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Prediction of Critical Heat Flux during Downflow in Fully Heated Vertical Channels

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Abstract: Boiling with downflow in vertical channels is involved in many applications such as boilers, nuclear reactors, chemical processing, etc. Accurate prediction of CHF (Critical Heat Flux) is important to ensure their safe design. While numerous experimental studies have been done on CHF during upflow and reliable methods for predicting it have been developed, there have been only a few experimental studies on CHF during downflow. Some researchers have reported no difference in CHF between up- and downflow, while some have reported that CHF in downflow is lower or higher than that in upflow. Only a few correlations have been published that are stated to be applicable to CHF during downflow. No comprehensive comparison of correlations with test data has been published. In the present research, literature on CHF during downflow in fully heated channels was reviewed. A database for CHF in downflow was compiled. The data included round tubes and rectangular channels, hydraulic diameters 2.4 mm to 15.9 mm, reduced pressure 0.0045 to 0.6251, flow rates from 15 to 21,761 kg/m^{2}s, and several fluids with diverse properties (water, nitrogen, refrigerants). This database was compared to a number of correlations for upflow and downflow CHF. The results of this comparison are presented and discussed. Design recommendations are provided.

Keywords: critical heat flux; downflow; tubes; rectangular channels; correlations; prediction

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1. Introduction

Boiling with downflow in vertical channels is involved in many applications such as boilers, nuclear reactors, chemical processing, etc. Accurate prediction of CHF (Critical Heat Flux) is important to ensure their safe design. Many experimental studies have been done on CHF during upflow and reliable methods for predicting it have been developed. There have been comparatively few experimental studies on CHF during downflow. There are differences in the results reported by various researchers. Some have stated that they found no difference between the CHF during upflow and downflow; for example, Barnett (1963) [1]. Some have reported that CHF during downflow is higher or lower than that during upflow under various conditions; for example, Chen (1993) [2]. During upflow, buoyancy force is in the direction of flow. During downflow, buoyancy force is against the flow direction. Hence, some differences in the CHF in these two directions may be expected. Only a few correlations have been published that are stated to be applicable to CHF during downflow. No comprehensive comparison of correlations with test data has been published. There is a lack of well-verified methods to predict CHF during downflow.

The objective of this research was to determine whether, in fact, there is a significant difference between CHF in upflow and downflow, and to develop a reliable prediction method for downflow CHF if a significant difference was found. To achieve this objective, literature was surveyed to identify experimental studies, data sources, and prediction methods. Of special interest were experimental studies in which CHF was measured with flow in both upward and downward directions. A comprehensive database was developed and compared to the best available correlations for upflow and downflow CHF. The results of this research are presented and discussed. It is to be noted that this research was confined to fully heated channels; partially heated channels are not included.

2. Previous Work

2.1. Experimental Work

Gambill and Bundy (1961) [3] measured CHF during downflow of water in rectangular channels. They compared their data with correlations based on upflow CHF. The agreement was fairly good.

Barnett (1963) [1] conducted tests at pressures of 38 bar and 138 bar with water flowing in a vertical tube. He found no effect of flow direction on the boiling crisis.

Pappel et al., (1966) [4] performed tests with nitrogen in a vertical tube. Nitrogen was subcooled at the entrance to the tube. They found that CHF in downflow was lower than that in upflow at low flow rates. The difference disappeared at high flow rates. Pappel (1972) [5] performed similar tests with zero inlet quality and the results were similar.

Kirby et al., (1967) [6] performed tests with up- and downflow with water at 1.7 bar in an annulus. They report that CHF in downflow was 10 to 30 percent lower in downflow, the larger difference being at the lowest flow rate.

Cumo et al., (1977) [7] performed tests with R-12 flowing up and down a vertical tube. They concluded that CHF during downflow is 10 to 30% lower than that in upflow, especially at low inlet qualities. They attributed this difference to the effect of buoyancy.

Lazarek and Black (1982) [8] performed tests with R-113 in a vertical tube. They found no difference between CHF during upflow and downflow.

Mishima et al., (1985) [9] performed upflow and downflow CHF tests on a 6 mm diameter tube with water at atmospheric pressure as the test fluid. Tests were done alternatively with a stiff system and a soft system. In the stiff system, precautions were taken to prevent instability, such as by applying strong throttling at tube inlet, while such precautions were not taken in the soft system. CHF in the stiff system was considerably higher than that in the soft system. They found no difference between the CHF in upflow and downflow.

Remizov et al., (1985) [10] did tests on a vertical tube in which critical quality was measured in upflow and downflow at identical inlet subcooling, flow rate, and heat flux. They found that at the lowest flow rate, critical quality was always lower for upflow, though the difference decreased with increasing heat flux. At the highest flow rate, critical quality was lower for upflow at low heat flux but higher at high heat flux.

Deqiang et al., (1987) [11] performed tests with R-12 in an 8 mm diameter vertical tube. They found the downflow CHF to be lower than the upflow CHF at low flow rates, but equal at high flow rates.

Chang et al., (1991) [12] performed tests with atmospheric pressure in vertical tubes. Their tests showed that CHF in up- and downflow was essentially the same at low flow rates. At higher flow rates, CHF in upflow was higher, though the difference was small. They found that it was more difficult to maintain stability in downflow. They proposed a correlation for CHF applicable to both upflow and downflow without any factor for the effect of flow direction.

Chen (1993) [2] analyzed experimental data for upflow and downflow critical heat flux of water and freon in a vertical tube. It was found that the total rms (root-mean-square) of the comparison of upflow and downflow data and predicting downflow data using upflow CHF correlation are in the range of 6–14%. The CHF for upflow was regularly greater than that for downflow, but was smaller than that in downflow in the range of low critical quality. The downflow CHF was 80% of the upflow value at the point of the maximum difference between the two. (This description is based on the abstract of this report.)

Ruan et al., (1993) [13] performed tests on downflow of water in a vertical tube. Tests were done with different amounts of instability. They found that, in a stable system, downflow CHF approached that for upflow. In very unstable systems, CHF value corresponded to flooding CHF.

Ami et al., (2015) [14] performed tests with water in a vertical tube. For the data in which the location of CHF was known, CHF in upflow and downflow was about equal at lower flow rates. At the highest flow rate, CHF in downflow was about 15% higher than in upflow.

Sripada et al., (2021) [15] measured CHF with water flowing downwards in a 6 mm diameter vertical tube. Their measured CHF was very low, even much lower than that by Mishima et al., (1985) [9] under unstable conditions. They had not done any throttling at the tube inlet. These data are clearly for unstable conditions. No conclusions can be drawn from such unstable CHF data.

2.2. Prediction Methods

While there are many correlations for CHF during upflow, only a few correlations have been proposed which are stated to be applicable to CHF during downflow. The more verified among them are discussed below.

Sudo et al., (1985) [16] have given the following correlation based on data for tubes and rectangular channels which is applicable to both upflow and downflow. It is given below.

$$q^* = 0.005G^{*0.611} \tag{1}$$

$$q^* = \left(\frac{A_F}{A_H}\right) x_{in} G^* \tag{2}$$

At very low flow rates, CHF was considered to be due to flooding and the following equation was given for it:

$$q^* = C^2\left(\frac{A_F}{A_H}\right)\frac{(D/\lambda)^{0.5}}{\left(1+(\rho_G/\rho_L)^{1/4}\right)^2} \tag{3}$$

For rectangular channels, D is replaced by the channel width W. The constant C^2 is 0.71.

G^* and q^* are defined as:

$$q^* = \frac{q_c}{i_{LG}[\lambda\rho_G(\rho_L - \rho_G)g]^{0.5}} \tag{4}$$

$$G^* = \frac{G}{[\lambda\rho_G(\rho_L - \rho_G)g]^{0.5}} \tag{5}$$

$$\lambda = \frac{\sigma^{0.5}}{[(\rho_L - \rho_G)g]^{0.5}} \tag{6}$$

For upflow, q^* is the larger of those given by Equations (1) and (3). For downflow, Equation (1) applies when $G^* > 10^4$. For $G^* < 10^4$, q^* is the larger of those from Equations (2) and (3).

Hirose et al., (2024) [17] have given the following correlation for downflow based on data from several sources:

$$q^* = 0.422G^{*0.564}(L_c/D)^{-0.902} \tag{7}$$

$$q^* = C^2\left(\frac{A_F}{A_H}\right)\frac{i_{fg}(\rho_G g D(\rho_L - \rho_G))}{\left(1+(\rho_G/\rho_L)^{1/4}\right)^2} \tag{8}$$

The higher of the q^* given by Equations (7) and (8) is to be used. Equation (8) is for CHF due to flooding. The constant C is to be determined from experimental data. They used C = 1.18.

Darges et al., (2022) [18] have given the following correlation, which is intended to be applicable to all flow directions:

$$Bo = 0.353We_D^{-0.314}\left(\frac{L_c}{D_{HP}}\right)^{-0.226}\left(\frac{\rho_L}{\rho_G}\right)^{-0.481}\left[1 - x_{in}\left(\frac{\rho_L}{\rho_G}\right)^{-0.094}\right] \times\left(1 + Fr_\theta^{-1}\right)\left(1 + 0.008\frac{Bd_\theta}{We_D^{0.543}}\right) \quad (9)$$

where,

$$We_D = \frac{G^2 D_{HP}}{\rho_L \sigma} \quad (10)$$

$$Fr_\theta = \frac{G^2}{\rho_L^2 \cdot D_{HP} Sin\theta g} \quad (11)$$

$$Bd_\theta = \frac{gCos\theta(\rho_{L-}\rho_G)D_{HP}^2}{\sigma} \quad (12)$$

This correlation was based on data obtained by a team at Purdue University through tests on partially heated channels using FC-72 and nPFH fluids for many years. Tests were done in earth gravity, as well as in micro gravity. All flow directions were included in those tests. All of these tests were done on channels 2.5 mm × 5 mm made of plastic with heaters inserted in their sides.

Chang et al., (1991) [12] have given a correlation based on their own data as well as some data for low pressure water. Its predictions are the same for both up- and downflow. The reported accuracy is not very good.

There are many correlations for CHF during upflow. The best known among them are Shah (1987) [19] and Katto and Ohno (1984) [20]. Both of these were verified with wide ranging databases. Shah (2017) [21] had compared these correlations as well as several other correlations to data for CHF in small diameter channels. Shah's correlation was found to be the most accurate, followed by the correlations of Katto and Ohno and Zhang et al., (2006). The correlation of Wojtan et al., (2006) [22] was found to give fairly good agreement with refrigerant data.

3. Data Analysis

Efforts were made to collect data for downflow CHF. As noted by Rohsenow (1973) [13], only the data taken under stable conditions can be correlated and interpreted. Hence, data which showed instability were not considered. The data of Sripada et al., (2021) [23] were not considered as they were clearly obtained under unstable conditions, as discussed in Section 2.1. Ruan et al., (1993) [10] and Mishima et al., (1985) [9] have pointed out which of their data were taken under unstable conditions. Those data were not included in the present data analysis.

The figures in Mishima et al., (1985) [24] show no difference in CHF between upflow and downflow. These figures show CHF to initially increase linearly with mass velocity but show little or no effect of mass velocity at higher flow rates. The behavior at higher flow rates is against the trend shown by most data and these data are greatly overpredicted by all correlations. Hence, these were not included in the present study.

Some of the papers did not provide sufficient details to enable the analysis of data in them. For example, Deqiang et al., (1987) [11] have not given the length of the test tube without which their data cannot be analyzed.

In the paper by Ami et al., (2015) [14], CHF location is not given for most of the data and was therefore not analyzable. Some data are given for a 10 mm tube for which CHF location is stated. These were analyzed and the results are discussed in Section 4.2.

All data were read from figures in the publications except those of DeBortoli et al., which were read from tables.

The data for downward flow CHF that were analyzed are listed in Table 1. These were compared to the correlations of Shah, Katto and Ohno, Zhang et al., and Wojtan et al., which are based on upflow data, as well as the correlations of Sudo et al., Darges et al., and Hirose et al., which are stated to be applicable to downflow CHF.

Table 1. Range of data for downflow in vertical fully heated channels and the results of their comparison with some correlations.

Source	Channel Shape	D (D_{HYD}), mm	L_c/D	Fluid	p_r	G Kg/m^{2}s	Y^*x10^{-4}	x_{in}	x_c	N	Deviations of Correlations, %. MAD (Upper Row)/AD (Lower Row)						
											Katto–Ohno	**Zhang et al.**	**Wojtan et al.**	**Darges et al.**	**Sudo et al.**	**Hirose et al.**	**Shah**
Dougherty et al., (1994) [25]	Round	15.9	153	water	0.0209	1706 8010	320 3200	−0.28 −0.15	0.00 0.26	28	17.3 17.3	21.1 21.1	37.3 −37.3	0.7 8.6	9.8 −5.5	36.7 −36.7	15.8 15.8
Mishima et al., (1985) [9]	Round	6.0	57.3	water	0.0045	20 239	0.067 6.0	−0.13 −0.04	0.55 0.84	13	20.7 20.7	8.6 −5.1	64.0 64.0	26.7 16.9	56.9 −56.9	26.8 −18.1	6.1 0.2
Lazarek & Black (1982) [8]	Round	3.1	81.9	R-113	0.0383	235 498	9.1 35	−0.22 −0.02	0.72 0.89	9	4.3 −0.5	12.3 −12.3	19.1 −19.1	88.7 88.7	51.5 −51.5	34.0 −34.0	26.1 −26.1
Chang et al., (1991) [12]	Round	9.0	76	water	0.0045	15 25	0.05 0.14	−0.15	0.77	3	18.8 18.8	13.0 −13.0	141.4 141.4	329.8 −329.8	19.0 −19.0	27.3 27.3	7.6 −7.6
			114				0.08 3.8	−0.15 −0.06	0.72 0.83	17	36.7 36.7	7.0 −1.2	64.2 64.2	105.2 105.2	19.8 −6.6	20.9 −14.7	8.8 8.2
Ruan et al., (1993) [26]	Round	9.0	44.3	water	0.0045 0.0317	26 203	0.12 5.7	−0.07 −0.01	−0.05 1.08	20	11.9 4.1	19.6 −18.9	44.2 43.0	24.9 5.2	65.5 −65.5	22.6 −12.1	17.0 −15.0
DeBortoli et al., (1957) [27]	Rect. 25.4 W, 2.46 H	(4.49)	153	water	0.6251	205 978	4.2 250	−0.20 −0.04	0.10 0.97	9	10.0 −6.4	18.3 5.5	50.0 −50.0	390.7 390.7	13.8 −0.2	24.0 −24.0	14.3 11.0
			68.1			313 457	9 18	−0.13	0.15	2	18.6 18.6	20.8 −20.8	69.3 −69.3	251.9 251.9	73.8 −73.8	57.0 −57.0	19.8 −19.9
	Rect, 1.27 W, 2.4 H	(2.42)	126			457 768	12 31	−1.31 −1.22	0.21 0.34	4	12.6 12.6	15.1 −15.1	72.7 −72.7	379.8 379.8	62.3 −62.3	65.2 −65.2	18.8 −18.8
Gambill & Bundy (1961) [3]	Rect. 2.5 W × 2.5 H	(2.5)	186	water	0.0500 0.1719	7465 21,761	1100 7700	−0.59 −0.33	−0.10 −0.06	7	18.1 9.7	16.8 4.7	63.6 −63.6	76.7 76.7	37.7 −37.7	65.5 −65.5	15.6 10.1
Pappel et al., (1966) [4]	Round	12.5	24.4	Nitrogen	0.2032 0.4859	119 434	9.5 81	−0.51 −0.19	−0.11 0.01	5	47.7 45.9	26.2 18.2	35.1 27.3	298.9 298.9	47.5 −47.5	122.9 122.9	69.6 69.6
					0.1016 0.4046	484 2557	100 2400	−0.51 −0.08	−0.36 −0.01	52	18.1 18.1	24.8 12.7	66.8 65.8	145.0 145.0	32.5 −20.3	173.6 173.6	26.5 26.5
Pappel (1972) [5]	Round	12.5	24.4	Nitrogen	0.1060 0.3004	168 455	16 98	0.00	0.14 0.33	12	19.1 17.8	20.3 20.3	78.4 78.4	192.4 192.4	33.6 −33.6	174.0 174.0	73.0 73.0
						488 2544	100 1900	0.00	0.04 0.12	40	12.2 11.3	60.9 60.9	179.7 179.7	221.9 221.9	28.4 13.3	334.9 334.9	24.0 12.0
Cumo et al., (1977) [7]	Round	7.8	282	R-12	0.2587 0.4231	130 1000	3.6 160	−0.44 0.28	0.37 1.1	74	20.4 13.8	32.1 29.4	31.4 −29.9	877.8 877.8	64.9 −18.8	33.4 27.4	14.9 4.8
Remizov et al., (1983) [10]	Round	10.0	234 511	Water	0.6209	350 500	18 34	−0.11 −0.06	0.76 0.88	6	23.5 23.5	39.9 39.9	37.9 −37.9	1181.4 1181.4	89.0 −89.0	16.8 16.8	25.9 25.9
						700	61	−0.03 −0.02	0.43 0.46	3	55.1 55.1	93.1 93.1	26.7 −26.7	1139.9 1139.9	94.0 −94.0	40.1 40.1	70.9 70.9
All sources	Round, rectangular	2.4 15.9	44 186	Water, R-12, R-113, N_2	0.0045 0.6251	15 21,761	0.05 7700	−1.31 0.00	−0.10 1.1	304	18.9 15.7	28.8 20.0	66.4 32.4	350.2 341.8	266.6 199.4	103.9 80.3	21.9 13.7

Calculation of CHF with the local condition part of the Shah correlation requires the insertion of critical quality x_c. As x_c depends on the critical heat flux which itself has to be determined, iterative calculations were done with assumed values of $\mathrm{x_c}$ until the assumed and calculated values converged to within 0.01. During these iterations, $\mathrm{x_c}$ is calculated with the heat balance equation:

$$\mathrm{x_c} = \mathrm{x_{in}} + 4\mathrm{BoL}_c/\mathrm{D}_{HP} \tag{13}$$

where,

$$Bo = \frac{q_c}{Gi_{LG}} \tag{14}$$

For the data in which $x_{in} > 0$, calculations for all correlations were done using the boiling length L_B in place of L_c. It is defined as:

$$\frac{L_B}{D_{HP}} = \frac{L_c}{D_{HP}} + \frac{x_{in}}{4Bo} \tag{15}$$

As q_c is to be determined, calculations were done with assumed values of q_c until adequate convergence was achieved.

Properties were obtained from REFPROP 9.1, Lemmon et al., (2013) [24].

The deviations listed in Table 1 are defined as below.

Mean absolute deviation (MAD) of a data set is defined as:

$$MAD = \tfrac{1}{N}\Sigma_1^N ABS\left(\left(q_{c,predicted} - q_{c,measured}\right)/q_{c,measured}\right) \tag{16}$$

Average deviation of a data set AD is defined as:

$$AD = \tfrac{1}{N}\Sigma_1^N \left(\left(q_{c,predicted} - q_{c,measured}\right)/q_{c,measured}\right) \tag{17}$$

The results in Table 1 show that the correlations of Shah, Katto and Ohno, and Zhang et al., are in fairly good agreement with most data while the other correlations, including those for downflow, have large deviations with most data.

4. Discussion

4.1. Accuracy of Correlations

In Table 1, it is seen that only the correlations of Shah, Katto and Ohno, and Zhang et al., show reasonable agreement with the downflow data. These correlations were developed and verified with upflow data. The correlations of Darges et al., Hirose et al., and Sudo et al., which were stated to be applicable to downflow, have large deviations with most data. The correlation of Hirose et al., has fairly good agreement with many data sets. Its overall MAD is very large because it has very large deviations with the data of Pappel et al., (1966) [4] and Pappel (1972) [5] for nitrogen. Those data are 36% of the total 304 data points. If the nitrogen data are left out, the MAD of the Hirose et al., correlation goes down to 33%, which is much more reasonable. The data analyzed by Hirose et al., did not include any for nitrogen or other cryogens.

Among the upflow correlations, Katto and Ohno have the least MAD of 18.9%. The next lowest is the Shah correlation with MAD of 21.9%. If the data of nitrogen at $G < 460$ kg/m^{2}s are left out, the MAD of the Shah correlation becomes about the same as that of the Katto–Ohno correlation.

The Shah correlation also has large deviations with the data of Remizov et al., (1985) [10] for $G = 700$ kg/m^{2}s. These data are also overpredicted by the Katto–Ohno and Zhang et al., correlations.

From the above discussions, it is clear that the correlations of Katto–Ohno and Shah give the best agreement with downflow CHF data.

Figures 1–3 show a comparison of some CHF data for downflow in tubes with various correlations.

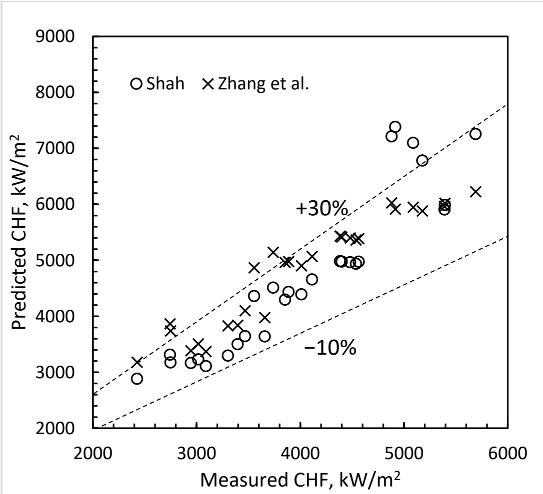

Figure 1. Data of Dougherty et al. [25] for downflow of water in a vertical tube compared to two correlations.

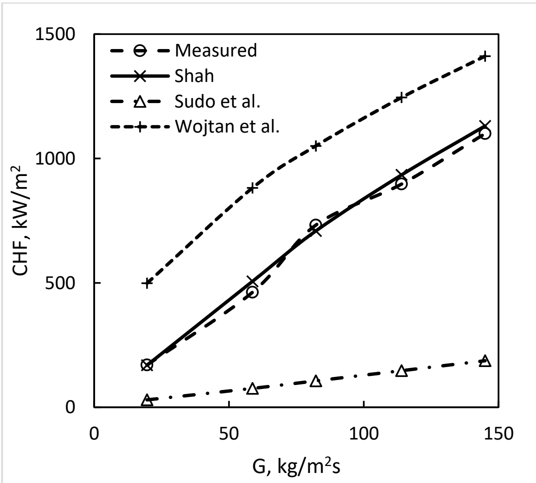

Figure 2. Data of Mishima et al., (1985) [9] for downflow of water in a round tube compared to some correlations. Pressure atmospheric, inlet quality −0.131.

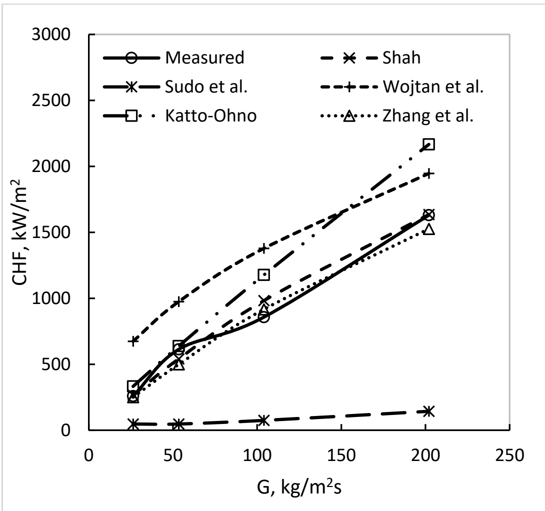

Figure 3. Data of Ruan et al., (1993) [26] for downward flow of water in a tube compared to various correlations. Pressure atmospheric, inlet quality −0.056.

4.2. Comparison of Upflow and Downflow Data

Some of the experimental studies on downflow CHF also included tests with upflow. Table 2 shows the deviations of Shah, Katto–Ohno, and Zhang et al., correlations with upflow and downflow data from those studies. The range of parameters during upflow was essentially the same as in the downflow listed in Table 1. The deviations of upflow and downflow data with the Shah correlation are seen to be comparable for all data except those of Pappel for nitrogen. If the data at low flow rate are left out, the MAD becomes about 25%, still significantly higher than about 16% for upflow. The results with the Zhang et al., correlation are similar. However, deviations of the Katto–Ohno correlations are about the same for upflow and downflow.

Table 2. Deviations of the best correlations with data from experimental studies in which both upflow and downflow CHF were measured.

Source	Channel Type	D_{HYD}	Fluid	Shah		Katto and Ohno		Zhang et al.	
				Downflow	Upflow	Downflow	Upflow	Downflow	Upflow
Pappel et al., (1966) [4]	Round tube	12.8	Nitrogen	30.3 30.3	17.0 12.4	20.7 20.5	13.2 5.6	25.0 13.2	21.2 −2.8
Pappel (1972) [5]	Round tube	12.8	Nitrogen	35.3 35.3	14.3 3.9	13.8 12.1	13.2 −9.4	51.5 51.5	26.9 21.9
Dougherty et al., (1994) [25]	Round tube	15.9	Water	15.8 15.8	14.5 12.7	17.3 17.3	14.4 13.7	21.1 21.1	21.4 21.4
Mishima et al., (1985) [9]	Round tube	6.0	Water	6.1 0.2	13.0 0.6	20.7 20.7	24.1 22.2	8.6 −5.1	15.0 −4.7
Lazarek & Black (1982) [8]	Round tube	3.1	R-113	26.1 −26.1	26.9 −26.9	4.3 −0.5	4.4 −1.9	12.3 −12.3	12.8 −12.8
Chang et al., (1991) [12]	Round tube	6.0	Water	8.8 8.2	10.6 8.9	36.7 36.7	37.9 37.9	7.0 −1.2	7.9 1.7
Remizov et al., (1983) [10]	Round tube	10.0	Water	40.9 40.9	42.2 42.2	34.1 34.1	35.7 35.7	57.6 57.6	59.5 59.5
DeBortoli et al., (1957) [27]	Rectangular channel	4.49	Water	15.3 −12.7	19.9 * −19.9	11.6 −8.6	9.0 * 9.0	18.7 0.71	17.5 * −17.5
		2.42	Water	18.8 −18.8	12.5 ** 0.2	12.6 12.6	19.8 ** 19.8	15.1 −15.1	2.8 ** −1.8
Cumo et al., (1977) [7]	Round tube	7.8	R-12	14.9 4.8	18.4 −7.6	20.4 13.8	17.7 −0.4	32.1 29.4	26.7 12.3
All sources				22.2 15.7	17.2 14.1	19.3 16.6	18.7 17.7	29.4 22.7	22.6 9.3

Note: * L/D =58; ** L/D = 11, L/D for others same as in Table 1.

Figure 4 shows the data of Chang et al., (1991) [12] for up- and downflow together with predictions of some correlations. It is seen that there is really no difference in the CHF in the two directions, even at very low mass flux. While the Shah correlation predicts CHF a little higher at high flow rates, this cannot be attributed to flow direction as the measured CHF in both directions is about the same.

Figure 5 shows the data of Cumo et al., (1977) [7] for both upflow and downflow at the highest flow rate. It is seen that the downflow CHF at low inlet quality is a little lower than for upflow; meanwhile, at high inlet quality, they are about the same. The Shah correlation predictions are in-between the measured values in the two directions and, thus, in close agreement with both.

Figure 6 shows the data of Cumo et al., (1977) [7] at the lowest flow rate. CHF in downflow is about 15% lower than that in upflow; the two get close with increasing inlet quality. The correlations of Shah and Zhang et al., are within about −15% of data.

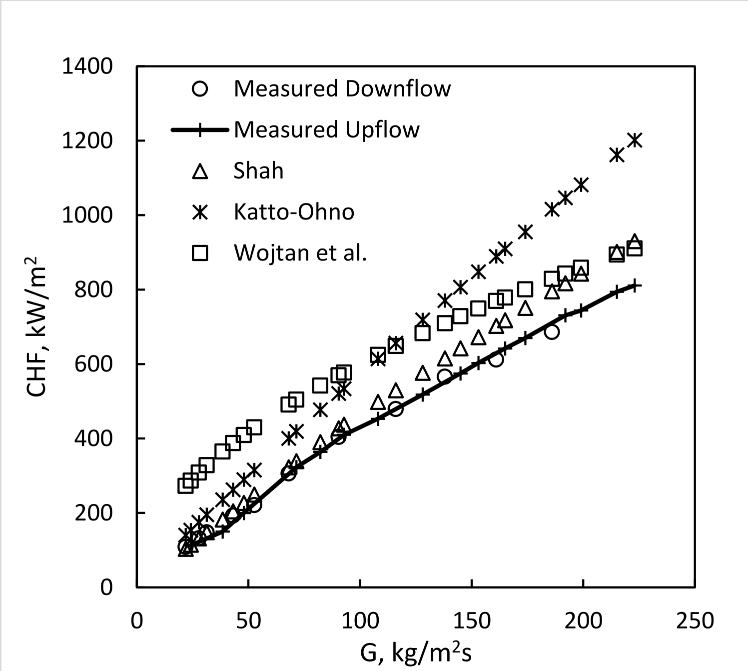

Figure 4. Data of Chang et al., (1991) [12] for up- and downflow of water in a vertical tube compared to various correlations. Pressure atmospheric, inlet quality −0.149, L/D = 114.

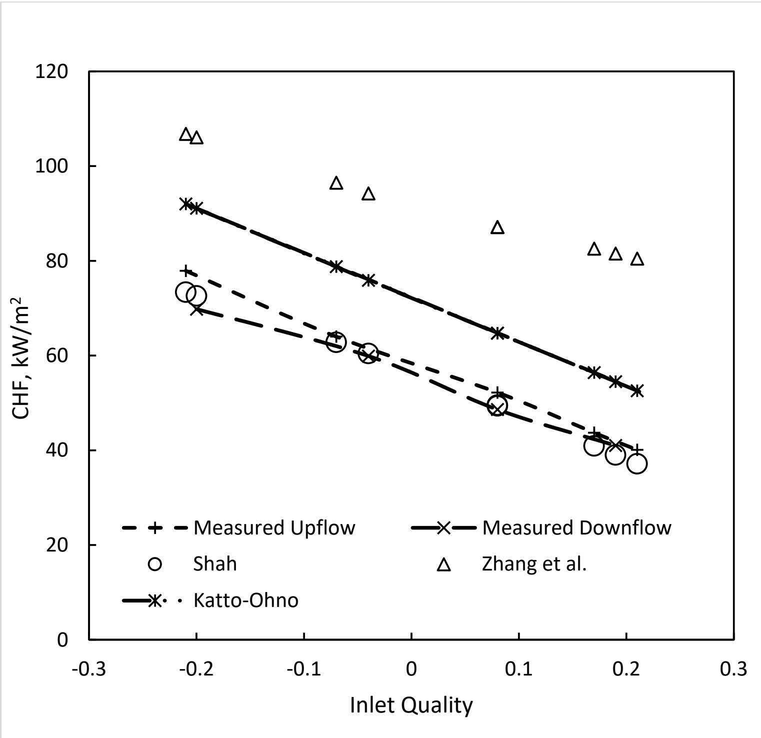

Figure 5. Data of Cumo et al., (1977) [7] at the highest mass flux compared to some correlations. G = 1000 kg/m^{2}s, pressure 10.5 bar.

Figure 7 shows the data of Pappel et al., (1966) [4] for nitrogen in both upflow and downflow. The data for downflow are considerably lower than upflow data at flow rates below about 500 kg/m^{2}s. Predictions of the Shah correlation are considerably higher than the downflow data for the lowest flow rates. On the other hand, the Katto–Ohno correlation gives good agreement throughout.

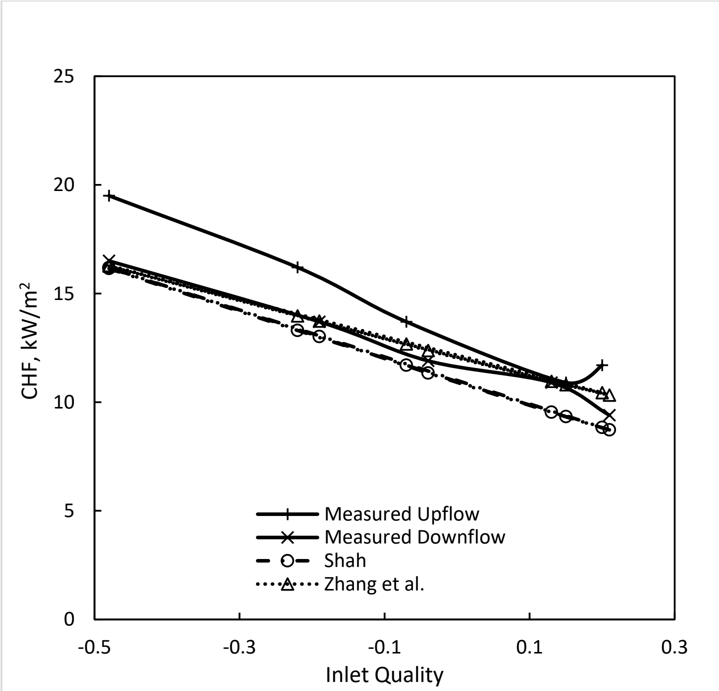

Figure 6. Data of Cumo et al., (1977) [7] for R-12 at the smallest flow rate compared to the Shah and Katto–Ohno correlations. Pressure 17.5 bar, G = 130 kg/m^{2}s.

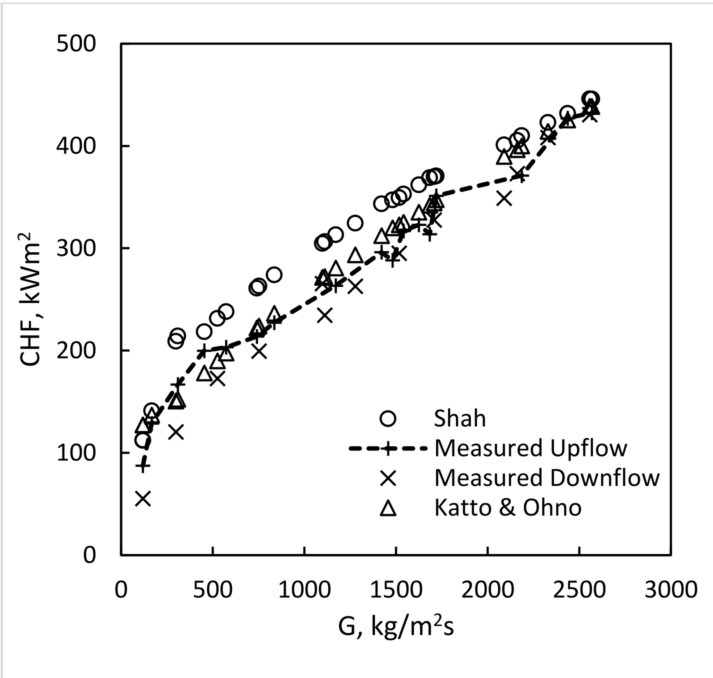

Figure 7. Data of Pappel et al., (1966) [4] for nitrogen compared with the Shah and Katto–Ohno correlations. T_{SAT} = 109 K, inlet subcooling 23.9 K.

Deviations of all three correlations are high for the downflow data of Remizov et al., but the deviations are also equally high for their upflow data. The data for flow in upward and downward directions cannot be directly compared as they provide critical quality at identical inlet quality and heat flux. Therefore, they were compared as the ratio of their deviations from the correlations of Shah and Katto and Ohno. This comparison is shown in Figure 8. It is seen that the downflow CHF is up to 12% higher than upflow CHF at the lowest mass flux, while it is up to 10% lower at the highest mass flux. Collier and Thome (1994) [28] have stated that the data of Remizov et al., show that downflow CHF is 10% to 30% lower than upflow CHF, the greatest difference being at the lowest flow rate. Remizov et al., did not make any such statement and the present analysis shows that CHF in downflow is up to 12% higher than in upflow at the lowest flow rate, and this is the maximum difference at any flow rate.

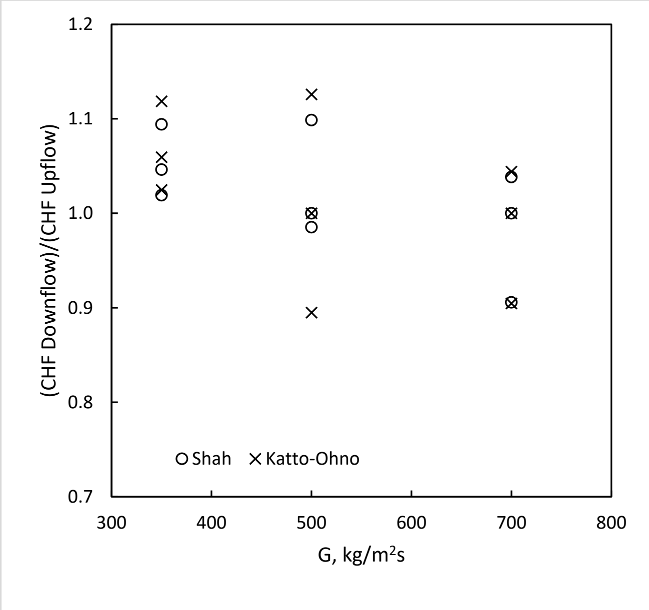

Figure 8. Ratio of CHF in downflow to that in upflow in the tests of Remizov et al., (1985) [10] estimated using the correlations of Shah and Katto–Ohno.

Figure 9 shows the ratio of CHF in downflow to that in upflow in the data of Lazarek and Black (1982) [8]. It is seen that the ratio is close to one over the entire range of mass flux. The inlet quality ranged from −0.25 to −0.02. Thus, inlet quality does not affect the ratio of upflow to downflow CHF, as indicated in the data of Cumo et al. Figure 6.

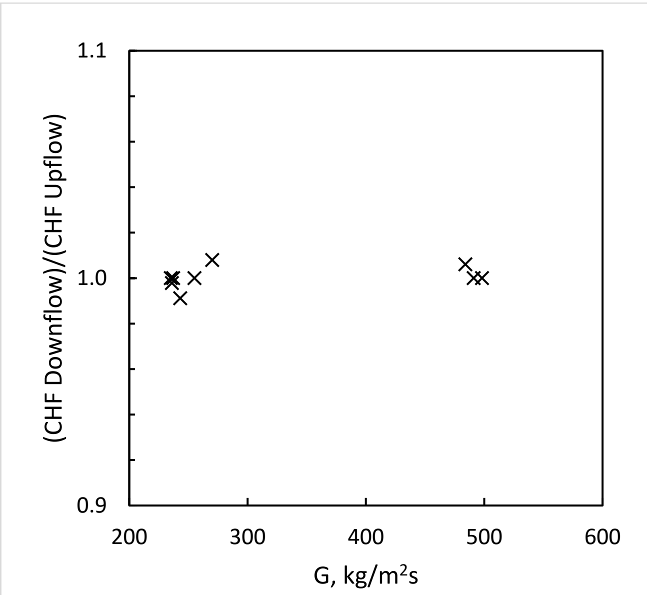

Figure 9. Ratio of CHF during downflow and upflow in the tests by Lazarek and Black (1982) [8].

Figure 10 shows the ratio of CHF in downflow to that in upflow in the tests by Ami et al., (2015) [14]. It is seen that the ratio increases with mass flux, with downflow CHF becoming larger than upflow CHF by up to 15%. The data for both upflow and downflow for higher flow rates are considerably lower than the correlations of Shah, Katto–Ohno, and Zhang et al. These three correlations are very well-verified with a vast amount of water data. This indicates that these data at a high flow rate are unusual and, hence, were not included in Tables 1 and 2.

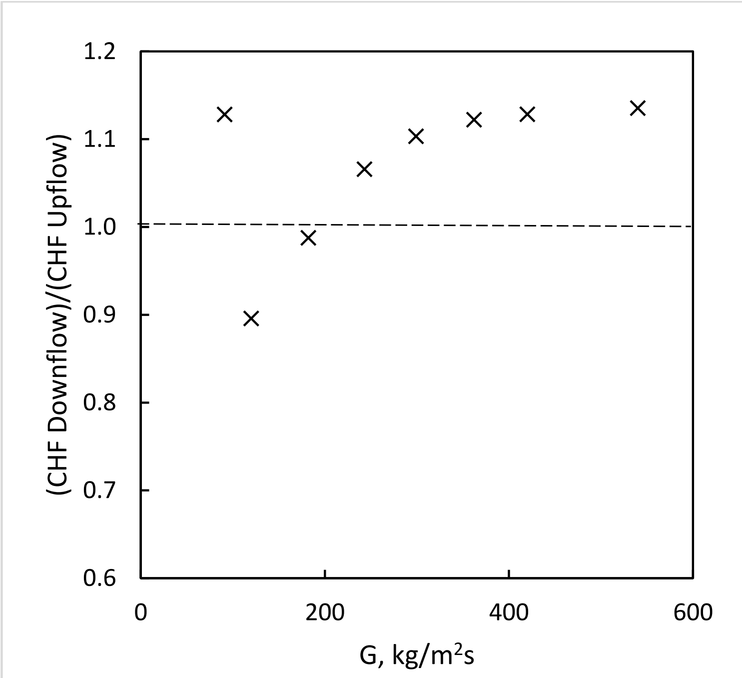

Figure 10. Ratio of measured CHF for water during downflow to that in upflow. D = 10 mm, L_c = 0.4 m, p = 3 bar, inlet temperature 60 °C. Data of Ami et al., (2015) [14].

In his tests with water, Barnett (1963) [1] found no effect of flow direction on CHF.

The previous discussions show that most of the experimental studies indicate that there is no or a small effect of flow direction on CHF. The only studies that show that CHF in downflow is much lower are Pappel et al., (1966) [4] and Pappel (1972) [5] for nitrogen. The two were done on the same test section and all parameters were the same except for inlet subcooling. Hence, it should be considered to be a single study.

4.3. Effect of Channel Shape

The data discussed earlier were all for round tubes. DeBortoli et al., (1957) [27] have listed data for CHF in rectangular channels in both directions. These are included in Tables 1 and 2. It is seen that the correlations of Shah, Katto–Ohno, and Zhang et al., are in good agreement with the data in both directions and deviations of each correlation are about the same in both directions. Figure 11 shows the comparison of some correlations with some downflow data from this source.

Gambill and Bundy (1961) [3] performed tests with water flowing downward in thin rectangular channels. As seen in Table 1, these are in good agreement with the correlations of Shah, Katto–Ohno, and Zhang et al. These data are shown in Figure 12.

It is seen that the correlations for downflow in tubes are in good agreement with the well-verified correlations for upflow CHF and there is no apparent effect of flow direction.

The effect of flow direction on CHF in shapes other than round and rectangular remains to be investigated.

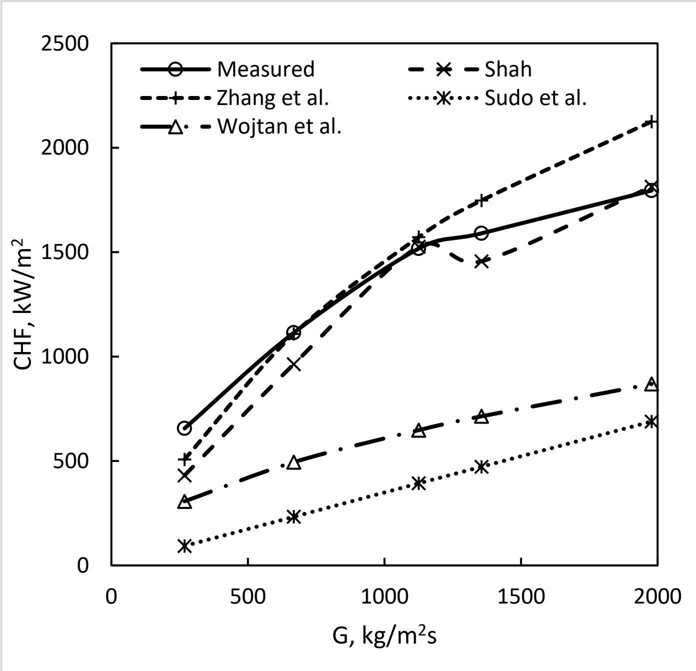

Figure 11. Data of DeBortoli et al., (1957) [27] for downflow of water in a rectangular channel 24.5 mm × 2.46 mm compared to some correlations. L/D_{HYD} = 153, p = 13.79 bar, x_{in} = −0.2.

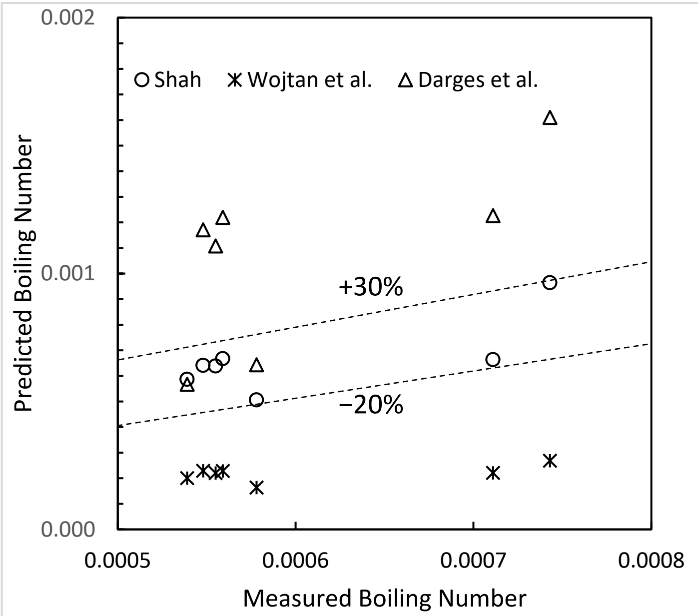

Figure 12. Data of Gambill and Bundy (1961) [3] for downflow in a rectangular channel compared to some correlations.

4.4. Recommendations for Design

The vast majority of the data analyzed show that there is no significant effect of flow direction on CHF and that CHF in downflow can be accurately calculated by reliable correlations for upflow CHF. While some data show decreases in CHF during downflow at low velocities, others (e.g., Remizov et al., and Ami et al.) show higher CHF in downflow. At near-zero mass flow rate, CHF will be due to flooding and then will be much lower than that predicted by the upflow correlations.

The recommendation for design is to use reliable upflow correlations to calculate CHF in downflow and apply a 15% safety factor. Also, calculate CHF due to flooding by a reliable correlation. Use the larger of the two calculated CHF values. The upflow CHF correlations recommended are Shah and Katto–Ohno.

5. Conclusions

1. Literature on CHF during downflow in vertical channels was studied. Some researchers reported up to 30% lower CHF in downflow compared to upflow at low flow rates. Many authors reported no effect of flow direction or even higher CHF during downflow.
2. Data were analyzed for CHF during downflow in fully heated channels from 11 sources. These included several diverse fluids (water, nitrogen, refrigerants) in round and rectangular channels, reduced pressure from 0.0045 to 0.625, mass flux from 15 to 21,761 kg/m^{2}s, inlet quality from -1.3 to 0, and exit quality from -0.2 to 1.09. These were compared to four correlations for upflow CHF and three applicable to downflow.
3. The correlations for CHF in downflow had large deviations with most data. The upflow correlations of Shah and Katto–Ohno gave good agreement with downflow data, their MAD being 21.9% and 18.9%, respectively for the 304 data points.
4. A comparison of data from studies in which CHF during both upflow and downflow was measured showed that most of them do not show any effect of orientation. Some show differences up to $\pm$15%, with some having higher CHF in upflow and others having higher CHF in downflow. Such deviations are well within the accuracy of most correlations.
5. The correlations of Shah and Katto–Ohno are recommended for calculating CHF during downflow, subject to the minimum calculated with a flooding correlation.

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Data Availability Statement: All data used in this research were obtained from the publications cited in this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

A_F	Flow area, m^2
A_H	Heated area, m^2
Bd_θ	Bond number defined by Equation (12), dimensionless
Bo	Boiling number at CHF, $=q_c/(G\ i_{LG})$, dimensionless
C_{pL}	Specific heat of liquid at constant pressure, kJ/kg K
CHF	Critical heat flux
D	Diameter of channel, m
D_{HP}	Equivalent diameter based on heated perimeter, =(4 $\times$ flow area)/(heated perimeter), m
D_{HYD}	Hydraulic equivalent diameter, =(4 $\times$ flow area)/(wetted perimeter), m
Fr_θ	Froude number defined by Equation (11), dimensionless
g	Acceleration due to gravity, m/s^2
G	Mass flux, kg/m^{2}s
G^*	Dimensionless mass flux defined by Equation (5), dimensionless
i_{LG}	Latent heat of vaporization, kJ/kg
H	Height of channel, m
K	Constant in Kutateladze formula for pool boiling CHF, dimensionless
k_L	Thermal conductivity of liquid, W/(mK)
L, L_C	Heated length of channel from the entrance to the location of CHF, m
MAD	Mean absolute deviation, dimensionless
N	Number of data points, dimensionless
p	Pressure, Pa
p_c	Critical pressure, Pa
p_r	Reduced pressure = p/p_c, dimensionless

q^*	Dimensionless CHF defined by Equation (4), dimensionless
q_c	Critical heat flux, kW/m^2
T	Temperature, K
ΔT_{SC}	$=(T_{SAT} - T_L)$, K
W	Width of channel, m
We_D	Weber number defined by Equation (10), dimensionless
x	Thermodynamic vapor quality, dimensionless
x_c	Critical quality, i.e., quality at CHF, dimensionless
x_{in}	Quality at inlet to heated section, dimensionless
Y	Parameter for correlating CHF in Shah correlation, dimensionless
Greek Symbols	
λ	Characteristic length defined by Equation (6), dimensionless
ρ	Density, kg/m^3
μ	Dynamic viscosity, Pa·s
σ	Surface tension, N/m
θ	Inclination of flow direction from horizontal, degree (0° is horizontal, 90° is vertical up)
Subscripts	
G	vapor
L	liquid
SAT	at saturated condition
SC	at subcooled condition
wall	of wall

References

1. Barnett, P.G. *An Investigation into the Validity of Certain Hypotheses Implied by Various Burnout Correlations*; Rep. AEEW-R-214; United Kingdom Atomic Energy Authority: Abingdon, UK, 1963.
2. Chen, B. The upflow and downflow critical heat flux of water and freon in a vertical tube and its flow direction factor. *At. Energy Sci. Technol.* **1993**, *27*, 112–119. (In Chinese)
3. Gambill, W.R.; Bundy, R.D. *HFIR Heat-Transfer Studies of Turbulent Water Flow in Thin Rectangular Channels*; ORNL-3079, TID-4500; Oak Ridge National Laboratory for the US Atomic Energy Commission: Oak Ridge, TN, USA, 1961.
4. Papell, S.S.; Simoneau, R.J.; Brown, D.D. *Buoyancy Effects on Critical Heat Flux of Forced Convective Boiling in Vertical Flow*; NASA Technical Note D-3672; NASA: Washington, DC, USA, 1966.
5. Papell, S.S. *Combined Buoyancy and Flow Direction Effects on Saturated Boiling Critical-Heat Flux in Liquid Nitrogen*; NASA TM X-68086; NASA: Washington, DC, USA, 1977.
6. Kirby, G.J.; Stainforth, R.; Kinneir, J.H. *A Visual Study of Forced Convection Boiling. Part 2. Flow Patterns and Burnout for a Round Test Section*; AEEW-R 506, Quoted in Cumo et al., (1977); United Kingdom Atomic Energy Authority, Reactor Group: Winfrith, UK, 1967.
7. Cumo, M.; Bertoni, R.; Cipriani, R.; Palazzi, G. *Up-Flow and Down-Flow Burnout*; Mechanical Engineering Pub for the Institution of Mechanical Engineers: London, UK, 1977.
8. Lazarek, G.M.; Black, S.H. Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113. *Int. J. Heat Mass Transf.* **1982**, *25*, 945–960.
9. Mishima, K.; Nishihara, H.; Michiyoshi, I. Boiling burnout and flow instabilities for water flowing in a round tube under atmospheric pressure. *J. Heat Mass Transf.* **1985**, *28*, 1115–1129.
10. Remizov, O.; Sergeev, V.; Yurkov, Y. Experimental investigation of deterioration in heat-transfer with up-flow and down-flow of water in a tube. *Therm. Eng.* **1983**, *30*, 549–551.
11. Deqiang, S.; Hong, J.; Junkai, F.E.N.G. An experimental study of upward and downward flow critical heat flux in a vertical round tube. In Proceedings of the 4th Miami International Symposium on Multi-Phase Transport Particulate Phenomena (Condensed Papers), Miami Beach, FL, USA, 15–17 December 1987.
12. Chang, S.H.; Baek, W.P.; Bae, T.M. A study of critical heat flux for low flow of water in vertical round tubes under low pressure. *Nucl. Eng. Des.* **1991**, *132*, 225–237.
13. Kays, W.M. Boiling. In *Handbook of Heat Transfer*; Rohsenow, W.M., Hartnett, J.P., Eds.; McGraw-Hill: New York, NY, USA, 1973; pp. 13-50–13-75.
14. Ami, T.; Harada, T.; Umekawa, H.; Ozawa, M. Influence of tube diameter on critical heat flux in downward flow. *Multiph. Sci. Technol.* **2015**, *27*, 77–97. [CrossRef]
15. Shah, M.M. *Two-Phase Heat Transfer*; John Wiley & Sons: Hoboken, NJ, USA, 2021.
16. Sudo, Y.; Miyata, K.; Ikawa, H. Experimental study of differences in dnb heat flux between upflow and downflow in vertical rectangular channel. *J. Nucl. Sci. Technol.* **1985**, *22*, 604–618. [CrossRef]

17. Hirose, Y.; Sibamoto, Y.; Takashi Hibiki, T. Critical heat flux for downward flows in vertical round pipes. *Prog. Nucl. Energy* **2024**, *168*, 105027.
18. Darges, S.J.; Devahdhanush, V.S.; Mudawar, I. Assessment and development of flow boiling critical heat flux correlations for partially heated rectangular channels in different gravitational environments. *Int. J. Heat Mass Transf.* **2022**, *196*, 123291.
19. Shah, M.M. Improved general correlation for critical heat flux in uniformly heated vertical tubes. *Int. J. Heat Fluid Flow* **1987**, *8*, 326–335.
20. Katto, Y.; Ohno, H. An improved version of the generalized correlation of critical heat flux for the forced convection boiling in uniformly heated vertical tubes. *Int. J. Heat Mass Transf.* **1984**, *27*, 1641–1648.
21. Shah, M.M. Applicability of general correlations for CHF in conventional tubes to mini/macro channels. *Heat Transf. Eng.* **2017**, *38*, 1–10.
22. Wojtan, L.; Revellin, R.; Thome, J.R. Investigation of saturated critical heat flux in a single uniformly heated microchannel. *Exp. Therm. Fluid Sci.* **2006**, *30*, 765–774.
23. Sripada, R.; Mendu, S.S.; Tentu, D.; Varanasi, S.S.; Veeredhi, V.R. Development of correlation for critical heat flux for vertically downward two-phase flows in round tubes. *Exp. Heat Transf.* **2021**, *34*, 393–410. [CrossRef]
24. Lemmon, E.W.; Huber, M.L.; McLinden, M.O. *NIST Reference Fluid Thermodynamic and Transport Properties, REFPROP Version 9.1*; NIST: Gaithersburg, MD, USA, 2013.
25. Dougherty, T.; Fighetti, C.; Reddy, G.; Yang, B.W. Critical heat flux for vertical upflow and downflow in uniform tubes at low pressures. In Proceedings of the Third International Symposium on Multi-Phase Flow and Heat Transfer, Xi'an, China, September 1994.
26. Ruan, S.W.; Bartsch, G.; Yang, S.M. Characteristics of the critical heat flux for downward flow in a vertical tube at low flow rate and low pressure conditions. *Exp. Therm. Fluid Sci.* **1993**, *7*, 296–306. [CrossRef]
27. DeBartoli, R.A.; Green, S.J.; LeTourneau, B.W.; Troy, M.; Weiss, A. *Forced Convection Heat Transfer Burnout Studies for Water in Rectangular Channels and Round Tubes at Pressures above 500 Psia*; WAPD-188, TID-4500; US Department of Commerce: Washington, DC, USA, 1958.
28. Collier, J.G.; Thome, J.R. *Convective Boiling & Condensation*, 3rd ed.; Oxford University Press: Oxford, UK, 1994.