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Further Study and Development of Correlations for Heat Transfer during Subcooled Boiling in Plain Channels

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Abstract: The author's published correlations for subcooled boiling in channels are further studied and developed in this work. The areas explored include choice of equivalent diameters for annuli and partially heated channels, effects of flow direction, micro-gravity, and orientation of heated surface. A new correlation is developed, which is a modification of the author's earlier correlation. The author's previous correlations and the new correlation are compared with a very wide range of test data for round tubes, rectangular channels, and annuli. Several other correlations are also compared with the same data. The authors' correlations provide good agreement with data, the new correlation giving the least deviation. The data included hydraulic diameters from 0.176 to 22.8 mm, reduced pressure from 0.0046 to 0.922, subcooling from 0 to 165 K, mass flux from 59 to 31,500 kgm^{-2}s^{-1}, all flow directions, and terrestial to micro gravity. The new correlation has mean absolute deviation (MAD) of 13.3% with 2270 data points from 49 sources. Correlations by others had MAD of 18% to 116%. The results are presented and discussed.

Keywords: subcooled boiling; annuli; tubes; minichannels; heat transfer; correlations

1. Introduction

Subcooled boiling heat transfer in channels is involved in many applications such as chemical processing, cryogenics, refrigeration and air conditioning, nuclear reactor safety analysis, etc. Its accurate prediction is therefore necessary to ensure correct design and analysis. In view of this need, many experimental studies have been performed and many correlations have been published. The present author presented a correlation, Shah (1977) [1], which was shown to agree well with data from many sources. Shah (2017a) [2] presented an improved version of this correlation which was more accurate. Various other correlations were also compared with the same data and were found to be considerably less accurate. Despite the satisfactory performance of the Shah (2017a) [2] correlation, some matters were left unresolved and there were some new aspects needing exploration that led to the work reported here. These are outlined in the following.

In Shah (2017a) [2], the choice of equivalent diameter to be used for partially heated channels was discussed. In most of the data analyzed therein, the difference in D_{HYD} and D_{HP} was so small that using either of them provided about the same prediction of heat transfer coefficient. Based on the experience with condensation heat transfer, Shah (2016) [3], use of D_{HP} was recommended. More data with considerable difference between D_{HYD} and D_{HP} has been published in recent years. It was therefore possible and desirable to analyze these newer data to make a more rational choice of the equivalent diameter to be used.

Further investigation of the choice of equivalent diameter to be used for annuli was also considered desirable. Shah (1977, 1983) [1,4] had recommended the use of D_{HYD} for annular gap > 4 mm and D_{HP} for smaller gaps. Based on further data analysis, Shah (2017a) [2] changed the transfer value to 3 mm. While this choice provided good agreement with data, there is a discontinuity at 3 mm gap. Alferov and Rybin (1969) [5] provided

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a method which does not involve any discontinuity. Shah (1982) [6] had evaluated this method in comparing data for saturated boiling with his correlation with good results. It was decided to try this method out with subcooled boiling data.

All the data for partially heated rectangular channels analyzed in Shah (2017a) [2] was for horizontal flow. Heating was at the bottom or both top and bottom. Recently data became available for vertical upflow and downflow as well as for heating on sides during vertical flow. It was desirable to check the ability of correlations to correctly predict heat transfer in these configurations.

Due to space explorations and planning for space habitats, there is a need for the ability to predict heat transfer in low gravity conditions. Some test data for subcooled boiling in microgravity has become available and its comparison with correlations is desirable to determine their capability to predict heat transfer at low gravity condition.

The Shah (1977, 2017a) [1,2] correlations involve the prediction of heat transfer at zero quality. This is performed using a formula first provided in Shah (1976) [7] correlation for saturated boiling in tubes and annuli and its modified versions such as Shah (1982, 2017b) [6,8]. Shah (2022) presented a new correlation for saturated boiling heat transfer which uses a new formula for heat transfer at zero quality. The Shah (2022) [9] correlation is a little more accurate than the various versions of Shah (1976) [7] correlation and avoids the discontinuity in them at Bo = 0.0011. The Shah (2022) [9] correlation is likely to replace the earlier versions. As boilers/evaporators often involve both subcooled and saturated heat transfer, it was felt desirable to develop a correlation using the new formula for heat transfer at zero quality provided in Shah (2022) [9]. This was performed and its comparison with test data is presented.

Channels with diameters smaller than 3 mm are generally considered minichannels. Applicability of correlations for macrochannels is often questioned. The matter of applicability of correlations to minichannels needs to be looked into. This was performed in the present research.

It is always desirable to evaluate a prediction method with as much data as possible to check its reliability. Much more data had become available since the preparation of the Shah (2017a) [2] correlation. Hence, comparison with these new data was needed.

The work to fulfil the needs described above and its results are presented in the following, but previous work is first discussed.

2. Previous Work

The experimental studies and prediction methods up to 2016 were discussed in Shah (2017a) [2]. Studies up to about 2020 were discussed in Shah (2021) [10].

2.1. Experimental Studies

Table 1 lists the salient features of data for rectangular channels. Data for several more studies on boiling in rectangular channels became available during the present effort. The first seven sources listed in Table 1 are for the new data while the rest were also analyzed in Shah (2017a) [2]. Some of them which are of particular interest are discussed in the following.

Table 1. Results for partially heated rectangular channels. All calculations were performed using D_{HYD} as the equivalent diameter.

Source	W × H, mm (Heat on)	Dhyd (Dhp) mm	Flow Dir.	Fluid	P_r	G kgm^{-2}s^{-1}	ΔT_{SC}, K	N	Mean Absolute Deviation, % (Upper Row) Average Deviation, % (Lower Row)								
									Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Mole and Shaw	Devahdhanush and Mudawar	Badiuzzaman	Shah 1977 [1]	Shah 2017a [2]	Present
Mudawar et al. (2023) [11] #	2.5 × 5 (1-side)	3.33 (20)	VU	nPFH	0.0674 0.0812	200 3800	3 29	126	35.6 −35.3	79.0 −79.0	19.7 −10.6	39.2 38.4	19.2 6.5	52.9 −52.6	21.0 −3.3	19.6 8.9	19.8 5.3
Devahdhanush and Mudawar (2022) [12]	2.5 × 5 (top and bottom for H, sides for V)	3.33 (10)	Hor.	nPFH	0.0787	1682	10 17	61	54.1 −54.1	82.4 −82.4	38.4 −38.4	5.2 −2.2	19.7 −19.7	66.3 −66.3	24.6 −24.6	22.9 −22.9	21.1 −21.1
			VD		0.0899	1600	15 22	41	46.7 −46.7	80.3 −80.3	30.5 −30.5	6.5 5.3	11.5 −11.5	63.9 −63.9	19.4 −19.4	16.2 −16.2	14.2 −14.2
			VU		0.0695	200	4 33	40	38.5 −38.5	90.8 −90.8	29.3 −29.3	12.5 9.8	9.2 −9.2	61.6 −61.6	28.2 −28.2	23.0 −23.0	15.9 −15.9
	2.5 × 5 (bottom)	3.33 (20)	VU		0.0674	1600	2 4	26	60.8 −60.8	84.9 −84.9	42.0 −42.0	45.8 45.8	17.2 −16.2	52.5 −52.5	11.6 −10.9	12.5 −11.4	12.2 −11.3
Yin et al. (2017) [13]	6.0 × 0.3 (bottom)	0.571 (1.091)	H	water	0.0046	261 981	1 32	24	19.1 −9.9	55.7 −55.7	20.7 7.8	73.0 73.0	13.3 5.1	98.3 98.1	24.3 12.8	38.3 26.9	38.2 26.3
Zhu et al. (2017) [14]	10 × 0.5 (bottom)	0.952 (2.0)	H	water	0.0046	200 400	0 33	49	18.0 −12.4	60.4 −60.4	18.8 3.1	47.8 47.8	31.4 1.1	72.7 72.7	16.2 −0.9	20.8 11.7	21.2 11.3
	10 × 1 (bottom)	1.82 (4.0)				200 400	2 15	10	34.1 −29.1	68.9 −68.8	18.9 −8.9	21.8 18.6	34.5 −26.9	66.3 66.3	25.2 −14.9	16.6 −3.2	16.9 −4.6
	10 × 2 (bottom)	3.33 (8.0)				200 400	0 19	101	17.4 −16.9	78.8 −78.8	21.7 18.5	6.1 4.0	9.7 −4.3	91.5 91.5	14.1 −10.7	14.1 −5.4	12.9 −4.7
Gupta et al. (2018) [15] *	10 × 1.5 (bottom)	2.61 (6.0)	H	water	0.0046	53 361	27 42	22	14.3 1.7	79.9 −79.9	14.1 13.5	23.1 23.1	18.7 18.7	49.5 49.5	13.1 −9.4	10.2 6.0	11.3 8.0
Krishnan et al. (2017) [16] *	0.305 × 2.9 (bottom or top)	0.297 (0.4)	H	water	0.0046	301 900	21 39	22	8.2 −7.7	26.8 −26.8	7.1 −2.2	72.3 72.3	20.5 8.2	44.9 44.9	10.6 8.4	8.1 2.2	7.9 1.6
	Same as above (1-side)		VU VD			301 602	22 38	19	10.6 −10.6	31.8 −31.8	7.3 −5.3	68.1 68.1	16.5 0.1	35.5 35.5	8.6 4.6	7.4 0.6	7.2 0.0
Li et al. (2017) [17]	5 × 0.52 (bottom)	0.942 (2.08)	VU	Water	0.0046	200 400	3 10	86	35.7 −35.7	44.3 44.3	14.7 8.1	14.7 9.1	23.8 −23.7	65.5 65.5	14.4 7.0	19.1 13.4	18.8 13.1
Kharangate et al. (2015) [18]	2.5 × 5.0 (top and bottom)	3.3 (10.0)	H	FC-72	0.0574	410 1592	17 24	13	42.0 −42.0	78.9 −78.9	28.9 −26.1	19.5 19.5	19.6 −19.6	57.7 −57.7	20.3 −17.0	16.7 −11.4	14.6 −9.3
	2.5 × 5.0 (bottom)	3.3 (20.0)				410 1801	18 24	14	28.9 =28.9	75.7 −75.7	14.5 −10.6	42.2 42.2	41.8 41.8	49.6 −49.6	7.4 −0.1	8.7 5.6	10.4 9.7
	2.5 × 5.0 (top)	3.3 (20.0)				410 1587	19 25	19	22.3 −22.3	79.0 −79.0	10.0 −5.4	48.8 48.8	23.9 23.9	45.8 −45.8	9.8 5.1	10.5 9.1	16.2 5.6

Table 1. *Cont.*

Source	W × H, mm (Heat on)	Dhyd (Dhp) mm	Flow Dir.	Fluid	P_r	G $kgm^{-2}s^{-1}$	ΔT_{SC}, K	N	Mean Absolute Deviation, % (Upper Row) Average Deviation, % (Lower Row)								
									Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Mole and Shaw	Devahdhanush and Mudawar	Badiuzzaman	Shah 1977 [1]	Shah 2017a [2]	Present
Qu and Mudawar (2003) [19] *	0.213 × 0.713 (bottom)	0.349 (0.397)	H	water	0.0053	255	2 33	7	34.6 −34.6	50.1 −50,1	28.2 23.9	31.4 −31.4	45.6 −45.6	12.9 −8.3	17.2 −17.2	22.1 −22.1	22.7 −22.7
Lee and Mudawar (2008a, 2008b) [20,21] *	0.260 × 1.041 (bottom)	0.416 (0.46)	H	HFE−7100	0.0517	671 6722	59 93	23	13.6 −9.1	53.5 −49.6	7.1 −0.2	165.5 16.5	36.5 36.5	32.8 −32.8	12.7 11.9	13.8 11.1	15.3 12.9
	0.235 × 0.577 (bottom)	0.334 (0.39)			0.0517	1340	31 53	6	28.0 −28.0	70.3 −70.3	14.8 −14.8	97.7 97.7	40.5 40.5	35.8 −35.8	8.8 8.8	13.4 12.6	16.0 15.4
	0.123 × 0.527 (bottom)	0.20 (0.22)			0.0517	1280	31 51	4	16.1 −16.1	48.6 −48.6	5.0 −3.3	97.7 97.7	60.3 60.3	26.3 −26.3	22.0 22.0	21.4 21.4	22.9 22.9
	0.123 × 00.305 (bottom)	0.176 (0.21)			0.0517	2216 5540	27 87	17	17.5 −17.5	49.8 −49.8	5.1 −3.3	168.9 168.9	53.5 53.5	31.2 31.2	20.6 20.6	20.4 20.4	22.0 22.0
Peng and Wang (1993) [22] *	0.6 × 0.7 (bottom)	0.646 (0.84)	H	water	0.0046	1574 3564	46 68	20	68.1 67.3	85.5 83.6	26.0 26.0	103.1 103.1	49.3 49.3	85.1 85.1	29.2 29.2	6.3 −6.1	6.2 −5.9
All sources		0.176 3.33	VU, VD, H		0.0046 0.0899	200 3800	0 39	750	29.0 −23.8	68.6 −63.9	19.1 −9.3	43.8 42.3	20.9 −0.2	62.6 6.5	17.9 −0.5	17.5 −0.8	17.0 1.0

* multichannel, others are single channels. # Tests performed at microgravity. All other studies were at earth gravity.

Krishnan et al. (2017) [16] studied heat transfer of water at atmospheric pressure in a rectangular channel heated on one side in five configurations. With horizontal flow, heating was done alternatively with the heated side at the bottom, at the top, or at the side. The other orientations were vertical upflow and downflow with one side heated. They found the heat transfer coefficient to be about the same in all orientations. The only difference was that with downflow, critical heat flux (CHF) occurred at a low heat flux. Prior to CHF, heat transfer coefficients in downflow were the same as in other orientations.

A team in Purdue University led by Prof. Issam Mudawar performed tests on partially heated rectangular channels 2.5 mm wide and 5 mm deep over several years in vertical up/down and horizontal orientations. The tests were performed under earth gravity. In some studies, only one side was heated while two opposite sides were heated in others. The objective was to understand the effect of gravity. Devahdhanush and Mudawar (2022) [12] gathered the data from those studies into a database. The data showed that orientation did not affect heat transfer nor was there any difference between heating on one side or two sides. They developed a new correlation which was in excellent agreement with this database.

Mudawar et al. (2023) [11] performed tests on a rectangular channel under microgravity in the International Space Station. The channel was vertical, 2.5 mm wide, and 5 mm deep. The 2.5 mm side was heated. Fluid used was nPFH (n-Perfluorohexane). A wide range of mass flux and subcooling was covered by the tests. The data reported in this paper are of great interest for understanding heat transfer in microgravity.

Various experimental studies on annuli are listed in Table 2 along with their salient features. The last three sources listed in it are new, the rest were also analyzed in Shah (2017a) [2]. Two of three new sources are for horizontal annuli. Only one of the previously analyzed data were for a horizontal annulus. Hence, the new data are important in determining general applicability of correlations to horizontal annuli. Data from several reported studies on annuli could not be analyzed as they did not provide sufficient details; an example is the study by Chernobylskii and Tananaiko [23].

Various studies on boiling inside round tubes are listed in Table 3 along with the range of parameters covered by them. Among them, the data of Guo et al. (2023) [24] for water was identified during the present work, the rest were included in Shah (2017a) [2].

Table 2. Range of data for annuli and results of comparison with correlations.

Source	Fluid	Test Section			p_r	G kg/m^{2}s	ΔT_{SC} K	No. of Data Pts.	Mean Absolute Deviation, % (Upper Line) Average Deviation, % (Lower Line)								
		D_{in} mm	D_{HYD} (D_{HP})	Tube with Boiling (Heated Tubes)					Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Mole and Shaw	Devahdhanush and Mudawar	Badiuzzaman	Shah (1977) [1]	Shah (2017a) [2]	New Correlation
Alferov and Rybin (1969) [5]	Water	15.0	10.0 (10.0)	Both	0.6638	319 1898	8 23	6	22.3 22.3	49.5 −49.5	36.0 36.0	14.3 −14.3	47.6 47.6	40.1 −40.1	10.1 3.2	6.2 −0.9	5.3 −1.3
			6.0 (6.0)	Both	0.6638	618 1780	7 12	10	11.2 9.8	51.5 −51.5	26.2 26.2	18.9 −18.9	20.4 20.4	49.0 −49.0	11.7 −6.0	8.7 −7.4	9.1 −8.2
			6.0 (14.4)	Inner	0.6638	311 750	7 31	6	8.6 8.3	72.7 −72.7	22.2 22.2	33.4 −33.4	22.4 15.3	52.7 −52.7	12.3 −12.3	8.8 8.8	8.9 −8.9
			6.0 (10.3)	Outer	0.6638	299 1860	7 28	7	10.1 10.1	68.1 −68.1	22.4 22.4	26.9 −26.9	29.9 29.0	47.6 −47.6	10.1 −8.0	11.2 −10.3	11.0 −10.2
			2.0 (2.0)	Both	0.6638	705 3006	8 43	5	21.2 16.4	30.5 −1.4	25.4 24.9	25.8 18.2	99.5 99.5	23.2 −18.0	23.1 10.8	15.8 3.5	16.1 3.3
			2.0 (4.3)	Inner	0.6647	295 3103	10 28	6	3.8 3.8	47.4 −47.4	13.9 13,9	11.0 −11.0	63.9 63.9	34.5 −34.5	4.2 1.3	4.2 −4.2	4.4 −4.4
			2.0 (3.8)	Outer	0.6638	303 3191	6 16	16	10.3 8.5	53.7 −53.7	14.8 −14.8	14.8 −14.8	34.0 34.0	44.3 −44.3	9.8 3.1	7.4 −4.5	7.9 1.4
			10.0 (26.7)	Inner	0.6647	319 1870	5 31	12	13.9 13.6	63.1 −61.1	28.3 28.3	36.8 −36.8	22.7 0.2	57.9 −57.9	14.6 −7.5	12.9 −11.0	13.2 −11.5
			10.0 (16.0)	Outer	0.6638	361 1944	6 31	6	13.0 13.0	52.1 −52.1	25.6 25.6	28.4 −28.4	24.6 15.7	51.6 −51.6	14.8 −6.9	14.0 −12.8	14.1 −13.1
			3.0 (3.0)	Both	0.6638 0.8914	602 5019	3 42	6	7.4 6.5	30.5 −30.5	20.5 20.5	15.7 0.4	57.7 50.5	23.2 23.1	14.4 4.2	9.3 −4.2	9.2 −4.3
			3.0 (6.6)	Inner (both)	0.6647 0.8914	309 3668	25 63	9	2.4 1.7	36.9 −36.9	5.0 5.0	13.2 10.2	116.4 116.4	23.9 −23.9	8.5 −8.2	7.8 −7.8	7.6 =7.6
			3.0 (6.6)	Inner	0.8914	310 2457	24 30	3	3.7 1.7	44.4 −44.4	5.6 5.0	11.6 11.6	94.9 94.9	46.3 −46.3	4.2 −3.2	8.0 −8.0	7.6 −7.6
			3.0 (5.5)	Outer (both)	0.6638 0.8914	307 2741	24 43	6	2.1 −1.0	34.7 −31.7	3.6 3.6	11.8 −0.4	98.4 98.4	24.5 −24.5	3.9 −2.4	9.0 −9.0	7.5 −7.5
			3.0 (5.5)	Outer	0.6638 0.8914	300 2685	10 65	11	8.1 5.0	36.7 −36.1	12.5 12.1	17.6 4.9	99.2 97.2	31.3 −27.6	8.4 11.7	7.5 −5.6	6.6 −3.6

Table 2. *Cont.*

Source	Fluid	Test Section D_{in} mm	 D_{HYD} (D_{HP})	 Tube with Boiling (Heated Tubes)	p_r	G kg/m²s	ΔT_{SC} K	No. of Data Pts.	Mean Absolute Deviation, % (Upper Line) Average Deviation, % (Lower Line) Liu and Winterton	 Gungor and Winterton	 Haynes and Fletcher	 Mole and Shaw	 Devahdhanush and Mudawar	 Badiuzzaman	 Shah (1977) [1]	 Shah (2017a) [2]	 New Correlation
Tarasova and Orlov (1969) [25]	Water	12.97	2.12 (4.6)	Inner	0.5854 0.8914	1140 3620	1 50	20	7.4 6.9	38.9 −38.2	25.4 25.4	14.1 −12.1	39.0 31.1	42.2 −42.2	9.0 6.5	7.1 −4.5	7.5 −4.9
		8.5	6.6 (18.3)	Inner	0.5983 0.9218	1360 2723	4 110	23	5.2 1.7	56.8 −56.8	13.9 13.8	30.7 −29.8	31.0 15.1	56.2 −56.2	12.4 −11.1	12.7 −12.2	13.0 −12.6
		34.6	4.3 (8.12)	Outer	0.2238	1353 2010	6 38	4	4.4 −1.8	46.6 −46.6	20.4 20.4	24.7 −24.7	30.3 13.5	14.3 −9.4	6.6 1.0	7.8 −7.8	5.4 −4.2
			4.3 (9.13)	Inner	0.4480 0.6663	1322 3044	4 66	23	4.4 3.6	39.5 −24.2	15.7 15.7	22.1 −17.2	52.5 42.8	31.3 −25.5	7.8 4.4	5.6 −5.1	6.0 −5.8
			4.3 (4.3)	Both	0.2238 0.8914	1127 1855	1 36	22	7.0 6.6	39.5 −39.5	25.0 25.0	16.6 −1.2	53.2 47.4	23.5 −20.7	8.1 7.1	7.2 −2.7	7.5 −3.4
		36.6	2.28 (4.7)	inner	0.448	1895	7 17	4	7.3 6.6	26.4 26.4	36.0 −36.0	16.8 −16.8	21.2 21.2	27.3 −27.3	12.7 9.2	7.0 −4.1	7.2 −4.9
			2.28 (4.43)	Outer	0.448 0.6638	1905 1965	6 29	6	8.5 8.5	22.3 22.3	24.1 −24.1	7.7 −7.7	53.1 53.1	25.9 −25.9	11.9 11.9	4.2 −0.3	6.9 4.0
			2.28 (2.28)	Both	0.44 0.6638	1905 1965	12 28	8	7.2 7.2	17.7 17.7	18.6 −18.6	3.5 2.2	83.5 83.3	17.1 −4.1	12.1 12.1	3.2 0.7	3.0 0.2
Lung et al. (1977) [26]	Water	10.0	12.0 (38.4)	Inner	0.009 0.0189	471 7674	10 54	30	18.8 −15.3	13.0 2.0	48.6 −45.6	37.7 −37.7	27.2 −27.2	14.8 −12.4	17.7 −0.6	16.6 −13.1	16.5 −12.9
Dougall and Panian (1972) [27]	R-113	19.0	12.8 (34.2)	Inner	0.2018 0.4241	542 2550	4 48	38	13.4 −7.8	60.6 −60.6	9.1 5.9	20.9 −16.6	21.0 −16.6	68.2 −68.2	12.0 −4.3	12.6 −7.5	11.9 −6.6
Thom et al. (1965) [28]	Water	17.8	5.12 (5.12)	Both	0.6268	987 1134	6 75	22	4.4 0.6	37.6 −37.4	9.1 9.1	16.1 −7.7	78.5 75.1	28.5 −23.7	7.1 −2.0	11.2 −10.0	11.5 −10.3
McAdams et al. (1949) [29]	Water	6.3	4.4 (11.5)	Inner	0.0189	3368 3401	11 83	26	15.5 15.5	46.6 −46.6	48.9 48.9	10.7 10.0	30.6 30.6	50.4 50.4	32.4 32.4	27.0 27.0	25.6 25.6
			13.2 (53.9)	Inner	0.0094 0.0281	276 1123	28 49	13	10.6 10.2	49.1 −49.1	29.0 29.0	26.7 −26.7	8.6 0.7	15.0 4.1	18.4 12.4	14.5 5.6	13.5 5.6
Rassokhin et al. (1969) [30]	Water	10.1	3.85 (9.16)	Inner	0.2743	2575 6132	8 9	9	7.8 7.4	29.2 −29.2	40.4 40.4	24.4 −24.4	5.4 −5.4	21.8 −21.8	19.9 19.9	12.1 9.1	12.7 9.3
		9.1	4.8 (12.3)	Inner	0.2828	3600 3770	4 46	13	21.8 21.8	27.3 −2.7	41.7 41.7	18.2 −17.7	22.8 14.7	13.6 −13.6	25.4 25.4	11.9 4.5	13.2 5.3
		8.0	6.0 (16.4)	Inner	0.2701	3100	1 29	4	8.8 8.8	35.4 −35.4	40.7 40.7	23.9 −15.8	26.3 2.3	16.2 −10.8	11.9 11.0	5.9 −0.2	6.3 −1.1

Table 2. *Cont.*

Source	Fluid	Test Section: D_{in} mm	Test Section: D_{HYD} (D_{HP})	Test Section: Tube with Boiling (Heated Tubes)	p_r	G kg/m^{2}s	ΔT_{SC} K	No. of Data Pts.	Mean Absolute Deviation, % (Upper Line) Average Deviation, % (Lower Line): Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Mole and Shaw	Devahdhanush and Mudawar	Badiuzzaman	Shah (1977) [1]	Shah (2017a) [2]	New Correlation
Colburn et al. (1948) [31]	Water	42.2	8.6 (19.0)	Inner	0.0048 0.0122	87 839	9 56	15	8.3 −7.1	47.0 −47.0	9.2 7.3	10.9 −5.5	13.2 −3.5	30.9 30.9	7.7 −0.3	11.0 −6.9	10.9 −7.1
	Metha-nol				0.0159 0.0395	79 1100	28 55	33	7.6 2.1	52.9 −52.9	15.7 14.5	9.7 7.6	17.8 −17.7	15.7 −15.7	10.7 −4.0	11.0 −7.7	11.0 −8.0
Lie and Lin (2006) [32] *	R-134	16.0	4.0 (9.0)	Inner	0.1209	200	1 10	15	15.4 9.5	77.3 −77.0	36.8 36.8	44.0 44.0	20.2 11.8	20.3 −12.5	11.3 5.5	12.0 4.5	12.4 4.2
		18.0	2.0 (4.2)	Inner	0.1209	200 300	0.4 7.8	12	17.3 0.3	73.4 −73.4	29.3 28.0	62.0 62.0	20.8 10.6	23.7 −7.13	16.6 10.2	17.1 11.8	17.3 11.1
Hasan et al. (1990) [33]	R-113	15.9	22.8 (77.8)	Inner	0.0544 0.0749	579 1102	4 60	59	10.4 −10.4	57.9 −57.9	10.7 10.1	9.5 −8.3	27.0 −27.0	58.3 −58.3	6.8 3.0	6.6 1.3	6.2 0.9
Hino and Ueda (1985) [34]	R-113	8.0	10.0 (32.5)	Inner	0.0429	514 1236	20 30	12	15.3 −15.3	67.0 −67.0	4.3 3.1	7.7 −4.3	16.8 −16.8	51.0 −51.0	6.1 0.0	8.4 −2.5	7.1 −1.7
Boye et al. (2015) [35]	Hexane	5.0	5.0 (7.5)	outer	0.0462 0.0760	100 183	0 19	15	27.1 −25.5	85.0 −85.0	12.0 −8.3	7.7 −0.1	15.6 −6.2	61.8 −0.9	24.7 −23.9	23.4 −20.0	14.9 −10.6
		12.0	3.0 (5.4)		0.0625	59	0 36	5	15.6 −15.6	88.3 −88.0	7.6 −3.8	8.2 6.4	14.3 6.7	65.4 −1.3	24.0 −24.0	18.3 −18.3	5.9 −5.1
		4.0	1.0 (1.8)		0.056 0.086	299 499	0 20	17	41.8 −41.8	79.0 −79.0	25.1 −25.1	16.9 9.8	15.2 −8.3	77.0 5.0	23.2 −23.2	16.8 −16.8	12.6 −10.7
Li et al. (2021) [36]	water	10.0	10.0 (20.0)	Inner	0.0046	564 1200	5 6	32	20.7 −20.7	53.3 −53.4	15.3 15.3	12.7 −12.7	46.0 −46.0	30.1 30.1	5.4 −3.8	5.9 −4.7	6.4 −4.3
Yin et al. (2000) [13] *	R-134a	16.66	10.31 (37.4)	inner	0.0748	100 300	8 10	32	22.9 −22.9	74.8 −74.8	8.2 −7.7	35.5 −35.5	42.8 42.8	50.9 −50.9	23.5 −24.5	20.3 −20.3	19.4 −19.4
Devadhanush et al. (2021) [37] *	HFE-7100	23.6	17.3 (81.5)	inner	0.0519	91 683	21 36	35	33.0 −32.0	86.2 −86.2	22.9 −21.7	31.9 −31.7	37.4 −37.4	72.0 −72.0	23.7 −23.6	24.6 −23.6	21.6 −20.1
All sources		4.0 42.2	1.0 22.8		0.009 0.9218	59 6132	0 110	656	14.0 −4.1	53.8 −51.9	19.0 13.1	26.2 −3.5	35.7 7.3	41.5 −27.3	13.5 −0.2	12.3 −5.7	11.6 −4.8

* Horizontal annulus. All other data are for vertical annuli with upflow.

Table 3. Range of data for round channels and results of their comparison with various correlations.

Source	Fluid	Test Section		p_r	G Kg $m^{-2}s^{-1}$	Sub-Cooling K	No. of Data Pts.	Mean Absolute Deviation (MAD), % Average Deviation (AD), %								
		Flow Direction	D_{hyd} (D_{hp}) mm					Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Moles and Shaw	Devahdhanush and Mudwar	Badiuzzaman	Shah (1977) [1]	Shah (2017a) [2]	New Correlation
Lazarek and Black (1982) [38]	R-113	V	3.1	0.0503	502	0.6 24	10	26.6 −26.6	80.8 −80.8	9.1 −9.1	43.2 43.2	8.6 1.8	32.7 −30.9	8.8 −8.2	7.8 −2.3	6.8 −0.8
Bao et al. (2000) [39]	R-123	H	1.95	0.0959 0.1378	167 452	0.2 48	51	26.7 −26.7	73.0 −73.0	13.8 −13.2	23.3 23.3	15.8 9.5	37.1 −37.1	15.3 −4.8	13.8 −12.5	13.2 −12.0
	R-11			0.0666 0.1070	167 560	3 46	49	17.6 −16.9	63.3 −63.3	6.4 −2.8	33.3 33.3	37.6 35.2	16.6 −14.7	12.0 −10.7	7.6 −4.5	6.7 −2.7
Boyd (1988, 1989) [40,41]	water	H	3.0	0.0352 0.0752	4600 31500	16 100	15	16.4 −16.4	45.8 −45.8	6.3 3.5	19.0 −19.0	21.9 21.9	12.3 8.1	5.5 1.6	7.2 −5.2	7.6 −5.9
Haynes and Fletcher (2003) [42]	R-11	H	1.95	0.0797 0.0959	150 1840	0 35	21	23.0 −23.0	58.3 −58.3	10.0 −6.9	154.7 154.0	24.7 13.2	75.2 33.6	15.8 −13.5	12.0 −7.8	11.9 −9.3
Papell (1963) [43]	water	V	7.9	0.0079 0.0337	1306 2200	99 133	13	5.8 −0.8	36.0 −36.0	9.6 7.9	68.3 68.3	20.0 18.6	14.3 13.2	4.7 −0.2	7.4 −6.6	7.5 −6.9
Hodgson (1968) [44]	water	H	11.8	0.0315 0.1723	1781 8130	10 129	58	15.0 15.0	30.8 −27.0	36.6 36.6	17.3 −10.2	41.7 41.7	16.6 15.2	22.6 22.5	13.1 11.8	12.5 11.0
Gouse and Coumou (1965) [45]	R-113	H	10.9	0.0325 0.0381	525 703	0 8.3	5	10.2 −9.8	45.3 −45.3	30.5 30.5	907.8 907.8	18.7 −18.4	276.1 241.3	26.7 26.7	21.8 21.8	21.6 21.6
Riedle and Percupile (1973) [46]	R-113	H	6.6	0.098 0.1343	1518 2466	1.4 4.9	13	32.7 −32.7	42.0 −42.0	11.8 −7.7	8.3 2.2	54.0 −54.0	64.6 −64.6	14.2 −12.1	24.0 −24.0	21.0 −21.0
	R-12			0.2202 0.2327	1457 2190	0.5 9.5	12	33.4 −31.9	57.3 −56.0	8.0 −1.5	23.4 19.7	43.2 −43.2	41.2 −41.2	15.1 −11.4	19.1 −19.1	18.8 −18.8
	R-11			0.1577 0.2054	1639 1703	0 9	8	26.3 −26.3	45.9 −45.9	15.6 6.2	71.8 61.8	42.9 −42.9	44.8 −25.6	16.4 −4.2	16.9 −13.3	16.2 −11.2
	R-12		18.8	0.1702 0.2391	1437 4489	0.8 11.1	25	17.6 −16.0	41.8 −41.7	19.4 19.1	13.9 2.0	46.2 −46.2	49.0 49.0	16.3 3.0	15.1 −6.6	15.9 −5.3
	R-113			0.1459 0.1944	1897 4733	2 18	17	30.6 −30.6	54.2 −54.2	11.4 −2.4	12.6 −8.1	42.3 −42.3	66.3 −66.3	15.4 −10.7	18.6 −15.0	19.4 −15.0
	R-11			0.1069 0.2077	1470 4698	0 17	26	14.7 −12.5	42.4 −42.4	23.0 23.0	26.2 10.8	30.2 −30.2	43.3 −41.6	16.7 8.0	17.5 1.6	19.1 2.4

Table 3. *Cont.*

Source	Fluid	Test Section: Flow Direction	Test Section: D_{hyd} (D_{hp}) mm	p_r	G Kg $m^{-2}s^{-1}$	Sub-Cooling K	No. of Data Pts.	Mean Absolute Deviation (MAD), % Average Deviation (AD), %: Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Moles and Shaw	Devahdhanush and Mudwar	Badiuzzaman	Shah (1977) [1]	Shah (2017a) [2]	New Correlation
Noel (1961) [47]	NH_3	V	6.2	0.1035 0.6363	570 24160	14 92	27	7.3 3.8	40.3 −40.3	16.2 16.2	13.7 −13.4	84.0 64.0	8.4 −7.2	11.1 9.1	9.7 4.6	9.2 4.9
Yan et al. (2015) [48]	water	V	9.0	0.1367 0.2274	6000 10000	27 165	42	13.5 13.0	27.2 −27.2	27.2 27.2	10.1 −4.3	67.0 67.0	15.2 14.7	19.7 19.5	15.8 13.7	15.5 13.3
Clarke and Rohsenow (1953) [49]	water	V	4.6	0.6268	5285	64 142	30	2.4 −0.5	17.9 −16.9	3.0 3.0	8.5 −0.3	115.5 115.5	9.2 −2.0	2.4 0.8	6.1 −6.1	6.0 −6.0
Bergles and Rohsenow (1964) [50]	water	V	2.4	0.0069	509 3293	60	20	3.5 1.2	36.1 −36.0	17.6 17.6	48.6 48.6	43.0 43.0	63.4 63.4	12.6 12.6	9.7 8.1	.9.3 7.6
Callizo et al. (2007) [51]	R-134a	V	1.22	0.2194	500 700	0 5.4	12	37.7 6.3	38.8 −14.7	19.0 14.2	65.8 65.8	28.6 −24.0	37.7 −37.7	19.2 13.4	20.0 −20.0	18.7 −18.7
Ciancolini et al. (2007) [52]	water	H	4.03	0.009 0.0235	529 839	0.5 34	20	6.9 0.9	38.8 −38.8	30.5 30.5	27.8 27.8	25.4 13.9	92.4 92.4	19.7 19.7	14.7 14.7	14.1 14.0
Baburajan et al. (2013) [53]	water	H	7.5	0.0055	476	17 65	11	6.9 −6.2	53.2 −53.2	13.7 10.9	22.5 18.0	22.2 17.2	49.3 49.3	5.2 −0.9	3.4 −0.9	3.2 −1.8
			5.5	0.0055	686 691	21 55	14	6.3 −6.6	22.8 −22.8	9.5 8.3	18.3 18.3	17.4 17.4	51.0 51.0	6.2 3.9	11.0 −7.4	11.0 −7.8
Styushin and Varshnei (1967) [54]	water	H	8.97	0.0068	1152	8 24	12	13.6 13.3	8.0 5.0	34.3 34.3	7.4 −0.6	18.5 −18.5	38.9 38.9	27.5 27.5	11.6 4.3	12.6 4.3
	Isopro-panol			0.0439	1427 1464	2 53	69	11.2 −10.2	49.4 −49.4	15.4 15.2	25.3 25.3	29.3 −29.3	50.2 −50.2	8.7 −0.5	11.1 −0.6	11.2 −1.4
Kreith and Summe-rfield (1949) [55]	water	V	14.9	0.0050 0.0492	1868 3815	50 145	42	6.7 −6.4	52.0 −52.0	6.0 5.7	19.3 17.5	6.0 −0.7	5.9 −1.5	13.8 −13.8	7.2 −7.1	9.7 −9.5
		H	13.6	0.0050 0.0471	1038 3346	37 90	11	2.5 0.1	46.0 −46.0	21.6 21.6	12.6 9.2	7.3 7.3	24.1 24.1	8.9 8.9	10.7 6.8	10.3 5.8
Liu and Bi (2015) [56]	Cyclo-hexane	H	2.0	0.492	318	16 116	6	7.9 −7.9	67.5 −67.5	3.8 −3.7	70.8 63.7	51.7 −51.7	49.9 −49.9	13.1 −13.1	13.4 −13.4	11.1 −11.1
Saraceno et al. (2012) [57]	FC-72	H	1.0	0.1612	1030 1145	67 77	14	28.9 28.9	110.2 110.2	22.2 22.2	250.3 250.3	91.6 91.6	19.0 −19.0	19.4 19.4	2.6 2.6	2.6 2.5
He (1988) [58]	Water	H	9.0	0.0046	495 891	74	11	18.9 18.1	40.6 −40.6	32.1 32.1	83.5 83.5	29.8 29.8	51.8 51.8	14.9 14.8	15.2 12.3	14.7 11.8

Table 3. *Cont.*

Source	Fluid	Test Section		p_r	G Kg $m^{-2}s^{-1}$	Sub-Cooling K	No. of Data Pts.	Mean Absolute Deviation (MAD), % Average Deviation (AD), %								
		Flow Direction	D_{hyd} (D_{hp}) mm					Liu and Winterton	Gungor and Winterton	Haynes and Fletcher	Moles and Shaw	Devahdhanush and Mudwar	Badiuzzaman	Shah (1977) [1]	Shah (2017a) [2]	New Correlation
Guo et al. (2023) [24]	Water	H	2.0	0.1363 0.1813	2000 3200	35 139	82	7.6 −5.4	43.6 −43.6	5.6 5.0	12.1 −1.9	94.9 94.9	32.2 32.2	4.5 0.2	6.8 −3.6	6.8 −3.5
			1.0	0.1363 0.2268	2700 3200	27 128	68	6.0 5.8	29.4 −29.4	17.9 17.9	20.9 20.8	138.3 138.3	64.2 84.2	14.9 14.9	10.8 9.7	10.7 9.6
Huai et al. (2004) [59] *	CO_2	H	1.33	0.5422	200 399	0 8	18	24.3 24.3	30.3 −1.1	39.5 39.5	64.5 64.5	37.6 30.6	28.0 −23.9	27.5 27.5	10.1 −8.2	10.1 −8.3
Zhao and Bansal (2009) [60]	CO_2	H	6.16	0.1128	200 300	0 16	32	19.6 5.0	34.6 −26.4	39.8 34.2	73.9 72.7	33.0 5.4	30.0 17.7	25.2 15.6	16.1 −0.2	15.9 −0.3
All sources			1.0 18.8	0.0046 0.6363	150 31500	0 165	864	13.8 −5.4	44.2 −38.9	17.3 13.4	36.0 28.1	50.8 32.7	37.5 4.6	13.2 5.2	11.6 −0.9	11.4 −0.9

* Multichannel, all others are single tubes.

2.2. Prediction Methods

Many correlations have been proposed based on very limited data. Some such older correlations for macrochannels are those of Thom et al. (1965) [28], Papell (1963) [43], Badiuzzaman (1967) [61], Kandlikar (1998) [62], Prodanovic et al. (2002) [63], and Baburajan et al. (2013) [53]. Among these, those of Badiuzzaman and Pappel have been compared by many researchers to data, with mixed results. The correlation of Badiuzzaman (1967) [61] is:

$$\frac{h_{TP}}{h_{LT}} = 178Bo^{0.75}Ja^{-0.9}\left(\frac{\rho_G}{\rho_L}\right)^{-0.06}\left(\frac{\Delta T_{SC}}{T_{SAT}}\right)^{0.45} \tag{1}$$

Ja is the Jakob number defined as:

$$\text{Ja} = \left(\frac{C_{PL}\Delta T_{SC}}{i_{LG}}\right) \tag{2}$$

The correlation of Pappel (1963) [43] was based on their own data for boiling in a tube and was also verified with the ammonia data of Noel (1961) [47]. It is expressed by the following equation.

$$\frac{h_{TP}}{h_{LT}} = 90Bo^{0.7}Ja^{-0.84}\left(\frac{\rho_G}{\rho_L}\right)^{-0.056} \tag{3}$$

Among the correlations based mainly on macrochannel data, which were verified with considerable data from many sources, are those of Gungor and Winterton (1986) [64], Liu and Winterton (1991) [65], Shah (1977) [1], and Shah (2017a) [2].

Examples of correlations based on minichannel data are those of Lee and Mudwar (2008b) [21] and Haynes and Fletcher (2003) [42]. These were based on very limited data, but the latter correlation was found to perform well by Shah (2017a) [2] on comparison with a wide-ranging database. The Haynes and Fletcher correlation is expressed by the following formula.

$$q = h_{LT}(T_w - T_B) + h_{PB}(T_w - T_{SAT}) \tag{4}$$

Devahdhanush and Mudawar (2022) [12] provided the following correlation based on their group's extensive studies on subcooled boiling of FC-72 and nPFH in rectangular channels described in Section 2.1.

$$\frac{h_{TP}}{h_{LT}} = 312.8Bo^{0.769}(0.1 + Ja)^{-0.632} \tag{5}$$

The single-phase heat transfer coefficient of liquid h_{LT} is calculated by the following equation provided by McAdams (1954) [66] based on the work of Dittus and Boelter (1930) [67].

$$h_{LT} = 0.023{Re_{LT}}^{0.8}{Pr_L}^{0.4}k_L/D \tag{6}$$

This equation is generally known as the Dittus–Boelter equation and is so called also in this paper.

Guo et al. (2023) [24] provided the following correlation based on their own data for water in 1 mm and 2 mm diameter tubes and verified it with data from two other sources.

$$\frac{h_{TP}D}{k_L} = 5.119Re_{LT}^{0.718}Bo^{0.731}Ja^{-0.694}Bo^{0.731}\left(\frac{\rho_G}{\rho_L}\right)^{-0.06} \tag{7}$$

Chen et al. (2021) [68] provided a correlation which was verified only with their own data for water boiling in a rectangular channel.

As the new correlation being presented here is a modification of the Shah (1977, 2017a) [1,2] correlations, they are now described.

2.2.1. Shah (1977) [1] Correlation

Shah (1977) [1] presented a correlation for subcooled boiling by extending his correlation for saturated boiling (Shah 1976) [7]. According to this correlation.

In low subcooling regime,

$$\Delta T_{SAT} = q/(h_{LT}\psi_0) \quad (8)$$

In high subcooling regime,

$$\Delta T_{SAT} = \left(\frac{q}{h_{LT}} - \Delta T_{SC}\right)/\psi_0 \quad (9)$$

ψ_0 is h_{TP}/h_{LT} at x = 0, calculated as the larger of those provided by the following two equations:

$$\psi_0 = 230Bo^{0.5} \quad (10)$$

$$\psi_0 = 1 + 46Bo^{0.5} \quad (11)$$

Equation (10) was developed in Shah (1976) [7]. Equation (11) was added later to avoid $\psi_0 < 1$ provided by Equation (10) at very low Bo.

The single-phase heat transfer coefficient is calculated by the Dittus and Boelter (1930) [67] correlation, Equation (6).

The boundary between high and low subcooling regimes is determined as follows:

The regime is low subcooling if $(\Delta T_{SC}/\Delta T_{SAT}) \leq 2$, or if,

$$\Delta T_{SC}/\Delta T_{SAT} \leq 63,000Bo^{1.25} \quad (12)$$

Otherwise, it is high subcooling regime. For annuli, equivalent diameter is D_{HYD} if annular gap is greater than 4 mm, otherwise the heated equivalent diameter D_{HP} is used. Their definitions are

$$D_{HYD} = (4 \times \text{Flow area})/(\text{wetted perimeter}) \quad (13)$$

$$D_{HP} = (4 \times \text{Flow area})/(\text{perimeter with boiling}) \quad (14)$$

The two-phase heat transfer coefficient h_{TP} is defined as:

$$h_{TP} = q/(T_W - T_B) \quad (15)$$

The same definition of h_{TP} is used in all correlations described earlier.

2.2.2. Shah (2017a) [2] Correlation

Shah (2017a) [2] made three changes to the Shah (1977) [1] correlation. Firstly, the following equation applies in the high subcooling regime:

$$\Delta T_{SAT} = \frac{0.67q}{\psi_0 h_{LT}} + 1.65(\Delta T_{SC})^{-0.44} \quad (16)$$

ΔT_{SC} is in K, q in Wm^{-2} and h_{LT} in $Wm^{-2}K^{-1}$.

The second change made was that the transition point for the equivalent diameter was changed from 4 mm to 3 mm. Thus, D_{HYD} is used if annular gap > 3 mm, otherwise D_{HP} is used.

The third change was to use the Saha and Zuber (1974) [69] correlation to determine the subcooling regime. According to Saha and Zuber, bubbles begin to depart (break-off) from the wall when:

$$\text{Pe} < 70,000,\ \Delta T_{SC} = 0.0022(qD/k_L) \quad (17)$$

$$Pe > 70,000, \ \Delta T_{SC} = 153.8q/(G\,C_{PL}) \tag{18}$$

If actual ΔT_{SC} is greater than that provided by Equations (17) and (18), the regime is high subcooling; otherwise it is low subcooling.

The first two changes were performed entirely for improving accuracy of the correlation. While the third change also improves the accuracy to a small extent, the main reason was that the Shah method for identifying the subcooling regime requires iterative calculations and hence more calculation effort.

3. Present Research and Development

3.1. New Correlation

Shah (2022) [9] provided a new correlation for saturated boiling heat transfer in tubes and annuli. In this correlation, the following equations are used for boiling at zero quality.

For all fluids other than carbon dioxide,

$$\psi_0 = 1 + 560\ Bo^{0.65} \tag{19}$$

For carbon dioxide,

$$\psi_0 = 1820\ Bo^{0.68} \tag{20}$$

If Equation (20) provides $\psi_0 < 1$, use $\psi_0 = 1$. Equation (20) was first provided by Shah (2014) [70] following comparison of data for carbon dioxide from many sources with the Shah (1982) [6] correlation.

The Shah (2022) [9] correlation is a little more accurate than the earlier versions and more importantly, it avoids the discontinuity at Bo = 0.0011. Hence it is likely to be preferred over the previous version. Many heat exchangers involve both subcooled and saturated boiling. To have seamless transition between the two regimes, it is desirable to have the same prediction at zero quality. It was therefore decided to have a new correlation which uses the new formulas for ψ_0.

The first step in developing the new correlation was to use Equations (19) and (20) for ψ_0 in place of Equations (10) and (11) in the Shah (2017a) [2] correlation. In comparison with all data, this correlation was found to have a little lower MAD than the Shah (2017a) [2] correlation.

It was noticed that for some data points, the Saha and Zuber correlation was predicting high subcooling regime even when $\Delta T_{SC} \leq 1$. This is physically incorrect. At such low subcooling, the regime must be low subcooling. This requirement was added to the correlation.

The choice of equivalent diameter for partially heated rectangular channels was investigated as described in Section 3.2. It was found that the use of D_{HYD} provides better agreement with data than if D_{HP} is used.

During the evaluation of the Alferov and Rybin (1969) [5] method for annuli described in Section 3.3, it was found that deviations are reduced for the annuli heated on the outer tube if D_{HYD} is used as the equivalent diameter. It was decided to incorporate it into the new correlation.

Based on the above, the new correlation is as follows:

For low subcooling, Equations (19) and (20);

For high subcooling, Equation (16).

Subcooling regimes are determined by the Saha and Zuber correlation Equations (17) and (18) but if $\Delta T_{SC} \leq 1$, regime is low subcooling irrespective of the prediction of the Saha and Zuber correlation.

For annuli choose equivalent diameter as below:

Boiling on the inner tube, D_{HYD} for annular gap > 3 mm, otherwise use D_{HP};

Boiling on outer tube, use D_{HYD};

If both tubes are heated but boiling only on one tube, use the above rules based on the tube with boiling.

For partially heated rectangular channels, use D_{HYD} as equivalent diameter.

3.2. Choice of Equivalent Diameter for Partially Heated Channels

In Shah (2017a) [2], data for many partially heated channels were analyzed. For all except one data set, D_{HYD} and D_{HP} were so close that it made little difference which of them was used. In order to determine which of the two is appropriate, efforts were made to collect data in which the two differed widely. The details of the data collected are in Section 5. The ratio D_{HP}/D_{HYD} in the data for rectangular channels was up to 6. In the Shah correlations, heat transfer coefficient is proportional to $D^{0.2}$. Hence these data provided an adequate source for investigation.

All data were compared with the new correlation as well as the Shah (1977, 2017a) [1,2] correlations alternately using D_{HP} and D_{HYD}. In each case, better agreement was found using D_{HYD}. The summary of the results for all data is in Table 4. It is seen that MAD using D_{HYD} is 4 to 5 percentage points lower than when using D_{HP}. It was concluded that D_{HYD} is the better choice.

Table 4. Results of comparison of data for partially heated rectangular channels alternately using D_{HYD} and D_{HP} as equivalent diameter with the new and earlier Shah correlations.

N	MAD, % (Upper Row) AD, % (Lower Row)					
	Shah 1977 [1]		Shah (2017a) [2]		New Correlation	
	D_{HYD}	D_{HP}	D_{HYD}	D_{HP}	D_{HYD}	D_{HP}
750	17.9 −0.5	23.0 −18.7	17.5 −0.8	22.1 −13.9	17.0 1.0	21.0 −9.3

3.3. Heat Transfer in Annuli

Application of correlations for tubes to annuli requires an equivalent diameter. As noted earlier, the Shah (1977) [1] correlation uses D_{HYD} as the equivalent diameter for annular gap > 4 mm and D_{HP} for smaller annular gaps. Shah (2017a) [2] changed this transition gap to 3 mm as it provided better agreement with data. While the agreement with data is good, there is a discontinuity at 3 mm. Alferov and Rybin (1969) [5] provided a method which did not involve any discontinuity. Shah (1982) [6] tried this method for saturated boiling in annuli with good result; it was decided to try this method.

According to Alferov and Rybin, single phase heat transfer in annuli is calculated by the following equation:

$$h_{LT} = 0.023E\left(\frac{GD_{HYD}}{\mu_L}\right)^{0.8} {Pr_L}^{0.4} k_L / D_{HYD} \tag{21}$$

The factor E = 1 when both tubes are heated or if only outer tube is heated. If only the inner tube is heated,

$$E = \left(\frac{D_{out}}{D_{in}} - 1\right)^{0.12} \tag{22}$$

All data for annuli was compared with the new correlation as well as the Shah (2017a) [2] correlation using Equation (21). Calculations were also performed using D_{HP} and D_{HYD} as specified in these correlations. The results of this comparison are provided in Table 5. It is seen that the deviations using the Alferov and Rybin method are lower if boiling is on the outer tube; this was therefore incorporated in the new correlation. If boiling is on the inner tube, it is seen that the deviations using the Alferov and Rybin method are significantly higher. It was therefore decided to retain the method as stated in the Shah (2017a) [2] correlation for annuli with inner tube heated. When both tubes are heated, D_{HYD} and D_{HP} are the same; the question of choice between the two, therefore, does not arise.

Table 5. Deviations of data for annuli with the present and Shah (2017a) [2] correlations using alternative methods.

Heating Mode	Number of Sources	N	MAD % Using			
			D_{HYD} if Annular Gap > 3 mm Otherwise D_{HP}		Alferov Rybin Method	
			Shah (2017a) [2]	Present	Shah (2017a) [2]	Present
Outer tube heated	3	93	12.9	12.5	10.4	10.1
Inner tube heated	13	484	12.8	12.4	13.7	13.3
Both tubes heated	3	79	8.7	8.9	8.7	8.9
All	15	656	12.3	12.0	12.5	12.2

3.4. Other Investigations

Investigation of the ability of correlations to predict heat transfer in various flow directions is important.

In Shah (2017a) [2], the data analyzed for rectangular channels were all for horizontal flow except for one for vertical upflow. No data were analyzed for vertical downflow. As seen in Table 1, several data sets for downflow were also analyzed during the present research.

In the data for annuli analyzed in Shah (2017a) [2], all were for vertical flow except for one for horizontal flow. As seen in Table 2, two more data sets for horizontal annuli were analyzed during the present research.

The results of flow direction revealed by these data analyses are discussed in Section 5.1.1.

Some conclusions about the effects of low gravity on heat transfer can be drawn from results on flow in various orientations at earth gravity. However, analysis of data at low gravity is essential to have confidence in this regard. The data of Mudawar et al. (2023) [11] obtained at microgravity conditions aboard the International Space Station were therefore analyzed. The results are discussed in Section 5.5.

Applicability of correlations to minichannels was investigated by comparison of data with various criteria for the boundary between macro and minichannels. This is discussed in Section 5.6.

4. Evaluation of Correlations

An extensive database was developed and analyzed to evaluate the new and other correlations as well as to investigate the other matters noted in the Introduction and in Section 3.

4.1. Data Collection

The wide-ranging database analyzed in Shah (2017a) [2] was available. Additional data were sought as needed for the current investigations. The previous database had data for horizontal annuli from only one source. Two more were found and added to the database. There was data from only one source for partially heated rectangular channels; data from several more sources were added. There were no data for carbon dioxide in the previous database; data from two sources were added. For rectangular channels, more data were obtained for vertical up and down flows as such data were scarce in the previous database. Data for low gravity condition were also added to the database. The complete range of data in the database is listed in Table 6.

Table 6. Range of all data for all types of channels that were compared with correlations.

	Range
Fluids	Water, ammonia, CO_2, R-11, R-12, R-113, R-123, R-134a, FC-72, nPFH, HFE 7100, isopropanol, hexane, cyclohexane, methanol
Geometry	Single round tubes, single rectangular channels, rectangular multichannels, round multichannels, annuli heated on inner/outer/both tubes. Rectangular channels heated on top, bottom, top and bottom, or vertical sides
Flow direction	Horizontal, vertical up and down
Tube material	Various stainless steels, copper, brass, zirconium-copper alloy, nickel, inconel, coated glass
D_{HYD}, mm	Round tubes: 1.0 to 18.8; rectangular channels: 0.176 to 3.33; annuli: 1.0 to 22.8
D_{HP}, mm	Rectangular channels: 0.21 to 20.0; annuli: 1.8 to 81.5
D_{HP}/D_{HYD} for rectangular channels	1.1 to 6.0
Annular gap, mm	0.5 to 11.4
Aspect ratio rect. channels, W/H	0.105 to 20
Reduced pressure, p_r	0.0046 to 0.922
G, kg $m^{-2}s^{-1}$	59 to 31,500
Subcooling, degree C	0 to 165
Re_{LT}	375 to 1,270,000
Bo × 10^4	0.53 to 91.2
Bond number	0.025 to 7100
We_{GT}	158 to 11,383,366
Data points	2270 data points from 97 data sets from 49 sources

Only data prior to CHF were considered. CHF was considered to have occurred when heat transfer coefficient showed significant deterioration.

4.2. Correlations Evaluated

The database was compared with the new correlation as well as the Shah (1977) [1] and Shah (2017a) [2] correlations. Comparison was also made with the correlations of Gungor and Winterton (1986) [64], Liu and Winterton (1991) [65], Moles and Shaw (1972) [71], Devahdhanush and Mudawar (2022) [12], Haynes and Fletcher (2003) [42], Badiuzzaman (1967) [61], Pappel (1963) [43], and Guo et al. (2023) [24].

4.3. Calculation Method

Fluid properties for all correlations except the Moles and Shaw correlation were calculated at the liquid bulk temperature. For the Moles and Shaw correlation they were calculated as specified by them. Properties of FC-72 and HFE-7100 were obtained from their manufacturer, the 3-M corporation. For analyzing data for nPFH, the properties of FC-72 were used as they are essentially the same. Properties of isopropanol were taken from Vargaftik (1975) [72] and Beaton and Hewitt (1989) [73]. For all other fluids, properties were calculated using REFPROP 9.1 (Lemmon et al. 2013 [74]).

Single phase heat transfer coefficient h_{LT} was calculated using the Dittus–Boelter correlation Equation (6) for all correlations at all Reynold numbers. An exception was made for the Haynes and Fletcher correlation for which the Pethukov and Krillov (1958) [75] correlation was used when $Re_{LT} < 10^4$. They had recommended the Gnielinski (1976) [76] correlation for Re_{LT} < 10,000. That equation yields negative h_{LT} for Re_{LT} < 1000 and there were many data points in that range. The Gnielinski correlation is in fact a modified form of the Pethukov and Kirillov correlation.

Pool boiling heat transfer coefficient required by the Haynes and Fletcher correlation was calculated by the following simplified correlation of Cooper (1984) [77].

$$h_{PB} = 55.1q^{0.67}p_r^{0.12}(-logp_r)^{-0.55}M^{-0.5} \tag{23}$$

The correlation is dimensional, h_{PB} in $Wm^{-2}K^{-1}$ and q in Wm^{-2}.

The deviations of the correlations with data were calculated as below:

Mean absolute deviation (MAD) is provided by:

$$MAD = \frac{1}{N}\sum_{1}^{N} ABS\left(\left(h_{predicted} - h_{measured}\right)/h_{measured}\right) \tag{24}$$

Average deviation (AD) is provided n by:

$$AD = \frac{1}{N}\sum_{1}^{N}\left(\left(h_{predicted} - h_{measured}\right)/h_{measured}\right) \tag{25}$$

4.4. Results of Evaluation

The overall results considering all data for all types of channels are shown in Table 7. It is seen that the new correlation had the least MAD of 13.3%, Shah (2017a) [2] MAD is 13.7%, and Shah (1977) [1] 14.8%. The next best is the Haynes and Fletcher correlation with MAD of 18.4% followed by the Liu and Winterton correlation at 19.0%. All other correlations had large MAD, ranging from 36% to 115%. Details of the results are presented and discussed in Section 5.

Table 7. Deviations of various correlations with data for all types of channels.

Channel Type	No. of Data Pts.	Mean Absolute Deviation (MAD), % (Upper Row) Average Deviation (AD), % (Lower Rpw)										
		Liu and Winter-ton	**Gungor and Win-terton**	**Haynes and Fletcher**	**Moles and Shaw**	**Devahdhanush and Mudawar**	**Badiuzzaman**	**Guo et al.**	**Pappel**	**Shah (1977) [1]**	**Shah (2017a) [2]**	**New Corre-lation**
Rectangular channels	750	29.0 −23.8	68.6 −63.9	19.1 −9.3	43.8 42.3	29.9 −0.2	**62.6** **6.5**	47.8 24.5	62.6 60.5	17.9 −0.5	17.5 −0.8	17.0 1.0
Annuli	656	14.0 −4.1	53.8 −51.9	19.0 13.1	26.2 −3.5	35.7 7.3	41.5 −27.3	68.5 43.7	99.6 67.5	13.5 −0.2	12.3 −5.7	11.6 −4.8
Round tubes	864	14.2 −4.0	44.8 −40.2	17.3 13.4	38.3 30.8	50.2 32.8	37.5 4.6	112.2 105.8	155.3 136.3	13.1 5.3	11.5 −0.8	11.3 −0.6
All types	2270	19.0 −10.6	55.0 −50.9	18.4 5.8	36.6 24.7	36.5 14.5	47.0 −4.0	78.3 61.0	115.9 84.4	14.8 1.8	13.7 −2.2	13.3 −1.3

5. Discussion

5.1. Partially Heated Rectangular Channels

Detailed results of comparison of all data for rectangular channels are presented in Table 1. D_{HYD} was used as the equivalent diameter for all correlations. For channels heated only at the bottom, heat flux was based on the area of bottom plus area of heat-conducting sides/fins.

It is seen that the new correlation has the least MAD among all correlations. Its MAD is 17.0% while those of the Shah (2017a) [2] and Shah (1977) [1] correlations are 17.5% and 17.9%, respectively. The best among others is that of Haynes and Fletcher at 19.1%. The correlation of Devahdhanush and Mudawar has a MAD of 20.1% but it provides large deviations with several data sets.

Figure 1 shows the comparison of some data of Devahdhanush and Mudawar (2022) [12] with various correlations. Only the new correlation and that of Devahdhanush and Mudawar (2022) [12] show satisfactory agreement. The deviations of the two correlations are about the same. The latter was based on these data themselves.

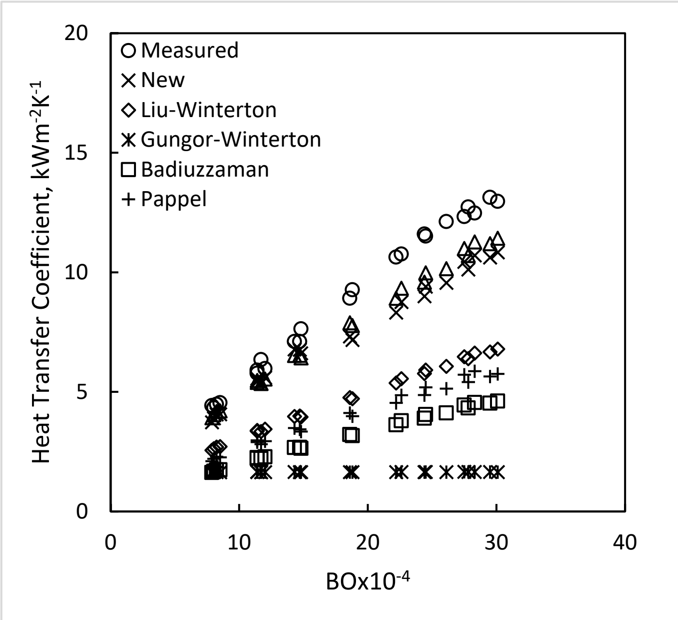

Figure 1. Comparison of various correlation with the data of Devahdhanush and Mudawar (2022) [12] for a partially heated rectangular channel. G = 1600 kgm^{-2}s^{-1}, subcooling 20–22 K, vertical downflow, heating on two sides, fluid nPFH.

Figure 2 shows the comparison of the data of Krishnan et al. (2017) [16] for water in a horizontal channel heated at the bottom side. The new correlation is in close agreement with the data. Other correlations overpredict.

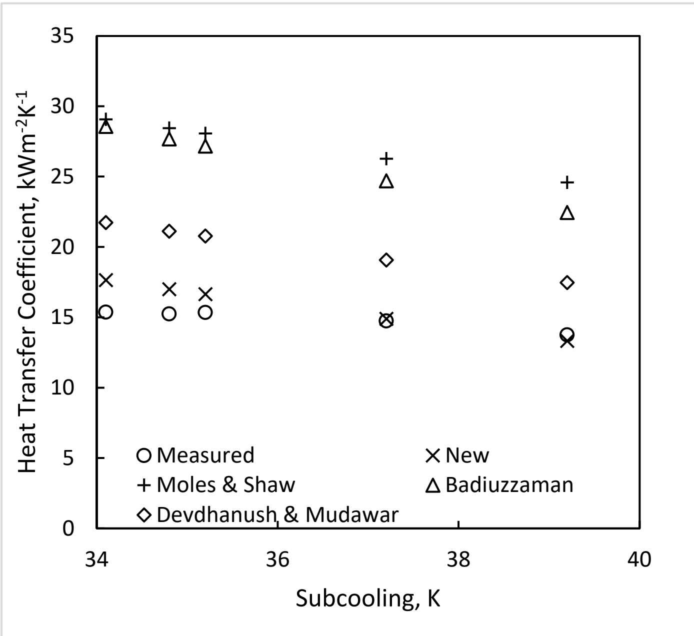

Figure 2. Comparison of the data of Krishnan et al. (2017) [16] for water at atmospheric pressure in a horizontal rectangular channel heated at the bottom. G = 900 kgm^{-2}K^{-1}, Box10^4 = 3.1 to 3.8.

Figure 3 shows the comparison of the data of Peng and Wang (1993) [22] for a multichannel with many correlations. Correlations other than the new one have large deviations; these include those of Liu and Winterton and Haynes and Fletcher which otherwise show good agreement with most data.

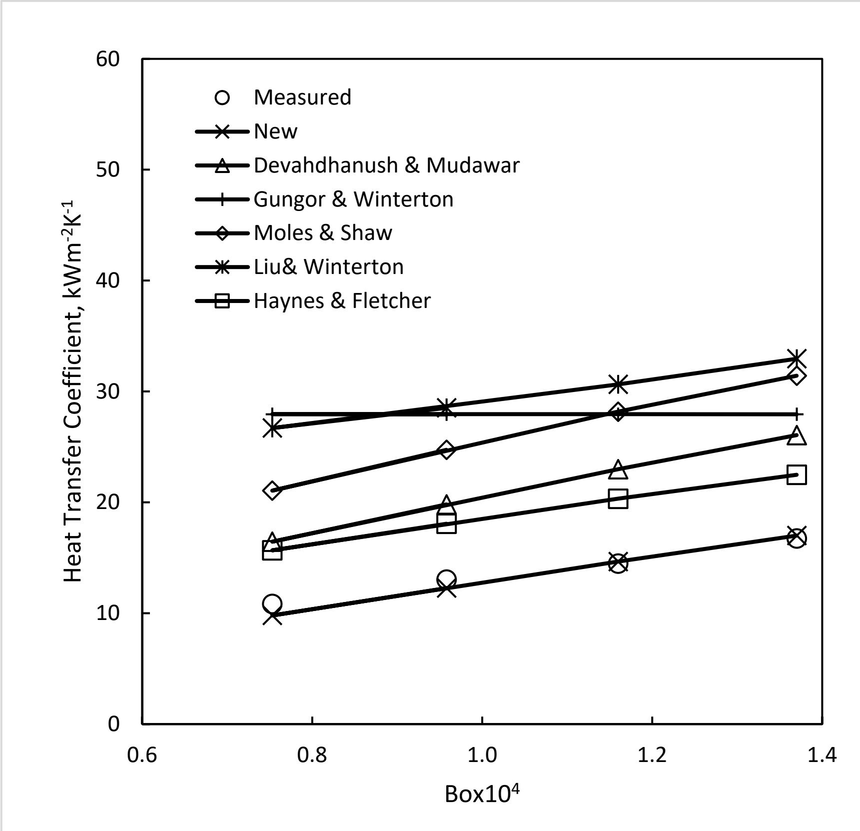

Figure 3. Data of Peng and Wang (1993) [22] in a partly heated rectangular multichannel compared with some correlations. G = 3237 kgm^{-2}s^{-1}, water at atmospheric pressure, subcooling 49.7 K.

Liu and Garimella (2007) [78] had reported good agreement of Shah (1977) [1] correlation with their data for water at atmospheric pressure in partially heated rectangular channels. These are likely to be in good agreement with the new correlation.

5.1.1. Effect of Flow Direction

As seen in Table 1, the flow directions in the data analyzed include horizontal, vertical up, and vertical down. The data in all orientations are in good agreement with the new correlation. The MAD of all data sets with the new correlation is plotted in Figure 3. It is seen that the deviations are not related to the flow direction or the hydraulic diameter.

A very thorough study of the effect of flow direction was performed by Krishnan et al. (2017) [16] which was described in Section 2.1. Heat transfer coefficients were the same in all orientations. The only effect of orientation was that CHF value was low in vertical downflow. This may be due to the effect of buoyancy opposing the downward flow.

Another comprehensive study on the effect of flow direction is that of Devahdhanush and Mudawar (2022) [12]. The channel was heated on top and bottom for horizontal flow and on the sides for vertical up and down flows. Heat transfer coefficients were found to be about the same in all orientations.

5.1.2. Effect of Channel Diameter

As seen in Table 1 and Figure 4, the hydraulic diameter of rectangular channels in the database varied from 0.18 to 3.3 mm. No effect is seen on the deviations from the new correlation. Depending on the extent of the channel area heated, D_{HP} was up to six times D_{HYD}. This shows that the new correlation can be used for a wide range of channel dimensions irrespective of the extent of channel area heated.

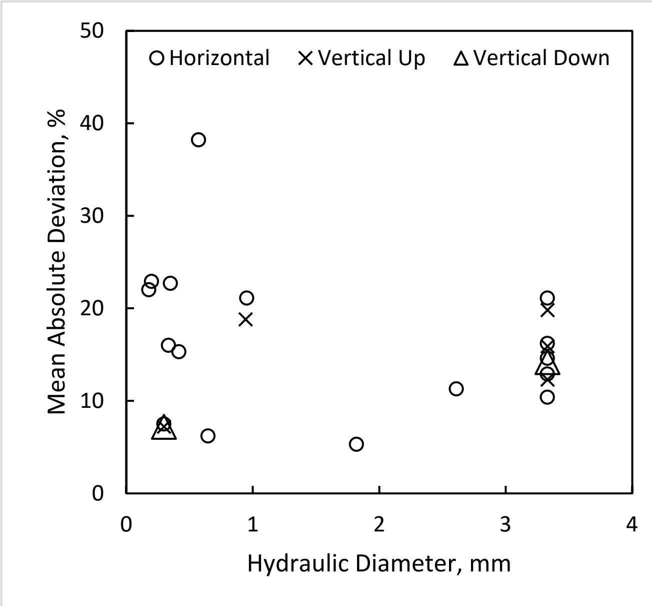

Figure 4. Effect of flow direction and hydraulic diameter of rectangular channels on MAD of the new correlation with data sets.

5.1.3. Effect of Channel Aspect Ratio

In Figure 5, the MAD of data sets is plotted against the aspect ratio of channels. It is seen that over the range of 0.1 to 20, there is no effect on the accuracy of the new correlation. The deviations of the Shah (2017a) [2] are about the same as of the new correlation and the same applies to it also.

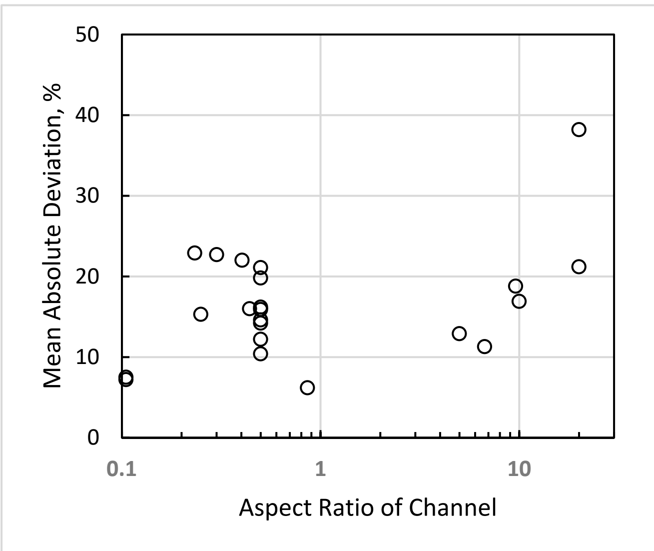

Figure 5. MAD of the new correlation with data sets for rectangular channels versus their aspect ratios.

5.2. Annuli

Table 2 lists the salient features and range of all data for annuli and the deviations of various correlations.

The choice of equivalent diameter used for various correlations was as follows: the choice for the new and previous Shah correlations is explained in Sections 2.2 and 3.1, respectively. Gungor and Winterton (1986) [64] had specified equivalent diameters in the same way as in the Shah (1977) [1] correlation. Liu and Winterton had specified the use of D_{HP}. For all other correlations, D_{HP} was used as the equivalent diameter.

It is seen in Table 6 that data from all sources are in good agreement with the new correlation as well as the Shah (1977, 2017a) [1,2] correlations. The highest MAD of the new correlation is 25.6%; the MAD of most data sets is below 15%. The range of data is very wide, the annular gaps being 0.5 to 11.4, inner tube diameter 4 to 42.2 mm, and all heating modes (inner tube heated, outer tube heated, both tubes heated with boiling on one or both), and a wide range of flow rates, reduced pressures, and subcooling.

The data includes horizontal flow and vertical upflow. Data for both orientations is satisfactorily predicted. There were no data for vertical downflow. As discussed in Section 5.1.1, tests on rectangular channels showed that heat transfer coefficients prior to CHF were the same in all orientations but CHF in down flow occurred at much lower heat flux than in other orientations. Behavior can be similar in annuli too.

The MAD of the present correlation for all annuli data is 13.3% and those of the Shah (1977, 2017a) [1,2] correlations are 14.8% and 13.7%, respectively. Among the other correlations, the next best is Haynes and Fletcher at 18.4% and Liu and Winterton at 19.0%. The rest of them have MAD of 36.5% to 115.8%, which are unacceptably high.

Figures 6 and 7 show comparison of some data in annuli with various correlations. The new correlation is seen to have good agreement while others show large deviations.

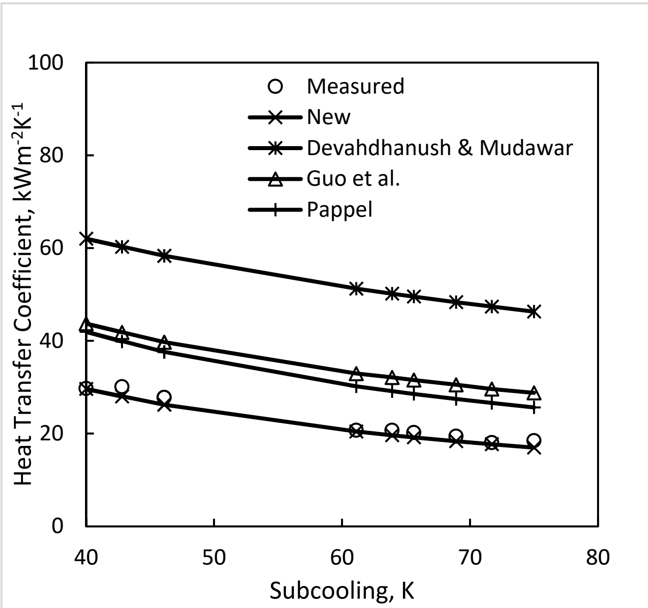

Figure 6. Data of Thom et al. (1965) [28] for water in a vertical annulus compared with various correlations. Pressure 138 bar, G = 1134 $kgm^{-2}s^{-1}$, q = 645 kWm^{-2}.

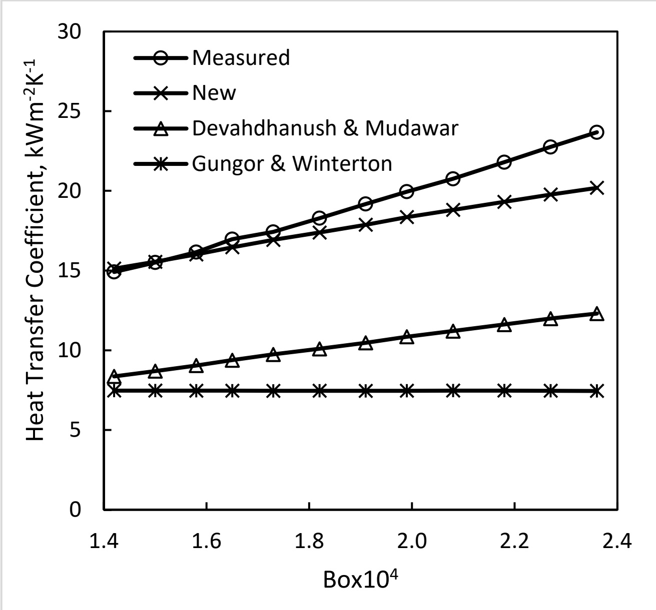

Figure 7. Comparison of various correlations with the data of Li et al. (2021) [36] with water in a vertical annulus. Pressure atmospheric, G = 874 kgm^{-2}s^{-1}, subcooling 5 K.

5.3. Round Channels

The range of data for round channels and results of their comparison with various correlations are provided in Table 3. All data are for single tubes except for one which is for a multichannel. The new correlation is in good agreement with data from all sources, MAD for the data sets ranging from 2.1% to 21.6%. The MAD for all data for the new and Shah (2017a, 1977) [1,2] correlations are 11.3, 11.5, and 13.7%, respectively. The Liu and Winterton correlation is the next best with MAD of 14.2%. The Haynes and Fletcher correlation has MAD of 17.3%. The MAD of other correlations ranges from 37% to 142%, which are unacceptably high.

Figures 8 and 9 show data for round channels compared with various correlations. The new correlation is seen to be in good agreement with data while others have large deviations.

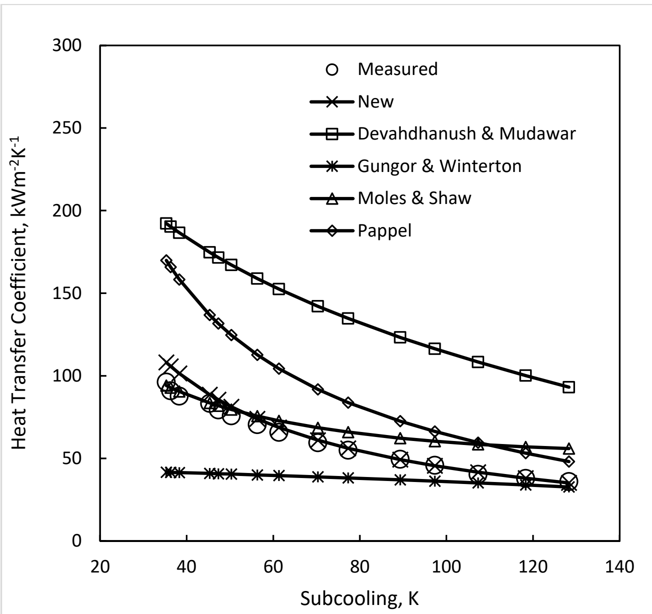

Figure 8. Data of Guo et al. (2023) [24] for water in a tube compared with various correlations. D = 1 mm, p = 40 bar, G = 2700 kgm^{-2}s^{-1}, and q = 265 kWm^{-2}.

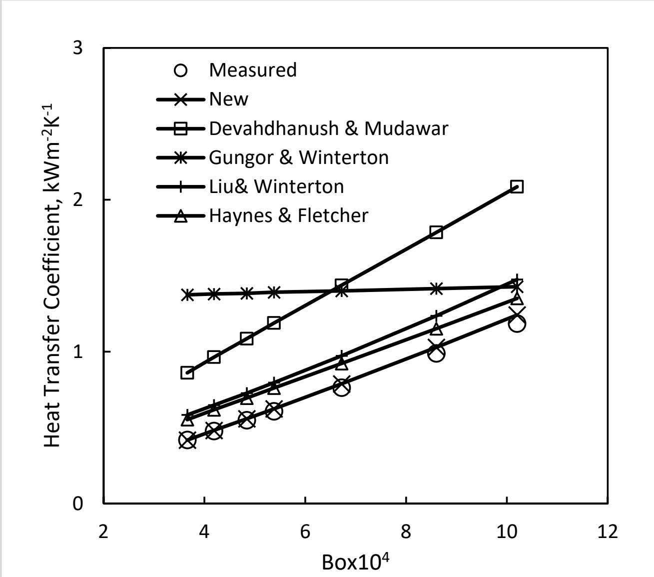

Figure 9. Data of Saraceno et al. (2012) [57] for FC-72 in a tube compared with correlations. Pressure 3 bar, G = 1145 kgm^{-2}s^{-1}, subcooling 70–77 K.

5.4. Haynes and Fletcher Correlation

As seen in the tables and the foregoing discussions, the correlation of Haynes and Fletcher, Equation (4), performs quite well. It is surprising in view of the fact that its authors had verified it with only their own data. It is therefore discussed here:

Equation (4) can be rearranged to the following form.

$$\Delta T_{SAT} = \left(\frac{q}{h_{LT}} - \Delta T_{SC}\right) / [(h_{LT} + h_{PB})/h_{LT}] \quad (26)$$

Applying the superposition method of Rohsenow (1953) [79], total heat flux in subcooled boiling is the sum of heat fluxes removed by pool boiling and by single phase forced convection. Using it, the following equation may be written at x = 0.

$$q = h_{PB}\Delta T_{SAT} + h_{LT}\Delta T_{SAT} \quad (27)$$

Rearrangement provided at zero quality,

$$\frac{q}{\Delta T_{SAT}} = h_{TP,x=0} = h_{PB} + h_{LT} \quad (28)$$

It follows then that

$$\psi_0 = \frac{h_{TP,,x=0}}{h_{LT}} = \frac{(h_{LT} + h_{PB})}{h_{LT}} \quad (29)$$

On substitution of ψ_0 from Equation (29) into Equation (26),

$$\Delta T_{SAT} = \left(\frac{q}{h_{LT}} - \Delta T_{SC}\right) / \psi_0 \quad (30)$$

This is identical to Equation (9), the Shah (1977) [1] correlation for the high subcooling regime. The difference between the two is the method of determining ψ_0.

5.5. Applicability under Microgravity

There is presently much interest in heat transfer during boiling under microgravity due to space exploration. Many studies were performed using parabolic flights and drop-towers. The gravity obtained by such tests is of short duration and is not very low. Most of such tests were for pool boiling. Mudawar et al. (2023) [11] provided data for forced flow boiling performed in the International Space Station at microgravity conditions. Having been performed under stable conditions over a long period, these provide high quality data. As seen in Table 3, these data have MAD of 19.8% with the new correlation. This shows that the new correlation is applicable in microgravity conditions.

It is interesting that the correlation of Haynes and Fletcher also provides good agreement with these data even though it requires calculation of pool boiling heat transfer coefficient. In the present analyses, it was calculated using the Cooper correlation, which is based on data taken under normal earth gravity. Pool boiling heat transfer coefficient has been found to decrease with decreasing gravity. Warrier et al. (2015) [80], on studying data from several sources, concluded that it is proportional to $g^{1/8}$. The decrease can be attributed to the fact that bubbles have difficulty in departing from the heating surface as reduced gravity reduces buoyancy. The good agreement with the Haynes and Fletcher correlation shows that the growth and departure of bubble during forced convection is similar to that under earth gravity. The likely reason is that the flowing liquid sweeps away the bubbles as they are formed, negating the effect of the absence of buoyancy. For more information on the effect of gravity on pool and flow boiling, see Shah (2021) [10].

5.6. Application to Minichannels

Several criteria have been proposed for the boundary between mini- and macro/conventional channels. The most widely used criterion is that of Kandlikar (2002) [81] according to which, channels with diameter ≤ 3 mm are minichannels and larger are macrochannels. As seen in Table 6, hydraulic diameter in the data analyzed range from 0.176 mm to 22.8 mm. This criterion really provides a rough indication of greater difficulties in manufacturing of heat exchangers rather than any change in physical phenomena.

Most other criteria consider the dominance of surface tension forces to be the basis for the channel to be considered a minichannel. When the surface tension forces are dominant, the correlations for macrochannels become inaccurate and hence inapplicable. Such criteria have been proposed based on studies on boiling, condensation, and two component processes. Here only criteria based on boiling studies are discussed. For detailed discussions on other criteria, see Shah (2018, 2021) [10,82]. Earlier reviews on this subject are in Cheng and Mewes [83] and Cheng and Wu [84].

Kew and Cornwell (1997) [85] compared data for boiling heat transfer in channels with various macrochannel correlations. They found that those correlations failed when Bond number Bd < 4. They decided that this is the boundary between mini- and macrochannels. Bond number is the ratio of surface tension and gravitational forces and is defined as:

$$Bd = \frac{gD^2(\rho_L - \rho_G)}{\sigma} \tag{31}$$

Ong and Thome (2011) [86] studied flow pattern transitions during boiling of refrigerants in tubes. They concluded that the minichannel regime starts when Bd < 1.

In the data analyzed during the present research, Bond number varied from 0.025 to 7100. So, according to these criteria, the data analyzed contained both mini- and macrochannels. Yet the present correlation seamlessly predicts all data even though it has no factor for surface tension effect.

Shah (2017b) [8] compared a wide-ranging database for saturated boiling in channels prior to CHF with several correlations for macrochannels including Shah (1982) [6]. He found that these correlations failed when the following criterion was met:

$$F = (2.1 - 0.008We_{GT} - 110Bo) > 1 \tag{32}$$

Thus, the minichannel regime occurs when F > 1. We_{GT} is the ratio of inertia and surface tension forces defined as:

$$We_{GT} = \frac{G^2 D}{\rho_G \sigma} \tag{33}$$

Correction factors were applied to the predictions of Shah (1982) [6] when F was >1.

The maximum value of F in the data analyzed in the present work was 0.6; most of the values of F were negative. Hence according to this criterion, none of the data are for minichannels.

The new correlation and the Shah (2017a, 1977) [1,2] correlations are in good agreement with all data analyzed. The Liu and Winterton, and the Haynes and Fletcher correlations are also in good agreement with most data. None of them contains any factor to account for surface tension effects. This indicates that surface tension effects were insignificant and all data were in the macro-channel regime.

Analysis of data with F > 1 will show whether the new correlation is applicable there or some modifications are needed as performed in Shah (2017b) [8] for saturated boiling.

5.7. Limitations of the New Correlation

Possible limitations on the applicability of the new correlation are discussed here.

The database analyzed includes 15 fluids that include water, halocarbon refrigerants, carbon dioxide, ammonia, chemicals, and dielectric fluids. Their properties cover the entire range of commonly used fluids. The list does not include cryogens. However, the equation for zero quality is common with the correlation for saturated boiling, Shah (2017b) [8], and that has been shown to be in good agreement with data for cryogens such as helium, hydrogen, argon, nitrogen, etc. Hence there does not appear to be any limitation as long as the fluid is Newtonian and non-metallic.

Reduced pressure range of data is 0.0046 to 0.922. This is very wide but caution must be exercised at pressures close to the critical pressure as correlations have been known to fail there.

The range of flow rates, subcooling, channel dimensions, and annular gaps, are so wide that they cover the entire practical range.

Regarding flow direction, there were no data for downflow in annuli. There may be some difference in behavior at low flow rates due to buoyancy effects but there is not likely be any difference from upflow at higher flow rates as inertia effect is likely to overwhelm any effect of buoyancy.

5.8. Recommendations for Design

The new correlation provides good agreement with all data for all channels. It is recommended for use in design; the possible limitations are discussed in Section 5.7. The Shah (2017a) [2] correlation with D_{HYD} for partially heated channels is a good alternative as its accuracy is only slightly lower. Shah (1977) [1] is also an acceptable alternative. None of the other correlations provide good agreement with all data.

The recommended correlations are applicable only prior to CHF. Therefore, it should be checked whether the heat flux being applied is below CHF. Well-verified correlations are available for vertical upflow in channels (Shah 1987, 2017) [87,88], vertical upflow in annuli (Shah 2015b) [89], and in horizontal channels (Shah 2015a) [90]. For other conditions, see Shah (2021) [10].

6. Conclusions

1. The choice of equivalent diameter of partly heated channels was investigated. It was determined that the hydraulic equivalent diameter should be used for partly heated channels;
2. A new correlation was presented for heat transfer during subcooled boiling in channels and annuli which is a modification of the author's earlier correlation, Shah (2017a) [2];
3. The new correlation together with 10 others was compared with a database that included various geometries (round tubes, rectangular channels, and annuli), hydraulic diameters from 0.176 to 22.8 mm, reduced pressure from 0.0046 to 0.922, subcooling from 0 to 165 K, mass flux from 59 to 31,500 $kgm^{-2}s^{-1}$, all flow directions, and ter-

restrial to micro gravity. The new correlation has mean absolute deviation (MAD) of 13.3% with 2270 data points from 49 sources. Correlations by other authors had MAD of 18.4% to 116%.

4. The data included up- and downflow as well as horizontal flow in channels. For annuli the data were for horizontal flow and upflow. Applicability to downflow in annuli remains to be investigated; new experimental studies are needed for it.
5. It was established that low gravity does not deteriorate subcooled flow boiling heat transfer and the correlations based on earth gravity data can be used under microgravity.
6. Data were compared with various criteria for minichannels. It was determined that there were no significant effect of surface tension and hence all data were for macrochannels.

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Nomenclature

A_R	Aspect ratio of channel, width divided by height (−)
Bd	Bond number = $g(\rho_L - \rho_G)D^2 \sigma^{-1}$, (−)
Bo	Boiling number = $q\ (G\ i_{LG})^{-1}$, (−)
C_{PL}	Specific heat of liquid at constant pressure, (J kg^{-1} $°C^{-1}$)
D	Diameter or equivalent diameter, (m)
D_{in}	Outside diameter of inner tube of annulus, (m)
D_{HP}	equivalent diameter based on perimeter with boiling, defined by Equation (8), m
D_{HYD}	hydraulic equivalent diameter, defined by Equation (7), m
D_{out}	Inner surface diameter of the outer tube of annulus, (m)
G	Total mass flux (liquid + vapor), (kg $m^{-2}s^{-1}$)
g	Acceleration due to gravity, (m s^{-2})
H	Height of channel, (m)
h	Heat transfer coefficient, ($Wm^{-2}K^{-1}$)
h_{LT}	Heat transfer coefficient with all mass flowing as liquid, ($Wm^{-2}K^{-1}$)
h_{PB}	Heat transfer coefficient during pool boiling, (W $m^{-2}K^{-1}$)
h_{TP}	Two-phase heat transfer coefficient defined by Eq. (15), ($Wm^{-2}K^{-1}$)
i_{LG}	Latent heat of vaporization, (J kg^{-1})
k	Thermal conductivity, (Wm^{-1} K^{-1})
N	Number of data points, (−)
p_r	Reduced pressure, (−)
Pr	Prandtl number, (−)
q	Heat flux, (Wm^{-2})
Re_{LT}	Reynolds number, = $GD\mu_L{}^{-1}$, (−)
T_B	Bulk liquid temperature, (°C)
T_{SAT}	Saturation temperature, (°C)
T_w	Wall temperature, (°C)
ΔT_{SAT}	= $(T_w - T_{SAT})$, (°C)
ΔT_{SC}	= $(T_{SAT} - T_B)$, (°C)
W	Width of channel, (m)
We_{GT}	Weber number for all mass flowing as vapor, defined by Equation (33), (−)
Greek	
μ	Dynamic viscosity, (kg m s^{-1})
ρ	Density, (kg m^{-3})

σ	Surface tension, (N m^{-1})
Ψ_0	Ratio of two-phase to single-phase heat transfer coefficient at zero quality, (−)
Subscripts	
in	inner
G	vapor
L	liquid
out	outer

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