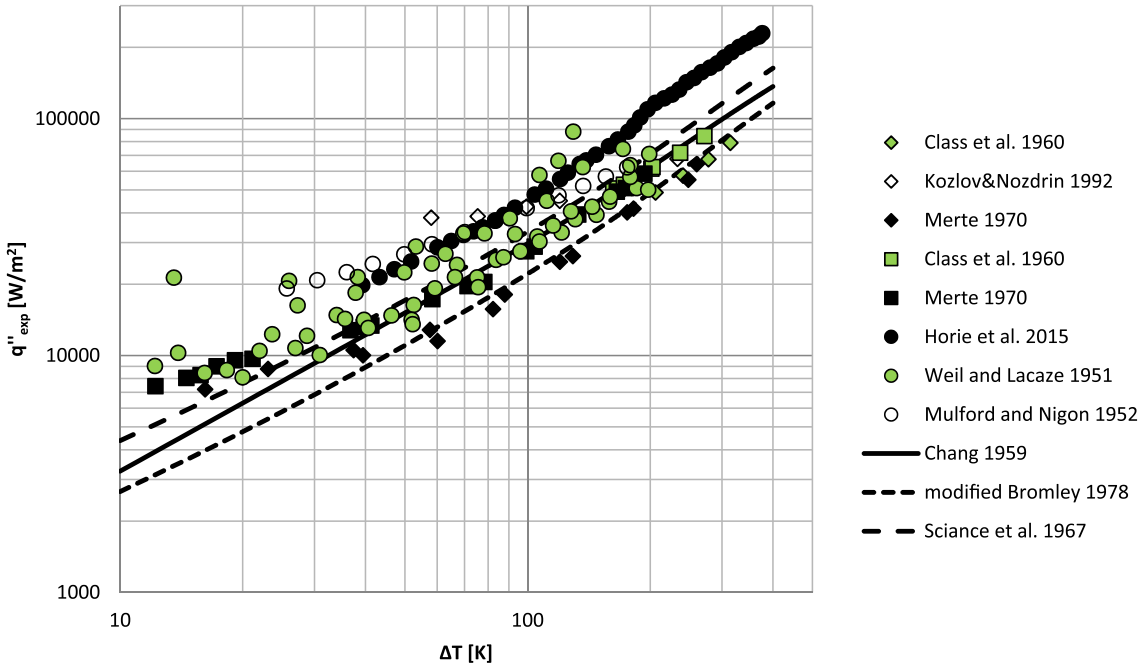

Fig. 4. Comparison of the LH2 film nucleate boiling data close to atmospheric pressure with the predictions of best-performing correlations for each orientation. Diamonds indicate flat horizontal surfaces; squares indicate flat vertical surfaces; circles indicate horizontal cylinders.

Table 5
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool film boiling of LH2.

	Berenson [22]	Modified Bromley [1]	Breen and Westwater [23]	Chang (horizontal) [20]	Chang (vertical) [20]	Sciance et al. [21]	Klimenko [24,25]	Sakurai et al. [28]
Mean	−0.17	−0.42	−0.34	0.00	−0.57	−0.12	0.05	−0.10
Standard deviation	0.23	0.25	0.19	0.28	0.30	0.35	0.27	0.14
Percentage of data for which $0.5 \leq \xi \leq 1.0$	90.91	86.84	80.65	96.97	34.21	99.07	96.97	97.20
Percentage of data for which $0.23 \leq \xi \leq 0.3$	60.61	36.84	7.46	54.55	26.32	38.00	59.09	89.74

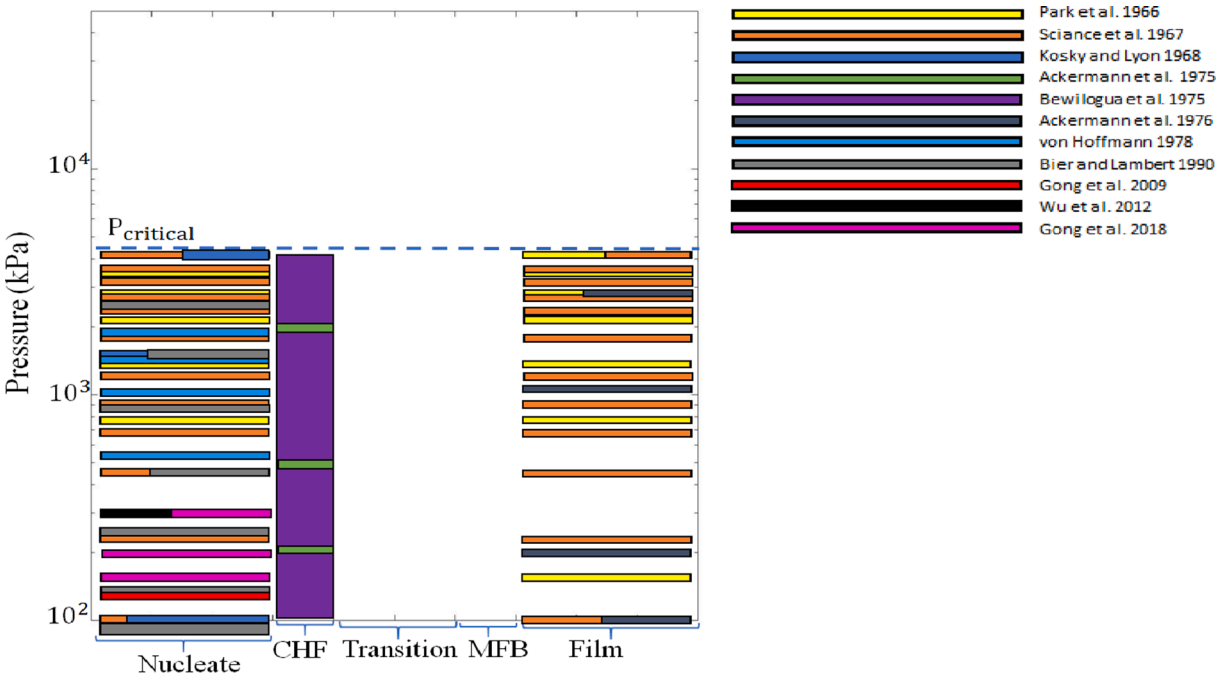

Fig. 5. The range of existing experimental data for pool boiling of LCH4.

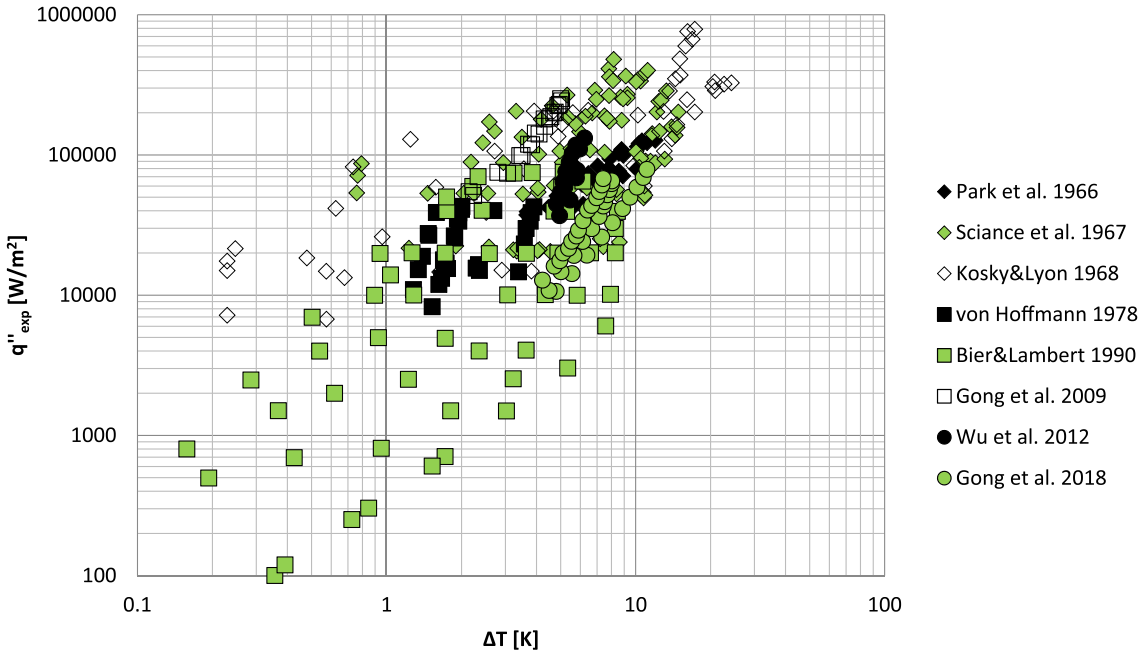

Fig. 6. Pool nucleate boiling experimental data for LCH4.

presented in Table 4 for this correlation are exclusively for copper surfaces.

4.2. Comparison of LH2 film pool boiling data with correlations

Data representing pool film boiling of LH2 are relatively few and deal with boiling on the outside surfaces of horizontal and vertical flat surfaces and horizontal cylindrical surfaces. Table 5 summarizes the statistics related to the comparison of LH2 film boiling data with the relevant models and correlations. As noted, the agreement between data and existing correlations is relatively good. Fig. 4 compares data with the best performing correlations.

For the film boiling of hydrogen on flat horizontal surfaces, it is recommended that the correlation of Klimenko [24,25] (Eqs. (38)–(42))

Table 6
Summary of past studies for pool boiling of LCH4.

Reference	Data Source	Boiling Type	Geometry & Orientation	Material	Operating Condition	Additional Comments
Park et al. [59]	Plots	Pool nucleate Pool film	Cylinder (horizontal) D = 1.12 cm	Gold	For nucleate: P = 7.9 bar, 14.7 bar, 21.6 bar, 28.5 bar, 35.4 bar For film: P = 1.7 bar, 7.9 bar, 14.8 bar, 21.6 bar, 28.5 bar, 35.4 bar, 42.3 bar	Other fluids: LN2 Roughness unspecified
Sciance et al. [21]	Plots	Pool nucleate Pool film CHF MFB	Cylinder (horizontal) D = 2.06 cm	Gold	P = 1 bar, 2.3 bar, 4.6 bar, 6.9 bar, 9.2 bar, 13.8 bar, 18.4 bar, 23 bar, 27.6 bar, 32.2 bar, 36.8 bar, 41.4 bar	Compared with correlations: For nucleate: Rohsenow (1952), Forster and Greif (1958), Madejski (1965) For CHF: Noyes (1963–1964) For MFB: Berenson (1961) New film boiling correlation proposed Roughness unspecified
Kosky and Lyon [4]	Plots	Pool nucleate	Disk (horizontal) D = 1.9 cm	Platinum	P = 1.1 bar, 16.4 bar, 41.2 bar, 45.4 bar	Compared with correlations: Rohsenow (1952), Forster-Zuber (1954), Forster-Greif (1958), Gilmour (1958), McNelly (1953), Kutateladze (1952), Borishanskiy-Minchenko (1961) Other fluids: LO2, CF4, LN2, LAr Roughness unspecified
Ackermann et al. [60]	Plots	CHF	Disk (horizontal) D = 1.92 cm	Copper	P = 2–35 bar	Other fluids: LN2, mixtures ε= 0.2 μm
Bewilogua et al. [48]	Plots	CHF	Disk (horizontal) D = 1.92 cm		P = 1.4 41.4 bar	Compared with correlation: Kutateladze (1952) Other fluids: LH2, LO2, LHe, LN2, LH2, LAr, LNe ε= 0.2 μm
Ackermann et al. [61]	Plots	Pool film	Cylinder (horizontal) D = 5 mm	Teflon	P = 1 bar, 2 bar, 11 bar, 28 bar	Other fluids: LN2, mixtures ε= 0.2 μm
Von Hoffmann [62]	Plots	Pool nucleate	Disk (horizontal) D = 90.27 mm	Copper	P = 5.2 bar, 10.3 bar, 15.2 bar, 19.1 bar	Compared with correlation: Happel and Stephan (1974) Other fluids: LN2, ethane, mixtures Roughness unspecified
Bier and Lambert [16]	Plots	Pool nucleate	Cylinder (horizontal) D = 8 mm	Copper	P = 0.2 bar, 0.5 bar, 1.4 bar, 2.5 bar, 4.6 bar, 8.7 bar, 15.6 bar, 24.8 bar	Includes newly developed correlation Other fluids: LN2, LAr, LCO2, C2H6, C2H4 ε= 1.6 μm, 2.0 μm
Gong et al. [63]	Plots	Pool nucleate	Disk (horizontal) D = 20 mm	Copper	P = 1.3 bar	Compared with correlation: Nishikawa (1982) Other fluids: Binary mixtures with ethane, propane, isobutene ε= 1.4 μm
Wu et al. [64]	Plots	Pool nucleate	Disk (horizontal) D = 30 mm	Copper	P = 3 bar	Compared with correlation developed for binary mixtures Other fluids: FC14, binary mixtures Roughness unspecified
Gong et al. [65]	Plots	Pool nucleate	For pool: Disk (horizontal) D = 30 mm	Copper	For pool: P = 1.5 bar, 2 bar, 3 bar	Compared with correlations: For pool: Labuntsov (1972), Nishikawa et al. (1982), Cooper (1984), Jung et al. (2003), Jung et al. (2004), Sun et al. (2007) Other fluids: Ethane, binary mixtures Includes a newly-developed correlation Roughness unspecified

Table 7
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool nucleate boiling of LCH4.

	Stephan and Abdelsalam [13]	Gorenflo [18]	Forster and Zuber [11]	Bier and Lambert [16]	Grigorev et al. [17]*	Rohsenow [9]
Mean	8.54	54.39	0.82	0.40	2.09	−0.01
Standard deviation	26.42	194.05	1.93	1.66	4.53	1.27
Percentage of data for which $0.5 \leq \xi \leq 1.0$	25.30	13.75	49.10	48.49	25.60	46.39
Percentage of data for which $0.23 \leq \xi \leq 0.3$	10.54	5.72	21.99	19.88	8.73	24.10

*For data obtained with copper surfaces only.

be used to predict heat transfer. Notably, all three considered correlations performed well, but Klimenko has improved upon the work pioneered by Chang [20] (Eqs. (28)–(30)) and Berenson [22] (Eq. (32)), keeping with the Taylor hydrodynamic theory of boiling and Taylor instability-driven bubble growth and expanding it to capture both laminar and turbulent flows within the film. Additionally, cryogenic fluids were used in the database for the development of the correlation.

For vertical flat surfaces, it is recommended that the modified Bromley correlation [1] (Eqs. (36) and (37)) be used to predict heat transfer, as it outperforms the correlation of Chang [20] by a noticeable margin. Both correlations have the same form and differ only by a coefficient. For the film boiling on the outside surface of horizontal cylinders, it is recommended that the correlation of Sakurai et al.[27] (Eqs. (43)–(53)) be used. The correlation was a result of a rigorous numerical solution of the

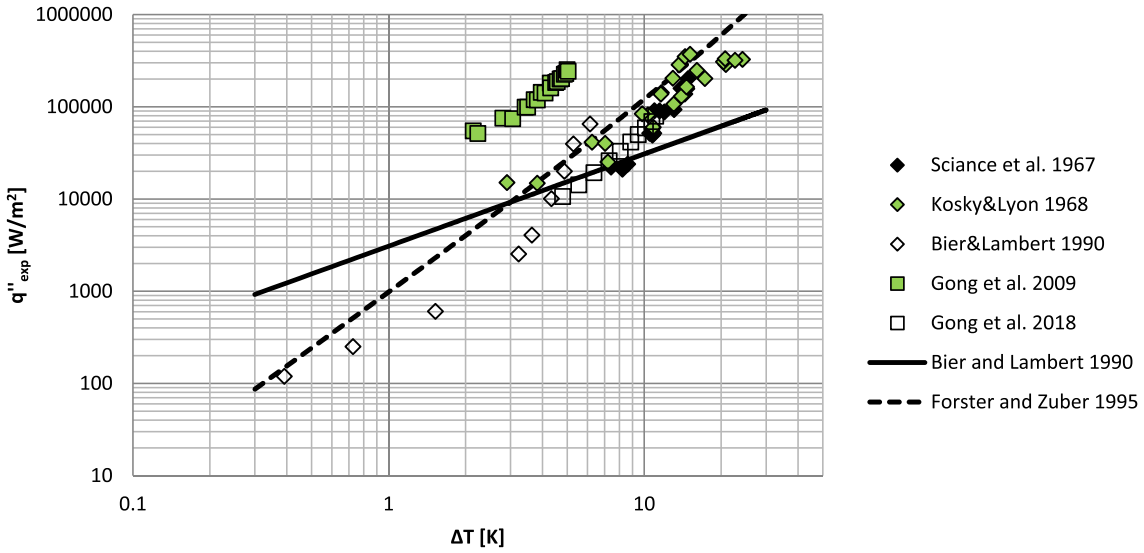

Fig. 7. Comparison of the LCH4 pool nucleate boiling close to atmospheric pressure with the predictions of best-performing correlations.

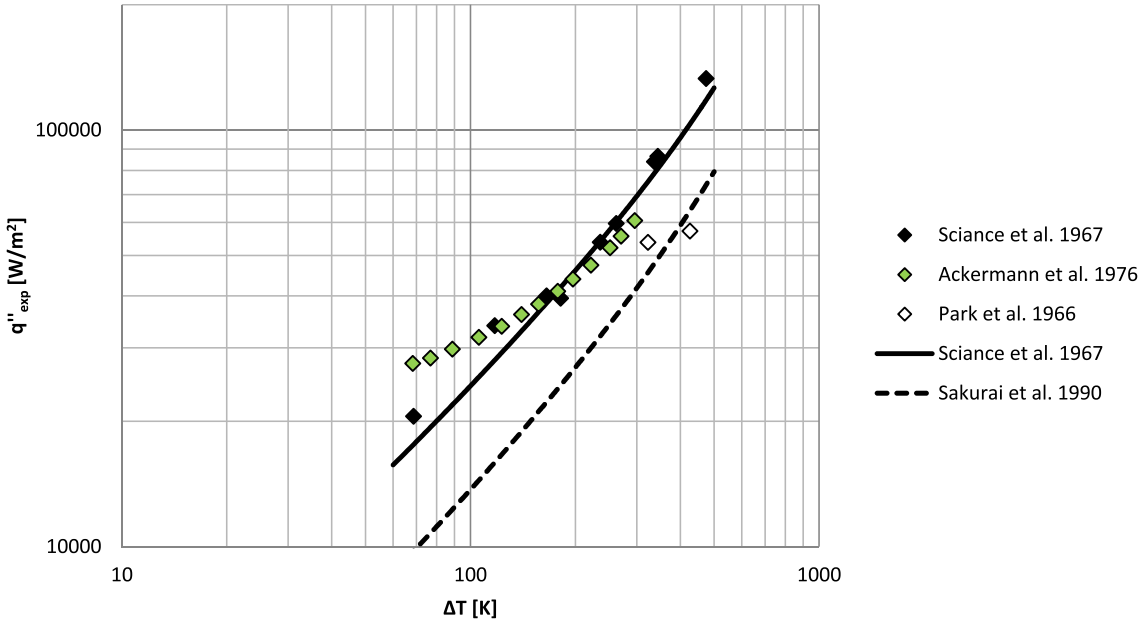

Fig. 8. Comparison of the LCH4 pool film boiling data at close to atmospheric pressure with the predictions of best-performing correlations.

Table 8
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool film boiling of LCH4.

	Breen and Westwater [23]	Sciance et al. [21]	Sakurai et al. [28]
Mean	−0.23	0.10	−0.33
Standard deviation	0.22	0.32	0.20
Percentage of data for which $0.5 \leq \xi \leq 1.0$	94.12	99.47	96.26
Percentage of data for which $0.23 \leq \xi \leq 0.3$	36.90	82.35	45.45

boundary layer conservation equations and included cryogens in its development and validation. Additionally, it specifically accounts for surface radiation and liquid subcooling. As evident in Table 5, almost 90% of the data are predicted by this correlation within a factor of 1.3. With the exceptions of the correlation of Klimenko [24,25] and horizontal correlation of Chang [20], the film boiling correlations tend to slightly under predict the experimental data.

5. Pool boiling of liquid methane (LCH4)

Fig. 5 displays the range of the available experimental data for the pool boiling of LCH4. As noted, the experimental data for the pool nucleate boiling regime are extensive and include experiments reported by several separate teams of investigators. The pool nucleate boiling data cover a vast range of pressures as well. The data for pool film

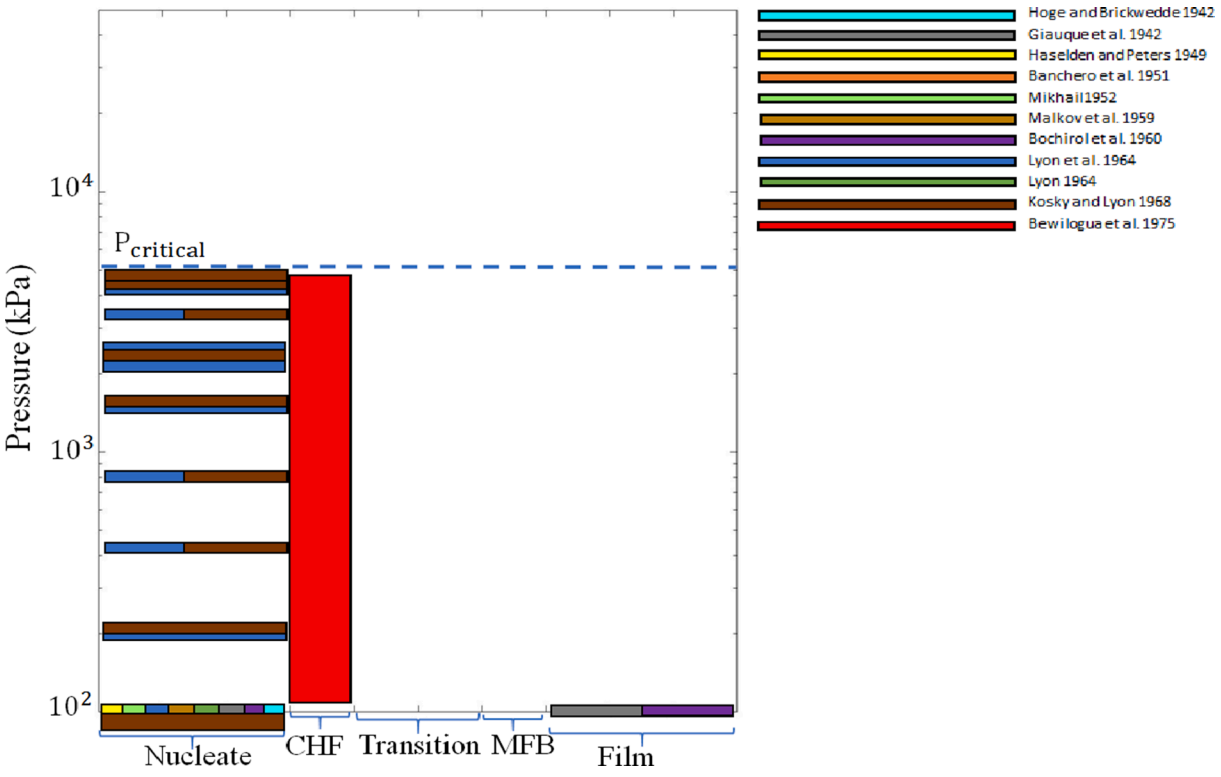

Fig. 9. The range of existing experimental data for pool boiling of LO2.

Table 9
Summary of past studies for pool and flow boiling of LO2.

Reference	Data Type	Boiling Regime	Geometry & Orientation	Material	Operating Condition	Additional Comments
Hoge and Brickwedde [66]	Plots	Pool nucleate	Cylinder (horizontal) D = 1.041 cm		Atmospheric pressure	Cannot access source; data extracted from Seader et al. [31] Roughness unspecified
Giauque et al. [67]	Plots	Pool nucleate Pool film	Cylinder (vertical) D = 6.985 cm	Copper	Atmospheric pressure	Cannot access paper; data extracted from Seader et al. [31] Roughness unspecified
Haselden and Peters [68]	Plots, Tables	Pool nucleate	Cylinder (horizontal, vertical) D = 1.588 cm, 0.952 cm	Copper	Atmospheric pressure	Other fluids: LN2 Surface condition described as "clean"
Banchero et al. [69]	Plots depicted in Seader et al., 1965 [30]	Pool nucleate	Cylinder (horizontal) D = 19.05 mm	Copper 304 stainless steel K-Monel 24 ST Aluminum Platinum	Atmospheric pressure	Cannot access paper Other fluids: Fluorine and Hydrazine Roughness unspecified
Mikhail [70]	Plots, Tables	Pool nucleate	Cylinder (horizontal) D = 4.76 mm	Nickel Platinum Silver Copper	Atmospheric pressure	Other fluids: LN2 Various "roughness ratios" provided; surface conditions range from smooth to rough
Banchero et al. [71]	Plots depicted in Seader et al., 1965 [30]	Pool film	Wire (horizontal), Cylinder (horizontal) Wire: D = 0.64–3.23 mm Cylinder: D = 19.05 mm	Stainless steel 304 Copper Platinum Aluminum	Atmospheric pressure	Roughness unspecified
Malkov et al. [32]	Plots	Pool nucleate	Coiled tube (vertical) D = 45 mm	Monel	Atmospheric pressure	Other fluids: LH2 Roughness unspecified
Lyon et al. [72]	Plots, Tables	Pool nucleate	Ring (horizontal) OD = 6.86 cm ID = 6.45 cm	Platinum	P = 1 bar, 2 bar, 4.1 bar, 8 bar, 15.7 bar, 21.1 bar, 26 bar, 32.5 bar, 41.3 bar	Compared with correlations: Rohsenow (1952), Kutateladze (1952) Other fluids: LN2 Roughness unspecified
Lyon [73]	Plots	Pool nucleate	Cylinder (vertical, horizontal) D = 0.952–6.98 cm	Gold	Atmospheric pressure	Other fluids: LN2, mixtures ε 0.065 μm, 0.695 μm
Brentari et al. [38]	Plots	Pool nucleate Pool film				This is a secondary source containing multiple experiments conducted at atmospheric pressure; furthermore it contains an extensive literature review Compared with correlations: For nucleate: Kutateladze (1952) For film: Breen and Westwater (1962) Other fluids: LO2, LN2, LHe
Seader et al. [31]	Plots	Pool nucleate Pool film				This is a secondary source containing multiple experiments conducted at atmospheric pressure; furthermore it contains an extensive literature review Other fluids: LO2, LN2
Bewilogua and Knöner [42]	Plot	Pool film	Cylinder (vertical)	Lead with stainless steel coating	Not specified	Data from this paper was not used due to the lack of experimental conditions and geometric parameters Other fluids: LO2, Lar; LN2, LNe Roughness unspecified
Kosky and Lyon [4]	Plots	Pool nucleate	Disk (horizontal) D = 1.9 cm	Platinum	P = 0.25 bar, 0.55 bar, 2.2 bar, 4.3 bar, 8.2 bar, 16.7 bar, 25.2 bar, 32.9 bar, 42.8 bar, 49 bar	Compared with correlations: Rohsenow (1952), Forster-Zuber (1954), Forster-Greif (1958), Gilmour (1958), McNelly (1953), Kutateladze (1952), Borishanskiy-Minchenko (1961) Other fluids: LO2, CF4, LN2, LAr Roughness unspecified
Bewilogua et al. [48]	Plots	CHF	Disk (horizontal) D = 1.92 cm		P = 1.4 41.4 bar	Compared with correlation: Kutateladze (1952) Other fluids: LH2, LO2, LHe, LN2, LH2, LAr, LNe ε= 0.2 μm

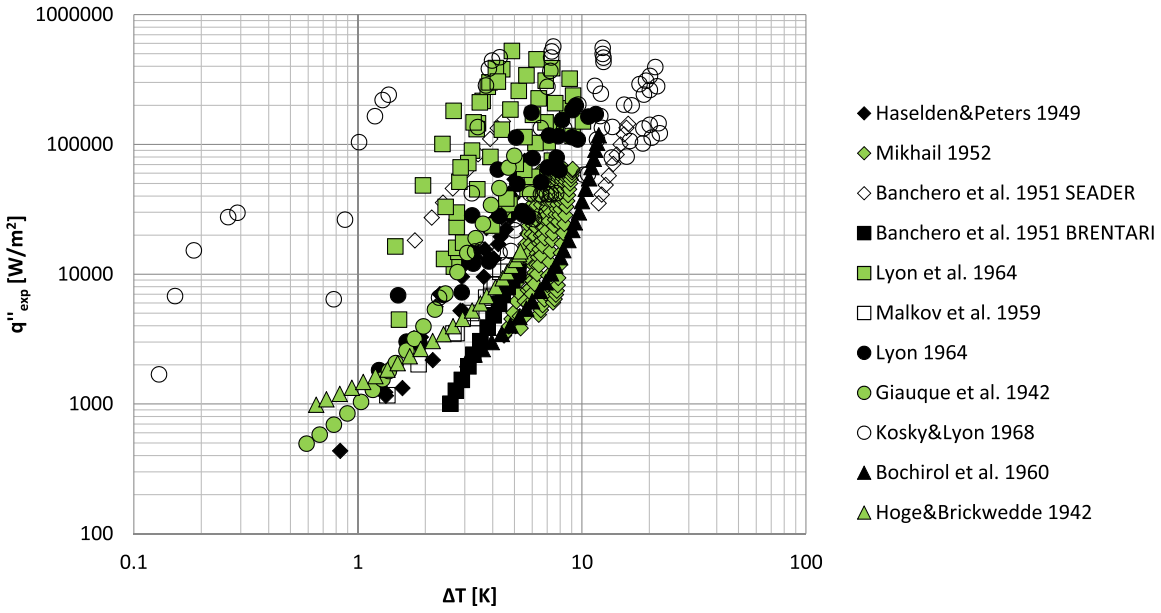

Fig. 10. Pool nucleate boiling data for LO2.

boiling is also extensive and covers the entire pressure range of interest, but these film boiling data are from only two sources. CHF data are available only from two sources, but cover a wide pressure range. However, experimental data could not be found for TB or MFB.

5.1. Comparison of LCH4 nucleate pool boiling data with correlations

With respect to pool nucleate boiling, data from eight different sources have been compiled, and these data were compared with the predictions of all the aforementioned correlations for pool nucleate boiling. In the forthcoming discussion, for brevity, only comparisons are shown for a few correlations which provide the best agreement with the experimental data.

Fig. 6 displays the compiled experimental data points in a heat flux vs. wall superheat plot. The displayed data represent pool nucleate boiling on horizontal upward-facing surfaces or the outside surface of horizontal cylinders, all at normal gravity. Table 6 presents a summary of past published studies dealing with the pool boiling of LCH4, including sources of experimental data that are used in the forthcoming discussions. Table 7 is a summary of the statistics related to the comparison of the entire experimental data with the predictions of various correlations for pool nucleate boiling. The depicted data in Fig. 6 all conform to the expected trend of pool nucleate boiling. However, they include data points representing very small wall superheats. Furthermore, considerable data scatter exists, even among data with similar pressure and geometrical conditions. The statistics related to the five best performing correlations with respect to the prediction of the compiled 339 data points are provided in Table 7. The correlations of Cooper [15] (Eqs. (13)–(15)), Kutateladze [3,8] (Eq. (2)), Borishanki and Zhokhov [12] (Eq. (9)), McNelly [3] (Eq. (4)), Borishanski and Minchenko [3] (Eq. (8)), and Kichigin and Tobilevich [10] (Eq. (5)) all greatly over predicted the experimental data, while the correlation of Kruzhilin [4] (Eq. (1)) greatly under predicts the experimental data. Again, the correlation of Girgorev et al. [17] performed well only when the boiling surface was made from copper, and the statistics presented in Table 7 for this correlation are exclusively for copper surfaces.

Fig. 7 compares the LCH4 nucleate pool boiling data with predictions of the two correlations which perform best among all pool nucleate boiling heat transfer correlations discussed earlier. The scatter of the data is significant, and neither correlation is capable of effectively reducing the scatter. The correlations of Forster and Zuber [11] (Eqs. (6)–(7)) and Bier and Lambert [16] (Eq. (16)) both perform remarkably well when compared to experimental data. The statistical analysis shows that the correlation of Forster and Zuber outperforms the correlation of Bier and Lambert correlation in all categories and is recommended for use in predicting the nucleate boiling heat transfer of LCH4. Forster and Zuber's correlation is phenomenological and is based on the growth of bubbles suspended within a thin superheated liquid film close to the heated surface, and because of its phenomenological nature provides for wide flexibility and applicability. Although slightly inferior, the correlation of Bier and Lambert is worthy of consideration as the correlation was developed with LCH4 as one of the primary fluids in its database, and contains parameters that are fluid-specific. Other cryogenic fluids that were included in the data base of the correlation of Bier and Lambert were LH2 and LO2. It is also noted that both of these correlations perform well when they are used for pool nucleate boiling of LH2, as shown earlier.

5.2. Comparison of LCH4 film pool boiling data with correlations

Only three useful data sets could be found, all focused on film boiling of LCH4 on the outside surface of horizontal cylinders. Fig. 8 compares the predictions of three correlations with the experimental data. The statistics related to the discrepancy between data and correlations are

Table 10
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool nucleate boiling of LO2.

	Stephan and Abdelsalam [13]	Cooper [15]	Gorenflo [18]	Kutateladze [8]	Forster and Zuber [11]	McNelly [4]	Borishanski and Zhokhov [12]	Kichigin and Tobilevich [10]	Labuntsov [5]	Kruzhilin [5]	Bier and Lambert [16]	Grigoreva et al. [17]
Mean	3.95	0.43	1.09	1.62	1.54	−0.78	5.54	2.39	−0.07	−2.95	−0.42	2.29
Standard deviation	5.15	2.72	6.55	6.33	2.86	5.87	9.37	13.34	5.89	30.92	2.71	40.24
Percentage of data for which $0.5 \leq \xi \leq 1.0$	29.55	38.75	13.70%	49.32	50.49	44.81	42.07	47.95	45.60	34.05	47.36	20.94
Percentage of data for which $0.23 \leq \xi \leq 0.3$	12.72	15.07	6.07%	21.33	21.14	22.11	18.40	20.35	20.94	10.57	17.22	8.02

provided in Table 8. The data are in reasonable agreement with the predictions of the three selected correlations, although there is considerable scatter in the data. It is recommended that the correlation of Sciance et al. [21] (Eq. (31)) be used for the pool film boiling of LCH4 on horizontal cylinders. The correlation was developed with almost 100 methane test data points over a wide range of pressures and outperforms the other two correlations.

6. Pool boiling of liquid oxygen (LO2)

Fig. 9 displays the range of the available experimental data for pool boiling of LO2. Data representing pool nucleate boiling are available from several sources and cover a wide range of pressures. However, data is evidently scarce for other pool boiling regimes. No experimental data was uncovered for TB or MFB. Table 9 is a summary of the past studies dealing with pool boiling of LO2.

6.1. Comparison of LO2 nucleate pool boiling data with correlations

Data from eight different sources have been compiled, and these data have been compared with the prediction of all the aforementioned correlations for pool nucleate boiling. Fig. 10 depicts all the compiled data on a heat flux vs. wall superheat coordinate system. Some of the experimental data of Kosky and Lyon [4], which were obtained in experiments conducted close to critical pressure of oxygen and were found to be clearly outlying in comparison with other published data, were excluded from further analysis.

Table 10 depicts the statistics related to the discrepancy between the entire experimental data and the pool boiling correlations. Most of the available correlations evidently do not agree with the data, and wide scatter in the data should be noticed.

Fig. 11 displays comparisons between the compiled 516 experimental data points and the predictions of three correlations. The correlations shown in these figures perform best among all the correlations examined in this study and predict most of the available data within an order of magnitude, although vast data scatter is observed. The correlation of Rohsenow [9] (Eq. (3)) was found to greatly under predict the experimental data, while the correlation of Borishanski and Minchenko [3] (Eq. (8)) over predicted the data. The results of the remaining better-performing correlations can be seen in Table 10. It is suggested that the Forster and Zuber [11] (Eqs. (6) and (7)) correlation be used to predict the heat transfer of pool nucleate boiling of LO2. The statistical analysis showed that the Bier and Lambert [16] (Eq. (16)) correlation performed better, but as seen in Fig. 11 it fails to accurately represent the data at very low and very high wall superheats corresponding to both the beginning and end of the nucleate boiling regime. The correlation of Forster and captures the nucleate boiling curve well and has a comparable performance to Bier and Lambert.

6.2. Comparison of LO2 film pool boiling data with correlations

Useful data could be extracted only from four sources, three of them related to film boiling on the outside surface of horizontal cylinders, and one for boiling on vertical cylinders. The data of Banchero et al.[71] were extracted from Brentari et al. [38] and Seader et al. [31]. However, some of the data between these two secondary sources were found to be conflicting. As a result, we removed the data related to boiling on wires as reported by Seader et al., and data related to cylinders reported in Brentari et al. The removed data were clearly outlying in comparison with other similar data as well as the predictions by all the relevant correlations.

Table 11 is a summary of the statistics related to the comparison of the experimental data with the relevant models and correlations. It is recommended that the correlation of Sakurai et al. [26–28] (Eqs. (43)–(53)) be used to predict the pool film boiling of LO2. Table 9 shows that the agreement between the experimental data and this correlation is

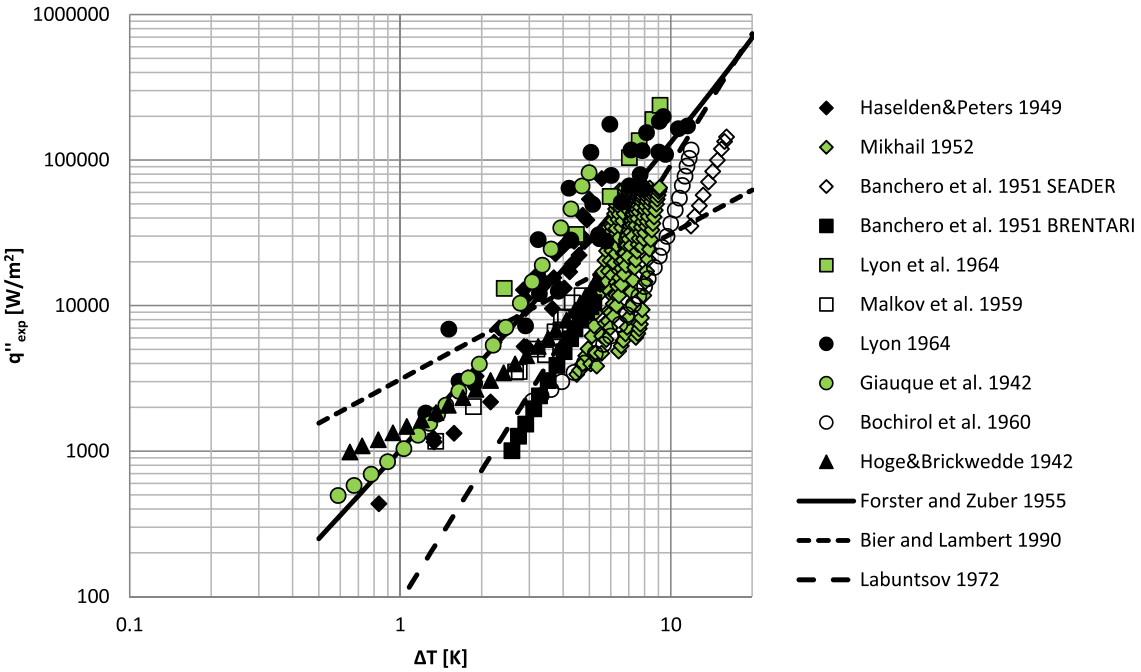

Fig. 11. Comparison of the LO2 pool nucleate boiling close to atmospheric pressure with the predictions of best-performing correlations.

Table 11
Mean and standard deviation of ξ, and percentage of experimental data points that fall within a factor of 2.0 and 1.3 of correlations for pool film boiling of LO2.

	Breen and Westwater [23]	Sciance et al. [21]	Sakurai et al. [28]	Hsu and Westwater [19]
Mean	−0.23	0.23	−0.04	0.26
Standard deviation	0.47	0.79	0.39	0.54
Percentage of data for which $0.5 \leq \xi \leq 1.0$	85.22	77.39	100.00	100.00
Percentage of data for which $0.23 \leq \xi \leq 0.3$	46.96	59.13	95.65	0.00

excellent, with more that 95% of the heat flux data with a factor of 1.3. Fig. 12 shows the excellent agreement between the aforementioned correlation and experimental data for cylinders and wires of varying diameters.

7. Conclusions

The experimental data available in the open literature for pool nucleate and film boiling of LH2, LCH4 and LO2 have been compiled. While the available data for pool nucleate boiling are considerable for all three cryogens, data representing pool film boiling is limited in comparison with nucleate boiling for all three fluids. The predictions of 19 pool nucleate boiling correlations were compared with experimental data for the three cryogens. The film boiling data were also compared with relevant models and correlations.

For pool nucleate boiling of LH2 data from 17 sources were compiled, and pool film boiling of LH2 data were compiled from six sources. The correlations of Stephan and Abdelsalam [13] and Forster and Zuber [11] performed best. They could predict the bulk of the existing pool boiling heat flux data within an order of magnitude. They could predict respectively, 38% and 27% of the data within a factor of two.

For pool nucleate boiling of LCH4 data from eight sources were compiled, and pool film boiling of LCH4 useful data were found only from three sources, all representing film boiling on the outside surface of horizontal cylinders. The correlations of Bier and Lambert [16] and Forster and Zuber [11] performed best for predicting the nucleate boiling heat flux. They could predict the bulk of the existing heat flux data within an order of magnitude. They could predict respectively, 58% and 49% of the data within a factor of two.

For pool nucleate boiling of LO2 data from 11 sources were compiled, and for pool film boiling of LO2 useful data could be found only from four sources, three for horizontal cylinders and one for boiling on a vertical cylinder. The correlations of Forster and Zuber [11] and Bier and Lambert [16] provided the best agreement with experimental data for heat flux in nucleate pool boiling, and could predict the heat flux data within an order of magnitude. They could predict respectively, 50% and 47% of the data within a factor of two.

Overall, pool nucleate boiling data for all three fluids displayed considerable scatter, and existing correlations are unable to effectively narrow the scatter to better than an order of magnitude. The film boiling data show smaller scatter in comparison, and can be predicted by existing correlations with reasonable accuracy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

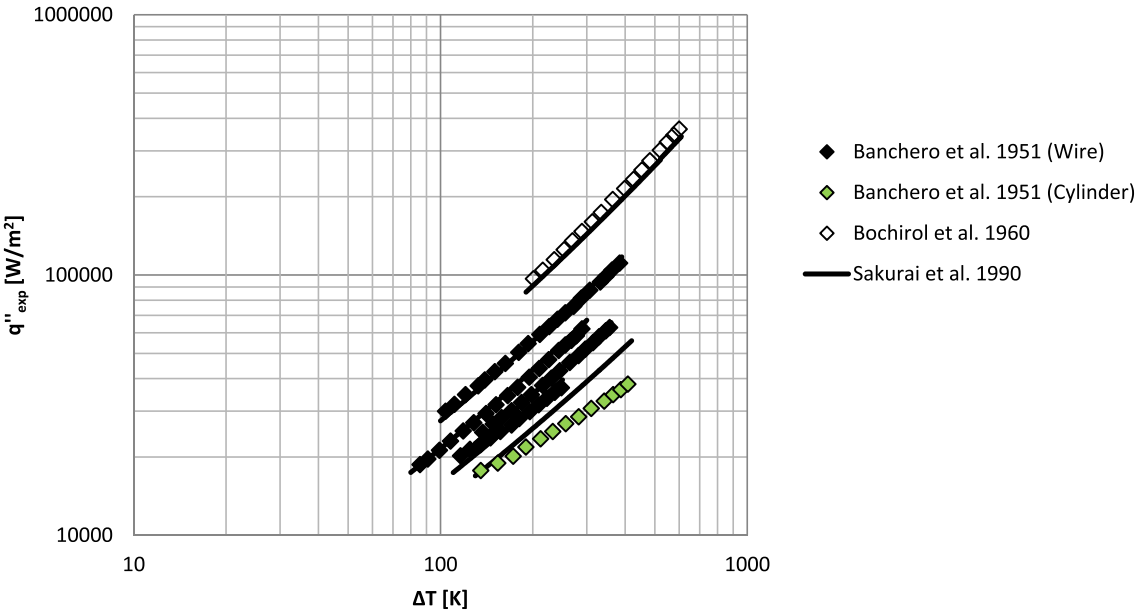

Fig. 12. Comparison of the LO2 pool film boiling close to atmospheric pressure with the correlation of Sakurai et al [26–28].

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