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Evaluation of General Correlations for Heat Transfer During Boiling of Saturated Liquids in Tubes and Annuli

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Six of the most verified correlations for boiling heat transfer were compared to data for horizontal and vertical tubes and annuli. The correlations evaluated were: Chen (1966), Shah (1982), Gungor and Winterton (1987), Liu and Winterton (1991), Kandlikar (1990), and Steiner and Taborek (1992). The database used to evaluate these correlations included 30 fluids, consisting of water, refrigerants, cryogens, and organic and inorganic chemicals. The data cover reduced pressures from 0.005 to 0.783, mass flux from 28 to 11071 kg/m^2*s, vapor quality from 0 to 0.95, and boiling numbers from 0.000026 to 0.00742. The correlations of Shah (1982) and Gungor and Winterton (1987) gave the best agreement with data with a mean deviation of about 17.5%, with only a couple of data sets showing large deviations. This paper presents and discusses the results of this study. Included are tables giving the range of dimensional and nondimensional parameters covered by each experimental study.*

INTRODUCTION

Hundreds of correlations were proposed for the calculation of heat transfer during the boiling of saturated liquids inside tubes and annuli. Most of them were compared to only a limited amount of data. However, some of them were shown to agree with a wide range of data with many fluids and are therefore considered general correlations. It is desirable to know their comparative accuracy and limitations so that the most reliable correlations may be used for practical calculations. This paper reports the results of such a study in which six of the best known general correlations were compared to a very wide range of data for 30 fluids. Included are tables giving the range of dimensional and nondimensional parameters covered by each experimental study.

AVAILABLE CORRELATIONS

A very large number of correlations were published. Most of them had very little verification. Only the ones that had extensive verification with a wide range of fluids and found wide acceptance are mentioned here.

The first general correlation was published by Chen (1966). It was based entirely on data for vertical channels. The correlation is

$$h_{TP} = F_{chen} h_{LO} + S h_{pb} \; . \tag{1}$$

It showed excellent agreement with the data analyzed by Chen. However, many later researchers compared it to large databases and reported that its agreement was satisfactory with neither horizontal nor vertical channels. Examples of such studies are Kandlikar (1990), Gungor

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and Winterton (1986, 1987), Liu and Winterton (1991), and Steiner and Taborek (1992). Hundreds of correlations in the form of Equation 1 were proposed, most based only on one data set.

The present author (Shah 1976, 1982) presented a correlation with the functional form

$$h_{TP}/h_{LO} = f(\mathrm{Co}, \mathrm{Bo}, \mathrm{Fr}_L) \ . \tag{2}$$

The Froude number (Fr_L) accounts for stratification in horizontal channels; it is not used for vertical channels. This was the first correlation applicable to both horizontal and vertical tubes. It was tested with large databases with mostly satisfactory results by many researchers, such as Kandlikar (1990), Gungor and Winterton (1986, 1987), and Liu and Winterton (1991).

Kandlikar (1990) gives a correlation applicable to both horizontal and vertical channels. It uses the same correlating parameters as the Shah correlation but also has a fluid specific multiplier for nucleate boiling. Values of this multiplier were given for only ten fluids; hence, it is applicable to only those ten fluids.

Gungor and Winterton (1986) presented a correlation similar to Equation 1 but incorporated the Froude number for horizontal channels in the same way as in the Shah correlation. Liu and Winterton (1991) also presented a similar correlation and showed it to be more accurate than the Gungor and Winterton (1986) correlation.

Gungor and Winterton (1987) presented a correlation similar to the Shah correlation and showed that it agreed with a wide range of data.

Steiner and Taborek (1992) give a correlation that is based on a large and varied database for vertical channels. It has the form

$$h_{TP} = ((F_{st}h_{LT})^3 + h_{pb}^3)^{1/3} \ . \tag{3}$$

CORRELATIONS TESTED

The following correlations were tested:

- Chen (1966) with pool boiling component calculated by the Cooper correlation (1984)
- Steiner and Taborek (1992)
- Shah (1982)
- Kandlikar (1990)
- Liu and Winterton (1991)
- Gungor and Winterton (1987)

The reason for using the Cooper pool boiling correlation with the Chen correlation is that the Cooper correlation was verified with an extremely wide range of data, while the pool boiling correlation originally used by Chen had very little verification. It was felt that this change will improve the accuracy of the Chen correlation. Hence, the Chen correlation incorporating this change is called the *Chen-Cooper correlation*. Note that the Cooper correlation was used with roughness at 1 μm and without the factor 1.7 for copper tubes.

The Gungor and Winterton (1986) correlation was not tested as that of Liu and Winterton (1991) was tested in the present study, and they had shown that their correlation gave better agreement with the data.

All of the above correlations require the calculation of a single-phase liquid heat transfer coefficient. For use with the Steiner and Taborek correlation, the formula of Pethukov and Krillov (1958) was used in accordance with their recommendation. For all other tested correlations, liquid convective heat transfer was calculated by the McAdams (1954) equation:

$$\frac{h_{LT}D}{k} = 0.023\left(\frac{GD}{\mu}\right)^{0.8}\mathrm{Pr}^{0.4} \tag{4}$$

Ogata and Sato (1974) compared their nonboiling helium data with Equation 4 and found that the constant should be changed to 0.015 to fit their data. Therefore, in analyzing their data, the constant in Equation 4 was changed to 0.015. For application to annuli, D was replaced by the equivalent diameter D_{hp}, defined as four times the flow area divided by the heated perimeter.

DATA ANALYZED

Efforts were made to collect data for as many fluids as possible, covering a wide range of parameters. Only single-component fluids and azeotropic mixtures were considered. For refrigerants, only those data were considered for which oil content was stated to be zero or negligible.

The salient features and range of data analyzed are listed in Tables 1 and 2. These include 30 fluids, namely, water, R-11, R-12, R-22, R-32, R-113, R-114, R-123, R-134a, R-152a, R-502, ammonia, propane, isobutane, carbon tetrachloride, isopropyl alcohol, ethanol, methanol, n-butanol, cyclohexane, benzene, heptane, ethylene glycol, pentane, nitrogen, argon, neon, hydrogen, nitrogen, and helium. The results for ethylene glycol are from Liu and Winterton (1991). Data for carbon dioxide (CO_2) from several sources were also analyzed but none of them agreed with any of the tested correlations. It was concluded that CO_2 is a special fluid requiring separate treatment; hence, CO_2 data were not included in Tables 1 and 2. This is further discussed later in the paper.

Most of the data analyzed are for local heat transfer coefficients. Some researchers reported only the average heat transfer coefficients and heat flux over the tube length as indicated in Tables 1 and 2. Comparison with such data was done by using the mean quality and the mean heat flux in the evaluated correlations.

The data of Ogata and Sato (1974) for helium showed strong hysterisis. The mean of the heat transfer coefficients for ascending and descending heat fluxes was used for comparison with all correlations.

FLUID PROPERTY DATA

The main source of fluid property data was the University of Ottawa Code UO0694. It did not give data for all fluids. For analyzing the data of Talty (1953), fluid properties used were those listed by him. For helium, properties used were from McCarty (1972). Properties of isobutane, propane, ammonia, R-32, R-502, hydrogen, argon, and neon were from the *ASHRAE Handbook* (ASHRAE 1997). Properties of other fluids (carbon tetrachloride, n-butanol) were from Beaton and Hewitt (1989).

RESULTS OF DATA ANALYSIS

The mean and average deviations of data from correlations are listed in Tables 1 and 2 for horizontal and vertical channels, respectively. The deviation δ for a data point is defined as

$$\delta = \frac{(h_{pred} - h_{meas})}{h_{meas}} . \tag{5}$$

The average deviation δ_{avg} of a data set is defined as

$$\delta_{avg} = (\Sigma(\delta)/N) , \tag{6}$$

where N is the number of data points in the data sets. The mean deviation δ_{mean} of a data set is defined as

$$\delta_{mean} = (\sum Abs \cdot (\delta)/N) . \tag{7}$$

Table 1. Results of Comparison of Data for Horizontal Tubes with Various Correlations

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	Fr_L	No. of data	Mean Deviation, % Average Deviation, %[†]					
												Shah 1982	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Mumm (1954)	11.8	SS (Elec.)	Water	0.014	345	157	0.00	0.53	0.04	1.1	184	11.4	10.9	13.2	13.3	31.8	32.2
				0.0624	1382	788	52.0	11.0	1000	20.0		–5.6	–0.2	–6.1	–10.1	–31.1	–30.9
Chawla (1967)	6.0	Copper (Elec.)	R-11	0.0135	40	2.3	10.0	2.0	0.02	0.025	57	14.8	19.9	28.3	13.9	36.1	21.2
					252	69.9	90.0	26.7	0.28	0.46		–14.8	–15.1	–28.3	–7.6	–34.1	–20.7
	14.0			0.0135	25	1.2	10.0	0.51	0.01	0.002	29	11.7	14.6	19.0	12.0	58.7	30.0
					130	23.3	90.0	24.3	0.28	0.045		8.2	–4.7	–3.4	10.9	51.4	24.7
	25.0			0.0089	22	1.8	10	1.3	0.01	8E-4	52	18.8	12.5	17.3	17.9	105.4	54.8
				0.0198	74	11.6	90	28.0	0.34	0.099		15.8	1.2	–0.9	13.2	103.6	54.8
Haynes and Fletcher (2003)	1.95	Copper (Elec.)	R-11	0.0987	150	53.0	0.00	7.75	0.46	0.63	6	27.0	13.2	35.3	19.2	73.8	25.1
					420		17.0	21.7	1000	4.93		–23.1	–5.2	–35.3	10.6	–73.8	–25.1
Wattalet et al. (1994)	7.0	Copper (Elec.)	R-12	0.088	50	2.0	10.0	1.1	0.01	0.019	50	12.9	15.5	16.2	11.8	20.2	8.5
					300	20.0	92.0	6.7	0.72	0.62		–12.3	–12.8	–10.4	–2.7	2.4	–3.7
			R-134a	0.086	300	50	5.0	0.85	0.02	0.022	52	16.3	13.3	13.5	NA	25.1	12.7
						300	90.0	5.1	1.2	0.80		–8.5	–12.0	–7.2		14.5	–3.4
Uchida and Yamaguchi (1966)	6.4	SS (Elec.)	R-12	0.097	345	14.4	0.00	1.9	0.01	0.25	40	21.8	20.8	15.6	15.7	18.3	18.3
					518	27.9	95.0	5.7	1000	2.5		–21.5	–19.9	–11.7	= 10.4	–19.2	–18.1
Chaddock and Noerager (1966)*	11.7	SS (Elec.)	R-12	0.1098	122	3.5	26.1	0.99	0.16	0.071	19	16.4	13.0	15.6	12.8	11.6	21.7
					585	35.2	54.5	7.94	0.36	1.63		–13.6	–5.5	2.3	–2.4	–7.9	–17.1

* Reported heat transfer coefficients are mean for the tube length. All other data are local heat transfer coefficients.

[†] For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 1. Results of Comparison of Data for Horizontal Tubes with Various Correlations *(Continued)*

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	Fr_L	No. of data	Mean Deviation, % Average Deviation, %†					
												Shah 1982	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Ebisu, and Torikoshi (1998)	6.4	Copper (Liquid)	R-22	0.11	300	7.5	20.0 80.0	1.2	0.04 0.41	0.88	4	20.2 –20.2	22.5 –22.5	17.5 –17.5	20.6 –3.9	12.2 4.1	16.5 –16.5
Mathur (1976)	9.5	SS (Elec.)	R-22	0.097 0.16	146 877	7.7 40.5	3.0 80.0	2.5 6.8	0.03 2.7	0.14 5.8	69	17.1 –8.7	18.4 –2.8	18.4 3.4	48.0 43.5	22.7 1.3	16.9 –10.4
Johnston and Chaddock (1964)*	11.6	Copper (Elec.)	R-22	0.0134 0.0581	15 571	1.7 21.5	9.7 38.5	3.2 13.3	0.09 0.28	0.0016 0.0147	22	13.8 –1.7	21.4 –20.4	50.1 –50.1	86.3 86.3	18.5 –15.4	25.9 25.3
Muzzio et al. (1998)*	8.9	Copper (Liquid)	R-22	0.117	90 400	5.2 24.0	0.45	2.9 3.0	0.16	0.058 1.14	4	26.7 –26.7	17.8 –10.4	17.6 –10.4	9.1 9.1	10.9 –7.4	19.6 –16.5
Pierre (1957)*	18.0	Copper (Liquid)	R-22	0.071	52 178	3.5 11.7	0.45	3.1	0.13	0.009 0.103	6	8.2 –1.3	11.6 0.3	22.3 –2.9	41.7 41.7	34.2 34.2	2.3 1.9
	12.0			0.049	132 225	12.8 21.5	0.55	4.4 4.8	0.08	0.082 0.232	8	5.1 5.1	6.9 6.9	8.0 8.0	41.8 41.8	30.0 30.0	1.8 –0.8
Jung et al. (1989a, 1989b)	9.0	Copper (Elec.)	R-22	0.080	362 516	17.0 44.0	10.0 70.0	2.2 4.1	0.06 0.66	0.87 1.8	12	13.4 –12.7	14.5 –8.9	13.7 –10.5	37.0 33.0	12.3 –2.7	25.3 –18.3
			R-114	0.081	362 516	10.0 36.4	12.0 70.0	1.5 4.1	0.05 0.56	0.69 1.4	20	7.8 3.4	14.7 10.4	14.4 13.7	12.5 10.7	29.9 29.9	5.6 –4.8
			R-152a	0.08	367	17.0 36.2	5.0 68.0	1.5 4.0	0.06 0.44	2.1	19	9.7 –9.7	13.0 –3.6	60.2 60.2	9.3 –7.0	35.9 35.9	10.4 –9.7
Reid et al. (1987)	8.7	(Elec.)	R-113	0.117	248	18.4	3.0 75.0	5.8	0.06 2.24	0.362	9	19.9 –19.5	13.5 –11.4	14.5 –9.9	9.9 –8.8	25.7 –24.1	18.4 –18.4

* Reported heat transfer coefficients are mean for the tube length. All other data are local heat transfer coefficients.

† For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 1. Results of Comparison of Data for Horizontal Tubes with Various Correlations *(Continued)*

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	Fr_L	No. of data	Mean Deviation, % Average Deviation, %[†]					
												Shah 1982	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Shin et al. (1997)	7.7	SS (Elec.)	R-22	0.145	424	18	10	0.69	0.05	1.54	35	8.5	13.4	12.7	51.5	23.4	6.5
					742	30	79	3.64	0.91	4.74		–4.7	4.9	9.0	50.9	17.9	–6.2
			R-32	0.20	424	30.0	5.0	1.7	0.18	2.3	12	9.6	9.0	13.6	NA	22.7	8.3
					583		50.0	2.4	1.9	4.4		–9.4	3.0	10.6		1.2	–8.3
			R-134a	0.109	424	30.0	10.0	2.7	0.05	1.52	16	8.5	14.3	14.2	NA	28.4	7.3
					583		79.0	3.7	0.6	2.9		1.2	7.3	9.9		20.3	–7.1
			Propane	0.158	424	30.0	10.0	1.44	0.09	9.1	12	5.9	16.3	26.9	NA	32.6	1.9
					583		68.0	1.98	0.98	17.1		3.8	14.2	26.9		32.5	0.8
			Isobutane	0.065	424	30.0	1.0	1.5	0.06	7.4	13	16.8	20.2	33.2	NA	46.5	3.7
					583		68.0	2.1	4.1	14.0		16.8	18.4	33.2		43.5	3.2
Gouse and Coumo (1965)	10.9	Glass, nickel-coated (Elec.)	R-113	0.031	517	12.9	2.2	1.3	2.2	1.05	10	8.4	18.8	41.4	23.6	24.6	9.2
				0.035	699	22.1	36.6	2.9	36.6	1.91		7.6	18.8	41.4	23.6	21.4	–9.2
Murata and Hashizume (1990)	10.3	Copper	R-114	0.061	300	30.0	20.0	4.1	0.08	0.39	3	13.0	9.1	14.1	9.2	18.6	27.7
							80.0		0.66			–13.0	–9.1	–14.1	–9.2	–13.4	–27.7
			R-123	0.0546	100	10.0	20.0	2.1	0.01	0.05	26	13.0	14.0	11.1	NA	16.1	17.1
					300	30.0	92.0	18.5	0.28	0.45		–12.3	–11.2	–4.1		–1.4	–17.1
Hambreaus (1995)	12.0	Copper (Elec.)	R-134a	0.049	137	6.0	30.0	2.1	0.02	0.09	21	18.9	17.3	20.6	NA	40.3	12.3
							90.0		0.17			11.5	1.3	14.2		40.2	2.3
Chaddock and Buzzard (1986)	7.7	Copper (Elec.)	R-502	0.0085	45	3.8	20	4.2	0.04	0.008	26	12.3	15.2	16.3	NA	29.4	9.7
				0.059	358	23.7	70	5.2	0.36	0.567		5.4	6.1	4.7		28.5	3.3

[†] For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 1. Results of Comparison of Data for Horizontal Tubes with Various Correlations *(Continued)*

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	Fr_L	No. of data	Mean Deviation, % Average Deviation, %†					
												Shah 1982	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Kattan et al. (1998)	12.0	Copper (liquid)	R-502	0.15	100	8.0	3.0	2.1	0.14	0.049	15	19.0	15.5	26.5	NA	32.7	8.7
					300	10.0	54.0	6.2	2.61	0.442		–17.1	–7.0	–9.8		–22.2	–7.0
Zurcher et al. (1998)	14.0	SS (liquid)	NH_3	0.044	10	8.0	0.03	0.76	0.01	0.0024	106	21.9	23.4	25.5	NA	29.8	27.5
					140	71.6	0.90	6.5	1.36	0.473		1.7	–4.7	–9.7		17.9	13.5
Steiner and Schlunder (1977)	14.0	Copper (Elec.)	Nitrogen	0.186	44	0.5	5.0	1.0	0.05	0.031	42	58.6	52.2	44.4	51.4	26.0	46.6
				0.461	460	34.6	75.0	9.2	2.2	3.3		–58.6	–52.2	–42.1	45.8	–6.8	–44.9
Klein (1976)	12.0	Copper (Elec.)	Nitrogen	0.0873	154	1.0	10	0.26	0.02	0.35	21	29.3	33.8	29.2	120.2	23.0	29.0
					209	50.0	90	17.4	0.74	0.61		–19.7	–17.5	–16.1	106.1	6.4	–29.0
Mohr and Runge (1977)	4.0	Copper (Elec.)	Neon	0.0564	78	1.0	13.0	6.0	0.05	0.11	15	48.4	40.4	63.4	52.4	56.8	60.0
					125	20.0	70.0	34.7	0.49	00.28		–48.4	–40.4	–63.4	43.6	–56.8	–60.0
Wright and Walters (1959)	6.3	Copper (Elec.)	Para H_2	0.0175	412	10.0	2.6	0.42	1.88	587	18	17.6	18.5	27.0	NA	13.2	45.7
					1180	99.7	5.2	2.5	4.15	4822		2.0	11.5	–27.0		–4.3	–46.7
Muller et al. (1983)	14.0	Copper (Elec.)	Argon	0.036	120	1.8	0.1	0.36	0.05	0.064	33	23.4	38.4	116.2	NA	169.7	38.0
				0.413	460	97.0	0.9	74.2	1.79	1.35		–0.3	24.5	114.9		164.7	28.5
All data	1.95			0.0134	10	1.0	0.0	0.26	0.01	0.0008	1086	17.5	18.9	26.0	27.8	36.8	23.7
	25.0			0.413	1382	788	95.0	74.2	1000	4822		–6.4	–4.9	–4.9	+6.6	+9.8	–7.5

† For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 2. Results of Comparison of Data for Vertical Tubes and Annuli with Various Correlations

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	No. of Data Points	Mean Deviation, % Average Deviation, %[†]					
											Shah	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Naitoh	16.5	SS	Water	0.783	1250	100	0.0	0.96	0.34	7	8.8	8.0	110.8	15.9	28.8	38.4
(1974)		(Liquid)				523	60.0	5.02	1000		–8.8	–0.2	110.8	–15.2	–28.8	–38.4
Wright	18.2	SS	Water	0.0053	434	99	1.0	0.56	0.15	71	10.1	11.4	14.5	8.7	25.0	12.6
(1961)		(Elec.)		0.0078	796	154	11.8	1.5	1.0		1.4	–8.6	11.2	–6.6	23.0	12.3
	12.0			0.0068	666	118	1.4	0.52	0.18	37	21.5	24.0	37.1	15.1	43.9	10.8
				0.014	2437	274	10.0	1.07	6.4		19.8	21.9	36.8	12.3	42.8	0.0
Dengler and	25.4	Copper	Water	0.011	721	95	1.7	0.6	0.15	5	11.5	21.3	34.7	13.1	40.1	12.2
Addoms (1956)		(Steam)				448	13.5	2.83	0.98		8.8	21.3	34.7	9.9	40.1	12.2
Piret and Isbin	27.1	Copper	Water	0.0046	394	19.4	0.19	0.22	1.27	4	9.7	40.9	88.3	10.2	53.4	6.4
(1954)*		(Elec.)			822	165	0.45	0.84	3.4		9.7	40.9	88.3	10.2	53.4	–3.6
			CCl_4	0.022	347	5.9	0.64	0.29	1.17	4	9.1	13.5	80.8	NA	26.9	5.6
					943	55.3	2.4	0.99	3.43		–8.5	13.5	80.8		26.9	0.2
			n-butanol	0.0204	555	16.9	0.4	0.51	1.62	4	7.8	3.7	47.9	NA	13.0	22.8
					706	70.0	1.5	1.73	4.6		–7.8	–1.5	47.9		–12.2	–22.8
			Isopropyl	0.011	681	10.8	0.26	0.29	1.02	4	6.5	7.8	90.7	NA	10.3	12.9
			Alcohol		779	85.7	1.6	1.8	4.43		–6.5	7.8	90.7		8.0	–12.9
Adorni et al.	3.2[a]	SS	Water	0.32	980	420	14.0	0.66	0.18	39	22.2	15.0	15.4	24.5	29.3	32.2
(1961)		(Elec.)			3000	1250	69.6	5.9	1.68		–14.7	–4.2	–5.5	–15.2	–22.2	–27.4
	3.2[b]			0.32	980	91	7.4	0.65	0.11	38	18.1	14.9	19.5	19.5	22.7	17.0
					3800	688	70.1	4.5	1.68		–11.2	5.9	–0.2	–13.8	–0.5	–11.7
	8.5[c]			0.32	1010	137	21.0	0.9	0.11	8	46.8	42.3	41.7	50.3	38.9	45.4
					2954	812	70.1	2.34	0.63		–46.8	–42.3	–40.6	–50.3	–38.9	–45.4
Morozov	13.8[d]	SS	water	0.228	6085	261	0.0	0.24	0.55	6	20.9	28.6	16.7	30.5	58.5	35.9
(1969)		(Elec.)			11071	375	20.0	0.26	1000		4.4	25.5	9.6	–17.5	32.0	11.8

* Reported heat transfer coefficients are mean for the tube length. All other data are local heat transfer coefficients.

[†] For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

a. Annulus, 8.2/5.0 OD/ID, bilateral heating, data for outer tube.

b. Annulus, 8.2/5.0 OD/ID, bilateral heating, data for inner tube.

c. Annulus, 8.2/5.0 OD/ID, heating on inner tube only.

d. Annulus, 20.0/14.2 OD/ID, inner tube heated.

e. Results are as reported in Liu and Winterton (1991).

Table 2. Results of Comparison of Data for Vertical Tubes and Annuli with Various Correlations *(Continued)*

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	No. of Data Points	Mean Deviation, % Average Deviation, %†					
											Shah	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Robertson and Wadekar (1988)	10.0	Copper (Elec.)	Ethanol	0.0244	145	25.5	3.0	2.1	0.05	51	21.3	17.7	23.3	NA	20.6	9.4
					290	104.6	56.0	7.0	0.90		–21.3	–17.7	23.3		–19.6	–6.6
Staub and Zuber (1966)	10.0	Copper (Elec.)	R-22	0.121	153	12.1	4.0	3.95	0.41	8	40.0	33.8	34.8	33.5	57.5	45.2
					896	70.7	21.0	3.98	1.12		–40.0	–33.8	–34.8	33.4	–57.7	–45.2
Lazarek and Black (1982)	3.15	SS (Elec.)	R-113		502	64.0	4.0	16.1	0.06	10	10.4	32.5	23.1	38.2	54.5	24.4
							60.0	25.2	1.14		5.4	32.5	–23.1	37.6	–54.5	–24.4
Johannes (1972)	2.1	Monel (Elec.)	Helium	0.477	130	0.5	3.2	2.0	0.92	7	27.2	35.6	35.1	NA	25.9	51.5
						1.5	25.0	5.8	5.86		19.2	31.6	–35.1		–25.9	–51.5
Keilin et al. (1975)	2.0	Copper (Elec.)	Helium	0.57	28	0.1	1.3	1.3	0.49	15	28.5	41.1	24.8	NA	19.5	39.7
				0.68	96	3.0	39.4	40.3	11.0		9.5	41.1	–24.8		–13.5	–39.7
Ogata and Sato (1974)	1.1	SS (Elec.)	Helium	0.477	87	0.2	2.0	0.9	0.53	14	11.2	12.3	15.1	NA	14.7	29.5
						1.4	40.0	8.1	8.62		–5.5	9.1	–14.1		11.3	–29.4
Pappel and Hendricks (1978)	2.0	SS (Elec)	Nitrogen	0.64	2210	212	0.00	9.2	1000	1	0.10	19.6	14.3	436.3	12.5	52.0
											–0.10	19.6	–14.3	436.3	12.5	–52.5
Klimenko and Sudarchikov (1983)	10.0	SS (Elec.)	Nitrogen	0.087	310	13.7	0	2.2	1.0	14	15.3	21.7	16.6	397	39.5	6.4
				0.203	490	20.3	0.08	3.3	4.5		15.3	21.7	15.8	397	39.5	4.8
Klimenko et al. (1987)	9.0	SS (Elec.)	Nitrogen	0.14	220	9.0	2.0	2.35	0.09	20	13.9	19.7	16.1	269.8	32.3	14.7
				0.26		27.0	70.0	7.05	7.05		–3.7	6.8	7.8	269.8	31.3	–7.2
Bennet (1976)^e	20.4		Ethylene glycol	0.026	206	136	0.0			101	21.4	23.4	21.9	NA		
					1030	576	26.9				–7.4	2.0	12.1			

† For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 2. Results of Comparison of Data for Vertical Tubes and Annuli with Various Correlations *(Continued)*

Data of	Dia., mm	Material (Heating by)	Fluid	p_r	G, kg/m^{2}s	q, kW/m^2	x, %	$Bo \times 10^4$	Co	No. of Data Points	Mean Deviation, % Average Deviation, %†					
											Shah	G-W	L-W	Kand-likar	S-T	Chen-Cooper
Talty	19	Brass	Heptane	0.037	231	7.7	0.14	0.99	0.53	33	18.6	18.6	19.7	NA	13.6	27
(1953)		(Liquid)			454	31.7	8.1	1.73	6.9		0.8	8.9	17.4		–9.1	–27
	25.3				266	13.6	0.20	0.69	0.77	28	16.9	10.5	17.1	NA	18.9	34.3
					391	35.6	5.00	1.59	3.98		–15.5	–6.8	7.9		–16.1	34.3
	19.0		Pentane	0.030	251	9.1	0.28	0.85	0.48	51	13.1	11.4	24.5	NA	12.2	20.5
					408	22.9	8.3	2.16	16.6		–0.9	9.1	24.0		–1.8	–20.0
	25.3				266	13.6	0.61	1.11	0.35	54	11.3	5.4	10.9	NA	17.4	36.4
					399	38.4	11.7	3.74	16.7		–10.6	–2.1	7.5		–16.5	–36.4
	19.0		Methanol	0.0156	280	26.2	0.12	0.85	0.48	22	25.9	16.7	38.8	NA	18.7	13.3
					459	49.7	4.3	1.40	7.3		–25.9	–16.7	38.8		–17.0	–1.4
	25.3				314	20.3	0.19	0.60	0.65	54	35.2	21.9	33.6	NA	12.1	22.2
					553	53.5	4.3	1.09	5.5		–35.2	–21.9	33.6		–10.7	–22.2
	25.4		Cyclo-	0.025	335	10.1	0.5	0.58	0.37	52	15.9	6.8	24.0	NA	16.8	26.0
			hexane		488	41.6	10.0	3.02	4.46		–15.9	–6.4	24.0		–15.6	–26.0
	19.0				390	7.9	0.36	0.46	0.57	23	8.9	9.8	51.4	NA	15.4	9.6
					482	24.1	6.1	1.86	5.71		–5.2	9.1	51.4		6.0	–9.2
	25.4		Benzene	.0203	347	12.7	0.20	0.59	0.39	55	13.7	9.3	24.7	NA	9.9	28.0
					600	41.4	8.5	2.58	8.4		–11.2	-0.3	24.6		–3.6	–28.0
	19.0				293	16.5	0.26	1.34	0.4	48	11.7	8.2	17.2	NA	16.6	22.0
					521	43.1	8.7	2.75	6.8		–5.9	1.2	16.8		–16.3	–21.3
All data	1.1			0.0053	28	0.2	0.00	0.22	0.09	888	18.0	15.9	24.8	65.4	20.4	22.7
	27.1			0.783	11071	1250	70.1	40.3	1000		–9.0	+9.5				

† For each data set, the upper row gives the mean deviation and the lower row gives the average deviation.

Table 3 gives the combined results for horizontal and vertical channels. In this table, the deviations for each correlation are given in two ways:

1. Giving equal weight to each data point.
2. Giving equal weight to each data set.

The second way probably gives a better indication of the reliability of the correlation.

DISCUSSION OF RESULTS

Accuracy of Correlations

It is apparent from the results in Tables 1–3 that the correlations of Shah (1982) and Gungor and Winterton (1987) are the most reliable, with a main deviation of about 17.5% for all 1960 data points. The Shah correlation is more consistent, as only 5 of the 69 data sets have a mean deviation of more than 30%, while the Gungor and Winterton correlation has 9 data sets exceeding 30% deviation.

These two correlations show reasonable agreement with almost all data sets. One notable exception is the data of Mohr and Runge (1977) for neon. These are much higher than all the correlations tested here. No other analyzable data for neon could be found. However, Pappel and Hendricks (1978) gave a correlation of their subcooled data for nitrogen and neon for subcooling starting from 2°C. The predictions of this correlation at 1°C subcooled neon agree satisfactorily with the Shah correlation and at 2°C subcooling are lower than the Shah correlation. This suggests that the Mohr and Runge data may be unusually high.

The other notable exception is the data of Steiner and Schlunder (1977) for nitrogen; these are much higher than the Shah correlation. However, nitrogen data from four other sources (Klimenko and Sudarchikov 1983; Klimenko et al. 1987; Klein 1976; Pappel and Hendricks 1978) agree well with this correlation. The Steiner and Schlunder data are also much higher than the Gungor and Winterton and Liu and Winterton correlations. Hence, these data are apparently unique.

The Liu and Winterton correlation's performance is erratic. While it agrees well with many data sets, it also shows large deviations with many data sets, such as the data of Muller et al. (1983) for argon, the cyclohexane data of Talty (1953), and the data of Piret and Isbin (1954) for water, CCl_4, n-butanol, and isopropanol.

Table 3. Summary of Results for Both Horizontal and Vertical Channels

Correlation of	Mean Dev. %	
	a	b
Shah	17.7	17.3
Gungor and Winterton	17.6	18.6
Chen-Cooper	23.2	22.4
Liu and Winterton	25.5	37.5
Steiner and Taborek	30.0	36.5
Kandlikar	32.3	55.0

a. Giving equal weight to each data point.
b. Giving equal weight to each data set.

The Steiner and Taborek correlation did not perform well in predicting horizontal tube data. Indeed, these authors recommended it only for vertical channels. Even with vertical channels, it shows large deviations with some data sets.

The Chen and Cooper correlation works fairly well with both horizontal and vertical tubes, but its accuracy is significantly less than the Shah and the Gungor and Winterton correlations.

The Kandlikar correlation could be compared with data for only those fluids for which he gave the nucleate boiling multiplying factors. Even among those fluids, it performed poorly with data for R-22, nitrogen, and neon. Figures 1 and 2 show the comparison of some data for R-22 and nitrogen with the correlations of Shah and Kandlikar. The Shah correlation is seen to be in good agreement with data, while the Kandlikar correlation predicts too high. These figures are typical of the results for these fluids.

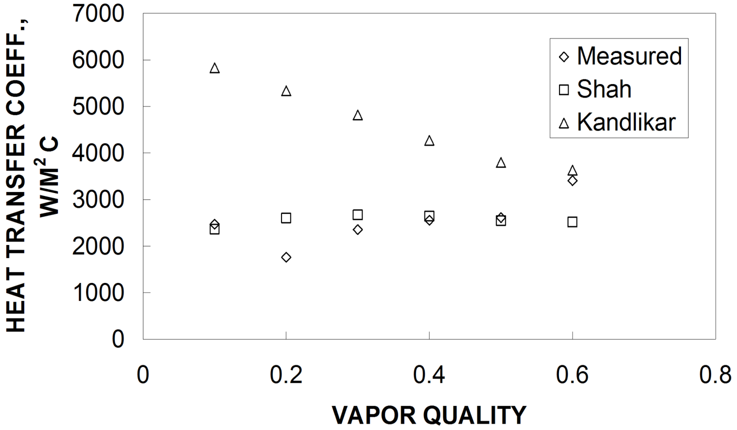

Figure 1. Comparison of some data of Mathur (1976) for R-22 with the correlations of Shah and Kandlikar; p = 4.83 bar, G = 146 kg/m^{2}s, q = 20 kW/m^2.

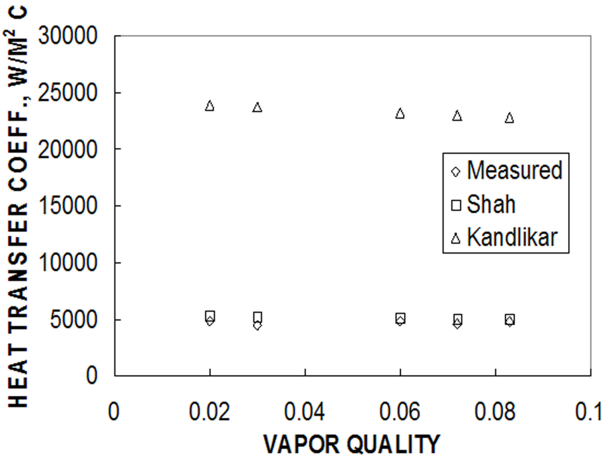

Figure 2. Comparison of some data of Klimenko and Sudarchikov (1983) for nitrogen with the correlations of Shah and Kandlikar; p = 6.9 bar, G = 310 kg/m^{2}s, q = 17.5 kW/m^2.

Tube Material

The data analyzed include many types of tube materials, including copper, stainless steel, monel, brass, and nickel-coated glass. All the test sections were made from commercial grade tubes except the nickel-coated glass used by Gouse and Coumou (1965). There is no indication that the accuracy of the correlations is affected by the type of material.

Tube Surface Microstructure

It is generally agreed that the intensity of nucleate boiling depends on the shape and population densities of cavities in the surface. This was demonstrated by pool boiling tests on surfaces with artificially prepared cavities. Information on cavity sizes and their population density is not available for any of the test data evaluated here. The fact that almost all data sets analyzed are in fair agreement with the Shah correlation (which does not have any factor for surface microstructure) indicates that the microstructures of most commercial tubes are normally similar. It may be noted that the most successful general correlations for pool boiling (those of Stephen and Abdelsalam [1980] and Cooper [1984]) do not have any factor for surface microstructure. It is statistically probable that some commercial tubes may have a microstructure very favorable to nucleate boiling. This may be the explanation for the data of Steiner and Schlunder and Mohr and Runge being much higher than the predictions of almost all tested correlations. However, it will be inadvisable to base designs on such unusually high data.

The designer of a heat exchanger does not have any way of knowing the microstructure of tubes that will be used during fabrication. It is therefore fortunate that heat transfer coefficients can be predicted with a high probability of accuracy without the knowledge of microstructure.

Heating Mode

The data analyzed include electric heating, heating by condensing steam, and heating by hot liquids. Data for all heating modes are satisfactorily correlated by the Shah and the Gungor and Winterton correlations.

Type of Fluid

The Shah and the Gungor and Winterton correlations show good agreement with 29 of the 30 fluids included in Tables 1 and 2. The only available single data set for neon does not agree with any of the tested correlations but, as was pointed out earlier, the measurements of Pappel and Hendricks (1978) appear to be in agreement with the Shah correlation.

CO_2 data from several sources were analyzed but none of the correlations tested here were found to agree with them. Among such data are those of Bredsen et al. (1997), Yoon et al. (2004), and Knudsen and Jensen (1997). These authors also compared their data with well-known general correlations with poor results. Thome and Hejal (2004) compared CO_2 data with their correlation that was based on data for several refrigerants but found poor agreement. They concluded that carbon dioxide is a unique fluid and developed a correlation specifically for CO_2. However, Park and Hrnjak (2005) found that it did not agree with their data.

Thus, the Shah and the Gungor and Winterton correlations appear to be suitable for all Newtonian, nonmetallic fluids except CO_2.

Annuli

The present analysis included only 94 data points from two sources. The present author (Shah 1982) compared the Shah correlation with 736 data points from five sources, covering a wide range of parameters. The mean deviation for all data was 17.1%. Hence, the Shah correlation is well verified for annuli.

Table 4. Complete Range of Data Satisfactorily Predicted by the Correlation of Shah (1982)

Parameter	Range of Data
Fluids	Water, R-11, R-12, R-22, R-32, R-113, R-114, R-123, R-134a, R-152a, R-502, ammonia, propane, isobutane, carbon tetrachloride, isopropyl alcohol, ethanol, methanol, n-butanol, cyclohexane, benzene, heptane, pentane, ethylene glycol, argon, hydrogen, nitrogen, and helium
Test channels	Tubes and annuli (heated on inside, outside, and bilateral); horizontal and vertical
Heating method	Electric, condensing steam, liquid
Diameter, mm	1.1 to 27.1
Reduced pressure	0.0053 to 0.78
G, kg/m^{2}s	10 to 11,071
q, kW/m^2	0.2 to 1,250
x, percent	0 to 95
Bo × 10^4	0.22 to 74.2

SUMMARY AND CONCLUSION

1. Six of the best known general correlations were tested with data for 30 fluids, including water, refrigerants, organics, and cryogens boiling in horizontal and vertical tubes and annuli. The data covered a very wide range of parameters.
2. The correlations of Shah (1982) and Gungor and Winterton (1987) gave good agreement with data, with the mean deviation around 17.5%. The Shah correlation is more consistent. The range of data satisfactorily predicted is given in Table 4. The other four correlations had mean deviations from 22% to 55%.
3. The results indicate that the Shah and the Gungor and Winterton correlations can be used with confidence for all Newtonian nonmetallic fluids (except CO_2).

NOMENCLATURE

Bo = boiling number = $q/(G\,h_{fg})$
D = ID of tube
D_{hp} = equivalent diameter of annulus
Co = convection number, $(1/x-1)^{0.8}(\rho_g/\rho_L)0.5$
F_{chen} = convective enhancement factor in Chen correlation
F_{st} = convective enhancement factor in Steiner and Taborek correlation
Fr$_L$ = Froude number, $G^2/(\rho_L^2 gD)$
G = total mass flux (liquid plus vapor)
g = acceleration due to gravity
h_{fg} = latent heat of vaporization
h_{LO} = heat transfer coefficient assuming liquid phase flowing alone
h_{LT} = heat transfer coefficient assuming all mass flowing as liquid
h_{meas} = measured heat transfer coefficient
h_{pb} = pool boiling heat transfer coefficient
h_{pred} = predicted heat transfer coefficient
h_{TP} = two-phase heat transfer coefficient
k = thermal conductivity of liquid
Pr = Prandtl number of liquid
p_r = reduced pressure
q = heat flux
S = nucleate boiling suppression factor in Chen correlation
μ = viscosity of liquid
ρ_L = density of liquid
ρ_g = density of vapor

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