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EVALUATION OF CORRELATIONS FOR PREDICTING HEAT TRANSFER DURING BOILING OF CARBON DIOXIDE INSIDE CHANNELS

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ABSTRACT

Applicability of available correlations to prediction of heat transfer during boiling of carbon dioxide prior to dryout in plain channels is evaluated by their comparison with a wide ranging database. Five general correlations, four correlations exclusively for CO_2 and one for mini channels, were evaluated. A modified form of the author's general correlation was also evaluated. These were compared with a database which included 1052 data points from 41 data sets for oil-free CO_2 from 32 published studies. Author's modified correlation and a published general correlation performed best with mean absolute deviation of 26% with all data. For the 31data sets which had deviations of less than 30% with at least one of these two correlations, the mean absolute deviations were about 21%. The range of data analyzed included single and multi-channels of circular, triangular, and rectangular geometries, several materials (copper, aluminum, stainless steels, nickel), electric and liquid heating of test channels, equivalent diameters from 0.51 to 14 mm, reduced pressure from 0.19 to 0.88, mass flux from 75 to 1500 kg/m^{2}s, and boiling numbers from 0.00003 to 0.0035. The performance of the correlation for mini channels was good but not better than that of three of the other correlations. The results for all data sets and correlations are presented in tabular and graphical forms, and are discussed. Recommendations are made for application to design.

KEY WORDS: Boiling and evaporation, Two-phase/Multiphase flow, carbon dioxide, tubes, heat transfer, correlations

1. INTRODUCTION

Due to concerns about ozone layer depletion and global warming, the CFC and HCFC refrigerants have been phased out. Alternative refrigerants are therefore needed which have low GWP (Global Warming Potential) and ODP (Ozone Depletion Potential). One of the alternative refrigerants is carbon dioxide which has zero ODP and its GWP is1. Further, it is completely non-flammable and non-toxic, and is compatible with most materials of construction. While CO_2 is already being used to some extent, its wider use is hampered by the lack of a thoroughly reliable method for calculation of heat transfer during boiling in tubes/channels. Many experimental studies have been done and many correlations have been proposed. Most of the proposed correlations have been tested with only one or two data sets. A few have been compared to several data sets. To gain full confidence in the reliablility of any of them, validation with many more data sets from many sources is needed. The present reseach was done to fulfil this need.

In the research described here, a number of correlations were compared with an extensive database that included a very wide range of data from many sources. While the conditions in an evaporator may include post-CHF (critical heat flux) conditions, only data prior to the occurrence of CHF were considered. (Note that in this paper, no distinction is made between CHF and dryout.) The correlations tested included five general correlations for conventional tubes, one general correlation for mini-channels, and four correlations developed specifically for carbon dioxide. A modified version of the Shah correlation (1, 2) was also

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evaluated. The results of this research are presented in graphical and tabular form and discussed in the following.

2. PREVIOUS WORK

2.1 Published Predictive Methods

Numerous correlations for saturated boiling heat transfer in plain tubes prior to CHF are available. These may be put in the following three categories:

- General correlations applicable to all fluids, verified for macro/conventional tube sizes.
- General correlations applicable to all fluids, intended only for micro/mini channels.
- Correlations developed specifically for carbon dioxide.

Among the most verified in the first category are the correlations of Shah [1, 2], Gungor and Winterton [3], Gungor and Winterton [4] and Liu and Winterton [5]. Shah [6] found the first two mentioned to be the most accurate on comparison with data for 22 fluids from many sources but all correlations tested performed poorly on comparison with most CO_2 data that were tested. Other researchers have found that some general correlations agree with some CO_2 data but disagree with other data.

The correlations in the first category have often been reported to be inaccurate for mini and micro channels. Many correlations for mini/micro channels have been proposed. Most of them have had little verification. However, the two correlations presented by Li and Wu [7, 8] were verified with a very varied and extensive data base that included data for CO_2.

Many correlations intended exclusively for carbon dioxide have been proposed. Most of them have had very little verification. The researchers at EPFL in Switzerland have made several attempts to correlate a wide range of data. Their most verified output is the correlation by Cheng et al. [9] which covers both pre-CHF and post-CHF regions. It was verified with data from 11 sources. Their database included mini-channels. However, Ami et al. [10] found this correlation to have very large deviations from their data for CO_2 in a 1 mm diameter tube. Other correlations specific for CO_2 include those of Hihara and Tanaka [11] and Yoon et al. [12]. The latter includes post-CHF region. A very recent correlation is by Fang (13) which is reported to give good agreement with data from many sources. Some other correlations have been mentioned by Masrullo et al. [14].

Mastrullo et al. [14] performed an assessment of predictive methods for carbon dioxide boiling in tubes, based on the results reported by various researchers. These included general correlations for all fluids as well as correlations specifically developed for carbon dioxide. They concluded that the available correlations are not adequate and there is need for development of suitable correlations for boiling heat transfer of carbon dioxide.

From the foregoing, it is seen that further evaluation of published correlations with more extensive data bases is desirable. This has been done in the research reported here.

2.2 Experimental Studies

Many experimental studies have been done on the boiling of carbon dioxide in horizontal tubes and channels of various shapes, sizes, and materials. Mastrullo et al. [14] listed and reviewed many of these studies. Literature search brought to light some more recent studies.

3. COMPARISON OF CORRELATIONS WITH TEST DATA

3.1 Correlations Evaluated

The general correlations for macro tubes that were evaluated were Shah [2], Gungor & Winterton [3], Gungor & Winterton [4], Liu & Winterton [5], and Chen [15]. While the standard Chen correlation has been found to perform poorly by many studies [3, 4, 5], Shah [6] had found that it gives reasonably good results if the Cooper correlation [16] is used for the nucleate boiling contribution. The Cooper correlation is:

$$h_{pb} = 55p_r^{0.12}(-logp_r)^{-0.55}M^{-0.5}\dot{q}^{2/3} \tag{1}$$

Cooper had tentatively suggested a multiplier of 1.7 for copper tubes. However, many researchers have found it gives better agreement without this factor, for example Shah [17]. Therefore this factor was not applied and Eq. 1 was used unchanged for all surface materials.

For mini-channels, both correlations given by Li and Wu [7, 8] have been shown to agree with a wide range of data but applicability limits have not been defined for the correlation in [8] while it is clearly defined in [7]. Therefore the latter was chosen for evaluation. The correlation is:

$$Nu_{TP} = 22.9(Bo\ Re_l{}^{0.5})^{0.355} \tag{2}$$

Its limit of applicability is given as:

$$Bo\ Re_l \leq 200 \tag{3}$$

According to Li and Wu [7], Eq. (3) gives the boundary between macro and mini channels.

The CO_2 specific correlations evaluated were those of Cheng et al. [9], Yoon et al. [12], Hihara and Tanaka [11], and Fang [13]. The first two cover both pre-CHF and post-CHF regions but the data analyzed in the present study were only pre-CHF.

During the data analysis, it was noticed that for the majority of data sets the heat transfer coefficients in the nucleate boiling region were considerably higher than the predictions of the Shah correlation [2]. Better agreement was obtained by replacing the nucleate boiling relation for zero vapor quality in the Shah correlation by the following relation:

$$\varphi_0 = \frac{h_{TP}}{h_{LT}} = 1820\ Bn^{0.68} \tag{4}$$

This φ_0 from Eq. (4) is also inserted in the expressions for the bubble suppression regime. This modified form of the Shah correlation was also evaluated along with the other correlations mentioned above.

3.2 Data Analyzed

Efforts were made to collect data from many sources covering the widest possible range of parameters. Only data prior to dryout/CHF were considered. CHF was considered to have occurred when the heat transfer coefficient started to decrease sharply with increasing vapor quality. While the carbon dioxide specific correlations for Cheng et al. and Yoon et al. also include the post-dryout region, the general correlations are inapplicable after dryout. Well-verified methods are available for the prediction of CHF and post CHF heat transfer, for example [18, 19], which may be separately evaluated for applicability to CO_2. Data for oil containing carbon dioxide were not considered. Oil affects heat transfer in a complex fashion and evaluation of the effects of oil was beyond the scope of the present research.

In validating their correlation, Cheng et al. had disregarded some data sets as they had considered them unreliable due to various reasons. In the present study, all data sets were considered even though it appears that some of them are not reliable. For example, the data of Bredsen et al. [20] are much higher than data from other sources and do not agree with any correlation. It was felt that it is difficult to judge which data are erroneous and as more data are analyzed, the erroneous data will become statistically irrelevant.

The data analyzed are listed in Table 1. The data are from 32 sources and contain 41 data sets. Data for different diameters are considered separate data sets even if they are from the same source. It is seen that these include conventional macro tubes as well as mini-channels of circular, rectangular, and triangular cross-sections, single channel as well as multiport. Hydraulic equivalent diameters are from 0.51 to 14.0 mm. Tube materials included are aluminum, copper, nickel, and stainless steel. Heating of channels is by electric resistance as well as by hot liquid. Reduced pressures range from 0.18 to 0.88 and flow rates are from 75 to 1500 kg/m^{2}s. Boiling numbers range from 0.29 x10^{-4} to 35x10^{-4}. Thus the data cover the entire range of conditions that may be encountered in practice.

3.3 Calculation Methodology

In calculations with the Cheng et al. correlation, equivalent diameter was calculated in accordance with the definition used by them. For all other correlations, hydraulic equivalent diameter was used. The Cheng et al. correlation requires the determination of flow patterns. This was done using their own flow pattern map [21]. Properties of carbon dioxide were calculated using REFPROP 9.1 [22].

3.4 Results of Data Analysis

Results of data analysis are given in Table 1. Mean absolute deviation of a data set is defined as:

$$\delta_m = \frac{1}{N}\sum_{1}^{N} ABS\left((h_{predicted} - h_{measured}) / h_{measured}\right) \tag{5}$$

Average deviation of a data set is defined as:

$$\delta_{avg} = \frac{1}{N}\sum_{1}^{N}\left((h_{predicted} - h_{measured}) / h_{measured}\right) \tag{6}$$

In Table 1, “Shah Mod.” is the Shah correlation using Eq. (4) for the nucleate boiling factor. Note that the results with the Li & Wu correlation are not listed in Table 1 as it was applied only to the mini-channel data as determined by Eq. (3); these are discussed later. The results for the Fang correlation are also not listed in Table 1. Those are discussed later.

4. DISCUSSION

4.1 Overall Performance of Correlations

It is seen in Table 1 that considering all data, the best performing correlations are the modified Shah and Liu - Winterton with mean absolute deviations of 26.8 and 26.2 percent respectively. Considering only the 31 data sets which have mean absolute deviation of less than 30 % with at least one of these two correlations, mean absolute deviations are 21.3 % and 22.8 % respectively for the modified Shah and Liu-Winterton correlations. Among the correlations specific for CO$_2$, best results are with the Cheng et al. correlation with a mean absolute deviation of 28.4 %. These figures will improve if the data that appear to be erroneous are disregarded.

Table 1 Range of data analyzed and deviations of various correlations. Test sections were electrically heated except where noted.

Researchers	D_{hyd} mm	Test Section	p_r	ṁ kg/ m^2s	Bn x10^{-4}	No. of Data Point	Deviation, Percent, for Listed Correlations (Mean Absolute Above, Average Below)								
							Shah [2]	Shah Mod.	GW 87 [4]	GW 86 [3]	LW [5]	Chen [14]	Hihara [11]	Yoon et al. [12]	Cheng et al. [9]
Bredsen et al. [20]	7.0	Aluminum, single round tube	0.36 0.54	200 400	0.29 1.4	53	55.2 -55.2	50.7 -50.7	53.6 -53.6	34.9 -34.9	46.3 -46.3	31.3 -31.3	45.1 -40.3	46.4 -46.4	37.3 -37.3
Knudsen & Jensen [52]	10.06	SS 316, single round tube	0.208	85 175	8 13	78	49.1 -49.1	10.6 -9.0	42.4 -42.4	7.6 5.5	15.3 -13.8	11.1 7.6	24.9 -18.7	37.2 -36.3	32.9 -0.4
Yoon et al. [12]	7.53	SS 316, single round tube	0.474 0.540	180 318	1.8 4.8	12	58.6 -58.6	25.8 -25.8	53.2 -53.2	25.6 -25.6	27.3 -27.3	25.3 -25.3	45.2 -45.2	22.1 -22.1	15.5 -15.5
Koyama et al. [25]	1.8	SS, single round tube	0.479 0.615	250 260	6.1 6.2	17	61.9 -61.9	20.6 -20.6	56.3 -56.3	14.4 -14.4	32.5 -32.5	13.3 -13.2	11.9 -10.9	19.7 -19.7	24.5 -24.5
Schael & Kind [26]	14.0	Nickel, single round tube	0.513	75 300	8.7 35.0	13	71.5 -71.5	30.2 -30.2	63.9 -63.8	52.8 -52.8	30.7 -24.4	34.8 -34.4	23.6 13.4	84.8 -84.8	15.1 10.8
Gao & Honda [27]	3.0	SS, single round tube SS	0.39 0.61	236 1179	0.86 2.6	29	25.1 -23.9	13.1 -2.1	17.7 -14.7	29.1 28.7	11.0 0.4	32.7 32.0	17.6 9.2	16.0 5.2	17.6 16.0
Park & Hrnjak [28]	6.1	copper, single round tube, liquid heating. Tube average heat flux given.	0.19 0.31	100 400	0.41 4.9	65	39.8 -30.4	27.9 - 10.5	35.3 -28.0	23.2 8.6	27.5 -14.6	25.8 13.0	32.5 -8.6	28.4 13.0	31.8 -3.1
Park & Hrnjak, [29]	3.5		0.19 0.31	200 400	0.41 2.8	55	19.9 -13.8	19.0 -9.0	28.9 -26.9	17.4 8.8	22.1 -19.3	19.3 12.8	23.4 -13.4	29.3 -20.3	22.0 4.1
Kim & Hrnjak [30]	11.2	Round tube, liquid heat	0.31	200	0.9 1.8	17	31.0 -18.4	14.3 4.2	22.3 -13.1	30.1 29.5	22.1 14.7	37.0 34.9	38.5 7.9	22.6 -13.4	56.1 56.1
Cho & Kim [31]	7.7	SS, single round tube	0.47 0.78	424	2.0 3.1	21	48.9 -48.9	30.2 -18.8	43.3 -43.3	24.3 -21.2	34.7 -0.1	26.4 -16.3	48.8 7.1	43.8 -41.5	35.3 -18.2
	4.0			424		23	49.1 -49.1	27.5 -19.8	43.3 -43.3	24.4 -8.3	32.6 -9.9	29.3 -3.1	45.9 4.9	31.3 4.4	31.6 -3.3
Zhao & Bansal [32]	4.57	SS, single round tube.	0.201	139 231	2.5 3.1	9	35.1 35.1	48.5 48.5	11.9 -11.4	48.4 48.4	8.6 3.8	44.3 44.3	17.1 17.1	19.6 15.1	17.4 17.4
Choi et al. [33]	1.5	SS, single round tube	0.612	300	3.4	7	20.3 -18.5	68.0 68.0	16.6 -6.9	91.4 91.4	32.2 32.2	81.6 81.6	52.7 52.7	57.3 57.3	50.6 50.6
	3.0		0.49 0.61	300	3.4 5.1	29	23.9 -23.6	48.5 48.0	16.0 -13.0	60.0 60.0	44.0 44.0	70.2 70.2	72.6 72.6	70.2 70.2	59.4 59.4
Choi et al. [34]	1.5		0.41 0.612	300 600	1.7 3.0	46	35.2 -20.1	43.3 28.9	33.5 -8.9	65.0 61.6	35.8 7.5	57.5 52.8	26.5 10.0	47.7 28.5	38.5 22.3
	3.0		0.41 0.612	300 500	2.0 5.4	41	53.6 -53.6	26.8 -21.0	49.1 -49.1	23.5 -18.1	32.8 -32.8	20.3 -17.9	22.2- 17.7	25.8 -23.7	24.5 -22.8

Mastrullo et al. [35]	6.0	SS, single round tube	0.38 0.54	200 349	1.1 2.3	52	27.8 -26.9	12.4 4.6	20.1 -18.8	35.9 35.9	17.6 14.3	38.4 38.1	40.1 19.3	23.3 12.4	19.3 17.3
Mastrullo et al. [36]	6.0	SS, single round tube	0.57	200 350	0.7 4.8	38	60.2 -60.2	42.7 -42.7	55.5 -55.5	24.9 -24.7	30.9 -30.9	23.4 -23.6	42.4 -33.2	38.3 -32.2	33.6 -32.2
Oh and Son [37]	4.57	SS , single round tube	0.54 0.779	400 800	1.65 3.31	52	32.2 -30.3	28.7 21.9	27.1 -21.4	16.6 -6.9	29.2 26.0	17.7 8.2	38.1 22.0	30.2 25.2	30.1 27.0
Hihara & Tanaka [11]	1.0	SS, single round tube	0.69	360 1440	0.71 5.71	28	26.1 -24.7	23.2 16.0	21.9 -10.8	50.8 50.8	12.0 2.0	44.0 44.0	18.1 7.1	23.7 21.8	10.5 8.6
Ami et al. [38]	0.51	SS, single round tubes	0.677 0.881	300	3.7 5.7	10	33.8 -29.0	47.1 38.3	27.6 -18.7	87.2 87.2	17.7 17.5	69.5 69.5	57.4 57.4	37.6 37.6	30.0 30.0
	1.0				3.7 5.8	13	39.5 -39.5	37.3 21.4	34.7 -31.8	48.7 48.7	20.5 4.3	43.2 41.7	32.0 24.9	27.0 23.7	25.6 17.8
	2.0				3.7 5.7	9	49.6 -49.6	20.7 -6.0	42.3 -42.3	27.4 19.5	14.9 4.2	30.8 29.3	42.2 29.0	23.4 22.8	22.3 19.8
Yun et al. [39]	1.14	Multi-channel with rectangular channels	0.54	200 400	10 20	20	43.2 -43.2	10.5 -6.3	34.3 34.3	33.2 33.2	16.9 -13.4	30.6 30.6	22.6 14.3	9.1 -2.8	11.7 -0.5
	1.53		0.54	300	1.5 3.1	11	62.3 -62.3	41.3 -41.3	56.6 -56.6	17.2 -14.0	42.2 -42.2	20.0 -14.9	37.1 -28.6	33.9 -33.9	36.5 -36.5
	1.54		0.54	200 400	2.3 4.7	9	32.9 -32.9	24.8 19.5	21.8 -21.8	59.3 59.3	10.8 10.8	57.1 57.1	41.6 41.6	27.5 27.5	25.2 25.2
Yun et al. [40]	2.0	SS, Single round channel	0.54	1500	0.93	3	15.9 -15.9	25.1 25.1	6.8 6.8	36.1 36.1	3.4 2.2	22.42 2.4	9.6 -8.9	33.8 33.8	2.8 -0.9
Yun et al [41]	6.0	SS, single round channel	0.54 0.61	170 340	1.9 6.0	24	55.7 -55.7	24.2 -21.2	48.7 -48.7	16.5 -14.6	22.3- 16.0	16.6 -8.5	30.1 24.4	22.9 -9.6	16.8 -8.4
Dang et al. [42]	2.0	SS 316, Single round channel, compressor used	0.69	360	1.4	9	38.4 34.3	18.2 -12.5	26.9 -26.9	42.3 42.3	7.5 3.0	43.1 43.4	31.6 17.3	18.3 16.2	19.3 19.3
Dang et al. [43]	2.0	SS, single round channel, no compressor	0.69	360 1440	0.71 5.7	34	25.0 -14.0	49.2 46.7	23.8 0.0	61.1 61.1	25.8 24.8	56.4 56.4	37.2 29.8	48.5 48.3	36.7 36.7
	4.0		0.69	720	1.42	6	12.5 -14.7	39.6 39.6	11.2 11.2	56.5 56.5	50.0 50.0	53.3 53.3	50.2 49.9	61.8 61.8	55.7 55.7
	6.0		0.69	720	1.42	6	9.6 9.6	70.9 70.9	25.0 25.0	62.9 62.9	70.0 70.0	51.0 51.0	40.0 40.0	66,0 66.0	79.8 79.8
Petterson [44]	0.8	Al., multi-channel, 25 round channels, liquid heat	0.47 0.78	190 570	0.89 3.0	32	46.3 -46.3	16.7 -15.6	36.3 -36.3	21.1 20.5	26.6 -26.6	15.4 13.4	23.3 -22.1	13.9 -11.7	17.7 -16.4
Jeong et al. [45]	2.0	Al, multi-channel with rectangular channels	0.61	450	0.9	5	32.9 -32.9	18.9 -6.1	19.2 -19.2	37.9 37.9	9.7 -9.3	29.8 29.8	25.9 -25.9	17.7 14.6	8.2 -0.7
Huai et al. [46]	1.31	Al, multiport, 10 round channels, liquid heat, local $\dot{q}$ given	0.54 0.64	283 310	1.7 2.4	9	38.0 -20.3	65.5 18.7	37.9 -18.5	71.0 71.0	19.9 12.2	61.2 61.2	51.2 46.9	37.4 34.2	38.7 38.7

Shinmura, et al. [47]	0.6	Al, multi-channel with round channels	0.551	400	2.4	6	33.8 -33.8	16.3 16.3	26.4 -26.4	34.9 34.9	23.0 -23.0	21.5 16.9	15.0 -8.2	10.7 -4.2	16.2 -15.0
Zhao et al. [48]	0.86	Al, multi-channel with triangular channels	0.612	300	1.87	6	47.5 -47.5	14.7 -14.7	37.2 -37.2	25.5 25.5	23.1 -23.1	20.3 20.3	14.2 -12.0	11.1 -11.1	13.5 -13.5
Cho et al. [49]	4.0	Round tube, inclined 45^0	0.47 0.78	318 530	1.5 7.7	85	56.0 -56.0	19.0 8.8	49.9 -49.9	25.6 -25.6	25.0 -25.0	20.8 -19.8	23.9 -10.0	16.4 -14.1	22.5 -22.1
Cho et al. [50]	4.0	Round tube, horizontal	0.41	318 656	1.9	18	32.5 -22.9	24.6 18.8	25.9 -14.9	39.9 30.2	35.4 9.6	49.9 35.3	66.2 34.2	32.4 17.6	44.2 25.6
Grauso et al. [51]	6.0	SS, single round tube	0.568	201	2.42	8	25.1 -25.1	19.7 17.6	14.7 -14.7	67.2 67.2	58.4 57.4	79.1 79.1	75.8 69.5	33.0 22.8	38.4 38.4
Zhao et al. [38]	6.0	SS, single round tube	0.61	160 320	1.6 4.8	44	48.9 -48.9	14.1 -6.3	40.6 -40.6	9.4 6.2	17.4 9.1	17.0 13.5	21.1 1.4	33.8 -1.6	15.2 0.8
All Data	0.51 14.0		0.19 0.88	75 1500	0.29 35.0	1052	42.0 -39.3	26.8 -3.9	36.4 -32.0	31.4 12.9	26.2 -6.2	30.7 14.2	32.1 -3.5	31.9 -3.8	28.4 3.4

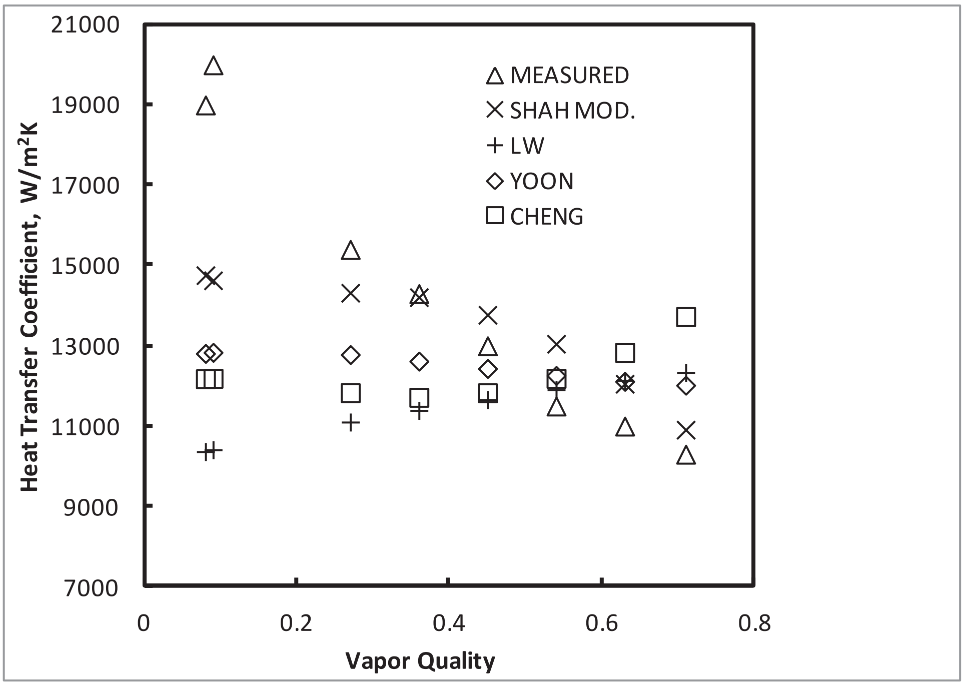

Fig. 1 Comparison of the data of Cho et al. [50] with various correlations. D = 4 mm, $\dot{m}$ = 656 kg/m^{2}s, $\dot{q}$ = 25.4 kW/m^2,T_{SAT} = -5 °C.

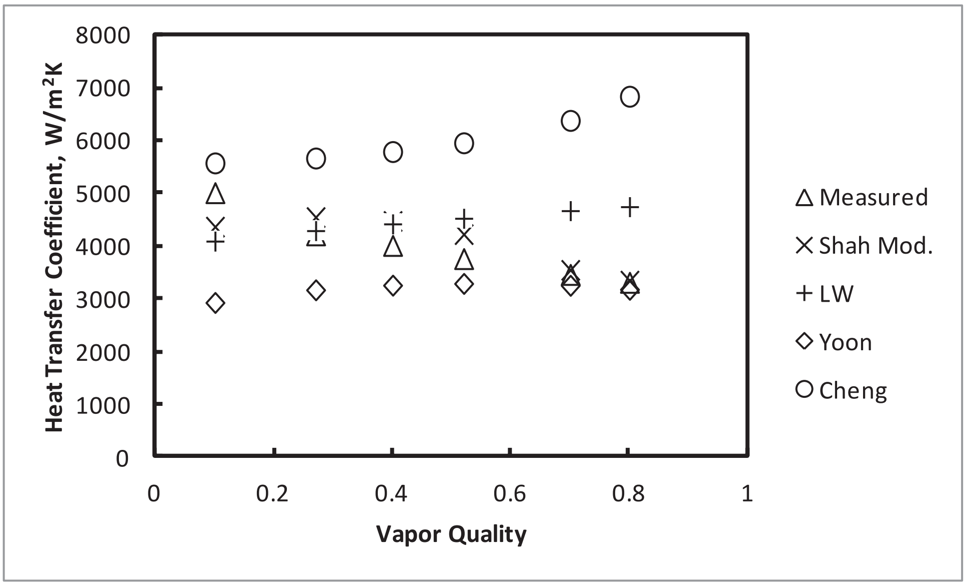

Fig. 2 Data of Kim & Hrnjak [30] compared to various correlations. D = 11. 2 mm, $\dot{m}$ = 200 kg/m^{2}s, $\dot{q}$ = 10 kW/m^2, T_{SAT} =-15 °C.

Figs. 1, 2, 3, and 4, show comparison of some of the data with correlations. In these figures, the names of the tested correlations have been abbreviated. “Shah Mod.” Is Shah correlation [2] modified with Eq. (4), “LW” is Liu & Winterton [5], “Hihara” is Hihara and Tanaka [11], “Yoon” is Yoon et al. [12], and “Cheng” is Cheng et al. [9].

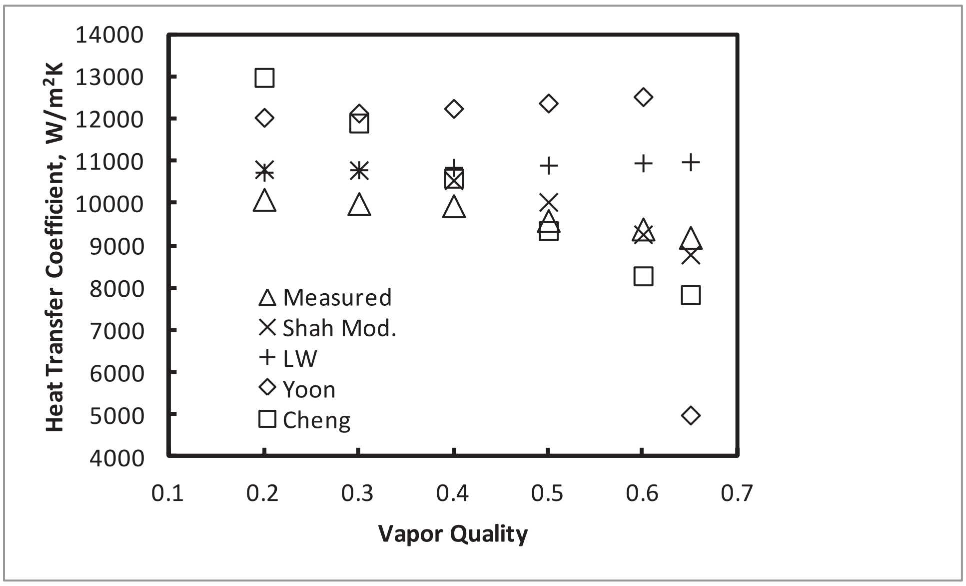

Fig. 3 Comparison of the data of Zhao et al. [38] with various correlations. D = 6 mm, ṁ = 320 kg/m^{2}s, q̇ = 20 kW/m^2, T_{SAT} = 10 °C.

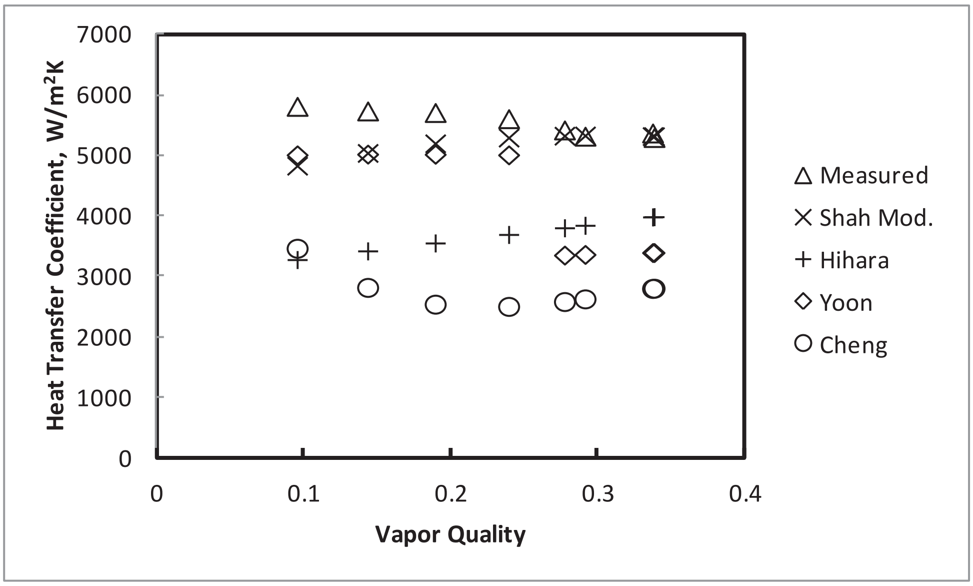

Fig. 4 Comparison of some correlations with the data of Knudsen & Jensen [52], ṁ = 175 kg/m^{2}s, q̇ = 13 kW/m^2 , T_{SAT} = -26 C.

4.2 Performance of Fang Correlation

Fang [13] compared his correlation with many data sets from many sources and reported a mean absolute deviation of 15.5 %. In the present data analysis, deviations were found to be much larger. Some of the data sets analyzed by Fang were also included in the present study. This large disagreement was therefore unexpected. A possible reason for this disagreement is discussed in the following.

Heat transfer coefficient is defined as:

$$h_{TP} = q/(T_w - T_{SAT}) \tag{7}$$

In all test data analyzed, heat flux is known and the correlations really predict the wall superheat ($T_w - T_{SAT}$).

The Fang correlation may be written as:

$$h_{TP} \propto \left\{ln\left(\frac{1.024\mu_l}{\mu_{lw}}\right)\right\}^{-1} \tag{8}$$

Where μ_l is the viscosity of liquid at the liquid temperature, T_{SAT}, and μ_{lw} is the viscosity of liquid at the wall temperature, T_w. The predicted heat transfer coefficient is therefore very sensitive to the wall superheat. When the measured wall superheat was used in the calculations, the mean absolute deviation of the Fang correlation with the database was 17.1 %, which is much lower than those of all the correlations tested and is comparable to that reported by Fang. However, this comparison using measured wall superheat is not valid as wall superheat is what is to be predicted. The correct procedure, as in designing a heat exchanger, is to perform iterative calculations with assumed wall superheat till the predicted wall superheat converges to the assumed wall superheat. When such iterative calculations were done, the mean absolute deviation of the Fang correlation for all data was 40 %. It appears that the mean deviations reported by Fang were obtained using measured superheats. To test it, some data shown in the figures in Fang's paper were analyzed using the measured superheats as well as by the iterative method described above. The results with the measured superheats matched those shown for the Fang correlation in the figures while the results with the iterative calculations showed large deviations.

4.3 Nucleate Boiling

The present data analysis showed that nucleate boiling effects are much stronger than in the Shah correlation for the majority of data sets and better agreement was obtained by modifying it by replacing its nucleate boiling factor with Eq. (4). The correlations of Shah [2] and Gungor & Winterton [4] use the boiling number to determine nucleate boiling contribution while the others use pool boiling correlations. These two were found to be the most accurate when compared with a very wide ranging database [6] for 22 fluids but under-predicted most of the present data sets. Hence nucleate boiling effects are usually stronger for CO_2 than given by these two correlations. However, there are 11 data sets for which the mean absolute deviations of both these correlations are less than 30 % and these are over-predicted by other correlations. Hence it appears that nucleate boiling effects are more variable for CO_2 than for other fluids.

It is known from experimentation and theory that bubble nucleation is affected by cavity size, shape, and distribution on the surface and that there is a wide range of these on all tube surfaces. It appears that the surface microstructure of typical commercial surfaces is generally more favorable for boiling of carbon dioxide than boiling of most other fluids. This may be because the surface tension of carbon dioxide is much lower than of most other fluids. For example, surface tension at 0 ^{o}C of CO_2 is 4.48 mN/m while that of R-134a is 11.8. This lower surface tension allows smaller cavities to be active for nucleation. This and other favorable effects of low surface tension on bubble nucleation and bubble dynamics are discussed in detail in texts such as Collier and Thome [56].

Heat transfer coefficients during pool boiling have been found to vary over a wide range on apparently similar commercial surfaces. In developing his correlation, Eq. (1), Cooper had to disregard many data sets which had large deviations. Similarly, Stephan and Abdelsalam [53] discarded more than half the data sets in developing their pool boiling correlation. While some of these deviations could be due to measurement errors, many of them are likely to be due to variations in surface microstructure. Flow boiling is much less sensitive to surface microstructure but variations have been reported. For example, Shah [6] found that his correlation agreed with data for nitrogen from several sources but data from one source was much higher. Hence the variations in nucleate boiling seen in the present analysis of CO_2 flow boiling data are not unusual. The most probable nucleate boiling contribution for the Shah correlation is represented by Eq. (4).

4.4 Mini Channels

The results for comparison with data for mini-channels are shown in Table 2 and Fig. 5. The distinction between mini and macro channels was made in accordance with the criterion of Li and Wu, Eq. (3). Best agreement is seen to be with the correlation of Yoon et al. with a mean absolute deviation of 18.7 %. The mean absolute deviation of the mini channel specific correlation of Li and Wu is 20.3 % and that of Cheng et al. correlation is 20.4 %.The correlation of Liu and Winterton and the modified Shah correlation also do fairly well.

The Yoon et al. correlation was developed using only their own data for a 7.5 mm diameter tube. It is therefore remarkable that it performs significantly better than the Li & Wu correlation which is specifically developed for mini channels. The performance of the correlation of Liu & Winterton and Cheng et al. which are not specific to mini channels is also good. So it appears that the Li-Wu criterion, Eq. (3), for distinction between macro and mini channels is really only the limit for the applicability of their correlation.

There are several other criteria for distinction between mini and macro channels, for example Kandlikar & Grande [23] and Cheng & Wu [24]. Investigation into the accuracy of various such criteria is beyond the scope of the present research. The criterion of Li and Wu, Eq. (3), was used as their correlation for mini channels is based on it.

4.5 Accuracy of Test Data

Heat transfer coefficients in CO_2 boiling are usually high. Therefore wall superheats are small and there is greater possibility of errors in their measurement and hence the estimation of heat transfer coefficients. Some of the researchers have given their estimates of the uncertainty in their measurements of various parameters and consequent possible errors in reported heat transfer coefficients. Most estimate maximum errors in heat transfer coefficients to be 5 to 15 %. Bredsen et al. [20] estimate maximum error to be 45%; their data do not agree with any correlation. Petterson [44] estimates possible error in maximum heat transfer coefficient to be upto 50 %. It is interesting that his measurements show good agreement with almost all correlations while some of the others with much lower estimates of error, such as Mastrullo et al. [36] with estimated error of 7 %, have large deviations with most correlations. In view of this, it appears that the researchers' own estimates of possible margins of error in their reported data are not reliable indicators of their accuracy. As more and more data from different sources are analyzed, it becomes clearer and clearer which data are probably erroneous.

4.6 CHF and Post-CHF Heat Transfer Prediction

CHF and Post-CHF heat transfer were not part of this study but some suggestions for their predictions are made here. One alternative is to use the CO_2 specific correlation of Cheng et al. or Yoon et al.. The Cheng et al. correlation has had much more validation. The alternative is to use general correlations for this purpose. For prediction of CHF, one of the most verified correlation is that of Shah [18] for vertical tubes. It can be used for horizontal tubes by applying correction factors such as that of Kefer et al. [54]. For dispersed flow film boiling, the non-equilibrium model of Shah and Siddiqui [19] is well-verified and has been reported to give good agreement with CO_2 data by Ayad et al. [55] and Petterson [44]. Ayad et al. [55] compared data for CO_2 boiling in mini channels from four sources with their computer model and found excellent agreement. This model used the Kefer et al. [53] correction factor for CHF and the Shah & Siddiqui model for film boiling.

Table 2: Deviations of various correlations with the data for mini-channels.

Researchers	D_{hyd} mm	No. of Data Point	Deviation, Percent, for Listed Correlations (Mean Absolute Above, Average Below)								
			Shah Mod.	GW 87 [4]	GW 86 [3]	LW [5]	Chen [14]	Hihara [11]	Yoon et al. [12]	Cheng et al. [9]	Li & Wu [7]
Koyama et al. [25]	1.8	1	51.5 -51.5	72.2 -72.2	33.9 -33.9	43.8 -43.8	25.9 -25.9	11.9 -11.9	34.8 -34.8	37.2 -37.2	62.9 -62.9
Choi et al. [34]	1.5	6	32.6 -32.6	45.7 -45.7	9.7 -9.3	33.9 -33.9	6.8 -3.6	10.4 -6.2	34.0 34.0	16.4 -16.4	39.4 -39.4
Hihara & Tanaka [11]	1.0	9	14.2 -7.2	31.4 -31.4	37.0 37.0	10.4 -6.4	37.4 37.4	22.2 14.5	7.5 1.7	9.5 8.5	17.9 -4.7
Ami et al. [38]	0.51	10	47.1 38.3	27.6 -18.7	87.2 87.2	17.7 17.5	69.5 69.5	57.4 57.4	37.6 37.6	30.0 30.0	20.3 0.6
	1.0	7	56.2 40.5	21.6 -14.1	88.8 88.8	26.2 26.2	76.2 76.2	52.7 52.7	49.9 49.9	43.8 43.8	28.9 15.3
Yun et al. [39]	1.14	20	10.5 -6.2	34.3 -34.3	33.2 33.2	16.9 -13.4	30.6 30.6	21.4 7.5	9.1 -2.8	19.3 13.3	12.6 1.4
	1.53	3	58.0 -58.0	64.9 -64.9	28.7 -28.7	49.2 -49.2	23.9 -23.9	29.4 -29.4	47.7 -47.7	36.5 -36.5	43.1 -43.1
	1.54	2	12.7 -8.6	45.2 -45.2	41.9 41.9	5.1 5.1	48.2 48.2	46.6 46.6	20.6 20.6	21.5 21.5	6.6 -6.6
Petterson [44]	0.8	29	15.8 -14.6	34.6 -34.6	21.9 21.9	26.1 26.1	15.8 15.1	27.1 -26.8	13.6 -11.1	17.3 -15.9	20.6 15.5
Huai et al. [46]	1.31	5	42.1 -42.1	47.4 -47.4	26.4 26.4	6.4 -6.4	39.0 39.0	59.6 59.6	4.5 -1.3	21.8 21.8	14.6 -9.6
Shinmura, et al. [47]	0.6	6	16.3 16.3	26.4 -26.4	34.9 34.9	23.0 -23.0	21.5 16.9	16.4 -13.6	10.7 -4.8	16.1 -15.0	9.5 -4.0
Zhao et al. [48]	0.86	6	14.7 -14.7	37.2 -37.2	25.5 25.5	23.1 23.1	20.3 20.3	17.7 17.7	11.1 -11.1	13.5 -13.5	10.0 7.7
All Data	0.51 1.8	104*	24.1 -5.6	35.1 -33.7	37.3 33.9	21.8 -13.6	31.9 28.9	30.0 4.9	18.7 -8.0	20.4 1.5	20.3 0.6

*Total number of data points compared with Cheng et al. correlation was 86.

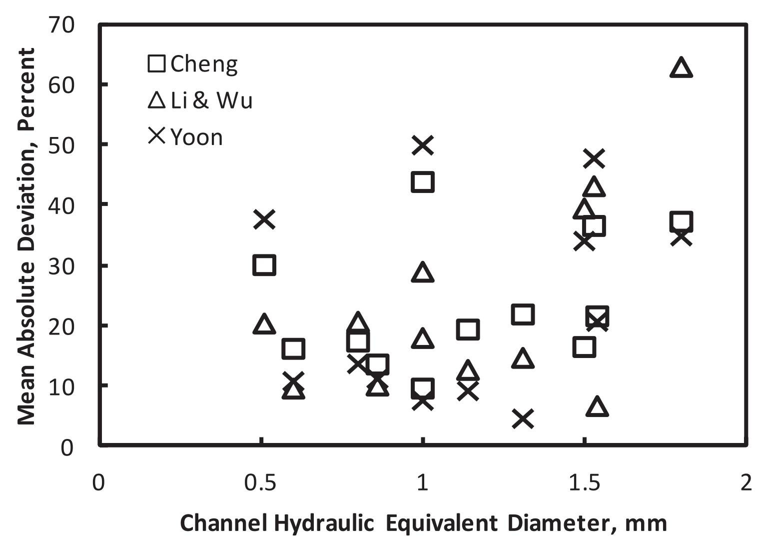

Fig. 5 Mean absolute deviations of data sets for mini channels compared to correlations of Cheng et al. [9], Li & Wu [7], and Yoon et al. [12]

5. CONCLUSIONS

a. A large data base for oil-free carbon dioxide boiling in plain tubes and channels of various shapes prior to CHF was compared to a number of correlations. The database consisted of 1052 data points from 41 data sets which are from 32 studies. It included single tubes as well as multiport channels of circular, trapezoidal, and triangular cross-sections. Test section materials were copper, aluminum, nickel, and stainless steels. The range of parameters included equivalent diameters from 0.51 to 14.0 mm, reduced pressures from 0.18 to 0.88, flow rates from 75 to 1500 kg/m^{2}s, and boiling numbers from 0.00003 to 0.0035.

b. The correlations tested included five general correlations for macro tubes, a modified general correlation, four correlations exclusively for CO_2, and one general correlation for mini-channels. Considering all data, best agreement was with the correlation of Liu and Winterton and the modified Shah correlation. Their mean absolute deviation is about 26% considering all data and 20 % for 31 of the 41 data sets. These correlations are recommended for macro channels. Considering the wide range of data analyzed here and their prior extensive verification with extreme range of data, there is no apparent limit to the applicability of these correlations.

c. For mini-channel data, the accuracy of the mini channel specific correlation of Li and Wu was found to be a little less than of some of the correlations for conventional/macro tubes. Best agreement was with the correlation of Yoon et al. with mean absolute deviation of 18.7 % and it is therefore recommended for mini channels.

d. The variations in heat transfer coefficients between various data sets appear to be mainly due to differences in nucleate boiling effects. It could be that bubble nucleation for CO_2 is more sensitive to surface microstructure than other fluids.

NOMENCLATURE

Bn	Boiling number = $\dot{q}/(\dot{m}\, h_{lg})$	(-)
Bo	Bond number = $g(\rho_l - \rho_g)D_{eq}^2/\sigma$	(-)
D	Diameter of tube	(m)
D_{eq}	Equivalent diameter of channel	(m)
D_{hyd}	Hydraulic equivalent diameter	(m)
g	Acceleration due to gravity	(m/s^2)
h	Heat transfer coefficient, also enthalpy	(W/m^{2}K), (J/kg)
h_{pb}	Pool boiling heat transfer coefficient	(W/m^{2}K)
h_{lg}	Latent heat of vaporization	(J/kg)
h_{LT}	Heat transfer coefficient assuming all mass flowing as liquid	(W/m^{2}K)
h_{TP}	Two-phase heat transfer coefficient	(W/m^{2}K)
k	Thermal conductivity	(W/m K)
$\dot{m}$	Total mass flux (liquid + vapor)	(kg/m^{2}s)
M	Molecular weight	(-)
N	Number of data points	(-)
Nu_{TP}	Two-phase Nusselt number = $h_{TP}D_{eq}/k_l$	(-)
p_r	Reduced pressure	(-)
$\dot{q}$	Heat flux	(W/m^2)
Re_l	Reynolds number assuming liquid phase flowing alone, = $\dot{m}(1\text{-}x)D/\mu_l$	(-)
x	Vapor quality	(-)

Greek

ρ	Density	(kg/m^3)
σ	Surface tension	(N/m)

Subscripts

l	Of liquid
g	Of vapor

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