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A NEW FLOW PATTERN BASED GENERAL CORRELATION FOR HEAT TRANSFER DURING CONDENSATION IN HORIZONTAL TUBES

Mirza M. Shah[1*]

Engineering Research & Consultation, 10 Dahlia Lane, Redding, CT 06896, USA

ABSTRACT

A flow pattern based general correlation for heat transfer during condensation inside horizontal plain tubes is presented. It is compared to a data base that contains 89 data sets from 39 studies. It includes 25 fluids (water, carbon dioxide, DME, halocarbon refrigerants, and hydrocarbon refrigerants), tube diameters from 2 to 49 mm, reduced pressures from 0.0023 to 0.95, flow rates from 13 to 820 kg/m^{2}s, and all liquid Reynolds numbers from 1012 to 84827. The 1568 data points are predicted with a mean absolute deviation of 16.7 %, with flow patterns determined with well-known flow pattern maps. The same data base is also compared to the author's published correlation which is purely empirical as well as several other general correlations. The present correlation performs significantly better than other correlations though the author's published correlation has slightly lower mean deviation. The results of data analyses are discussed and presented in graphical and tabular forms.

KEY WORDS: Condensation, Two-phase/Multiphase flow, heat transfer, tubes, correlation

1. INTRODUCTION

Prediction of heat transfer during condensation of vapours flowing inside plain tubes is of great importance as many heat exchangers involve this mode of heat transfer, for example condensers for air conditioning and refrigeration systems. To ensure optimum design, accurate correlations for prediction of heat transfer are needed. Many correlations, theoretical and empirical, have been published for heat transfer during condensation inside plain tubes. One of the most widely used has been the author's correlation [1]. That correlation is limited to higher flow rates where heat flux has no effect. Shah [2] modified it to extend it to low flow rates and pressures close to the critical. This correlation has three heat transfer regimes. The boundary between Regime II and III for horizontal tubes for this correlation was not given in [2]; it was provided in Shah [3]. This correlation was shown to agree with an extremely wide range of data for horizontal and vertical tubes. It has three heat transfer regimes which are entirely empirical. As noted by many researchers, for example Liebenberg and Meyer [4], correlations that take into consideration flow patterns are preferable. One benefit of having the correlation in terms of flow patterns is that it opens the possibility of considering its application to channels of other geometries such as rectangular and triangular by using flow pattern maps for those geometries. In the present paper, the heat transfer regimes for horizontal round tubes in this correlation have been replaced by flow pattern regimes so as to give it a physical basis. Thus a flow pattern based general correlation is presented for horizontal tubes. It is shown to give good agreement with a very wide range of test data from 89 data sets from 39 independent studies. The entire data base is also compared with the Shah [2, 3] correlation as well as a number of other well-known correlations.

In the following, the development of the correlation is described and its validation with a very wide range of test data is presented. The results of comparison with several other general correlations are also presented.

*Corresponding Author: mshah.erc@gmail.com

2. THE PUBLISHED SHAH CORRELATION

The flow pattern based correlation presented here is a modification of the published Shah correlation [2, 3]. Hence the published correlation is first given. This correlation has three heat transfer regimes. The boundaries of these regimes are different for horizontal and vertical tubes. The heat transfer equations are the same for all orientations. This paper is concerned only with horizontal tubes.

2.1 Heat Transfer Equations

The correlation uses the following two heat transfer equations:

$$h_I = h_{LS}\left(1+\frac{3.8}{Z^{0.95}}\right)\left(\frac{\mu_l}{14\mu_g}\right)^{(0.0058+0.557p_r)} \tag{1}$$

$$h_{Nu} = 1.32\,\mathrm{Re}_{LS}^{-1/3}\left[\frac{\rho_l(\rho_l-\rho_g)gk_l^{3}}{\mu_l^{2}}\right]^{1/3} \tag{2}$$

Eq. (1) is the same as that in the Shah [1] correlation except that it did not have the viscosity ratio factor. Eq. (2) is the Nusselt equation for laminar film condensation in vertical tubes; the constant has been increased by 20% as recommended by McAdams [5] on the basis of comparison with test data. This equation can also be expressed in terms of heat flux or temperature difference instead of Reynolds number. This form has been preferred as it is more convenient for this correlation and often it is also more convenient for design calculations. These equations are used according to the heat transfer regime as below:

In Regime I,

$$h_{TP} = h_I \tag{3}$$

In Regime II,

$$h_{TP} = h_I + h_{Nu} \tag{4}$$

In Regime III:

$$h_{TP} = h_{Nu} \tag{5}$$

h_{LS} in Eq. (1) is the heat transfer coefficient of the liquid phase flowing alone in the tube. It is calculated by the following equation:

$$h_{LS} = 0.023\,\mathrm{Re}_{LS}^{0.8}\,\mathrm{Pr}_l^{0.4}\,k_l / D \tag{6}$$

Z is the correlating parameter introduced by Shah [1] defined as:

$$Z = (1/x-1)^{0.8}\,p_r^{0.4} \tag{7}$$

2.2 Heat Transfer Regimes for Horizontal Tubes

The boundaries between were determined by data analysis described in Shah [2, 3]. Regime I occurs when:

$$J_g \geq 0.98(Z + 0.263)^{-0.62} \tag{8}$$

Regime III occurs when:

$$J_g \leq 0.95(1.254 + 2.27Z^{1.249})^{-1} \tag{9}$$

If neither of the above conditions are satisfied, it is Regime II.

J_g is the dimensionless vapor velocity defined as:

$$J_g = \frac{xG}{\left(gD\rho_g(\rho_l - \rho_g)\right)^{0.5}} \tag{10}$$

3. DEVELOPMENT OF THE FLOW PATTERN BASED CORRELATION

A number of flow pattern maps/correlations have been proposed specifically for condensation inside horizontal tubes, for example those by Breber et al. [6], Tandon et al. [7], and El Hajal et al. [8]. The El Hajal et al. map has been validated by using it in comparing the flow pattern based heat transfer correlation of Thome et al. [9] with a condensation heat transfer database that included many refrigerants and hydrocarbons over a very wide range of parameters. It was therefore the first choice. This correlation has five flow patterns, namely stratified, stratified wavy, intermittent, annular, and mist. Flow patterns predicted by this correlation were compared with the heat transfer regimes predicted by the Shah correlation as well as the deviations of the heat transfer coefficients predicted by it. For fluids other than water, it was found that for the vast majority of data:

- Heat transfer Regime I corresponded to the intermittent, annular, and mist flow patterns.
- Heat transfer Regime II corresponded to stratified-wavy flow pattern.
- Heat transfer Regime III corresponded to stratified flow pattern.

For the data of Varma [10] for water, the El Hajal et al. map predicted stratified flow pattern which according to the results with the other fluids will place it in Regime III and thus Eq. (5) should apply. However, the data showed agreement with Eq. (4) which corresponds to Regime II for which the data for other fluids indicate the stratified-wavy flow pattern. The El Hajal et al. map had not been compared to water data. Further, its recommended range of tube diameter is < 21.4 mm while the Varma data are for D = 49 mm, and the minimum recommended reduced pressure is 0.02 while the Varma data are at a reduced pressure of 0.0023. In view of these limitations, it was felt that the El Hajal map's predictions may be incorrect for these data. The Baker [11] map is known to work well with air-water mixtures near atmospheric pressures as well as with many other gas-liquid mixtures and it was based on data for pipes of diameters from 25 to 100 mm. While it was based on adiabatic data, it has also been known to work fairly well for non-adiabatic situations. For example, Shah [12] found it to be in fair agreement with his visual observation on an ammonia evaporator with 25.4 mm diameter tube. It was therefore felt that it may be applicable to the Varma data. The Baker map predicted stratified-wavy flow pattern and use of Eq. (4) resulted in excellent agreement with the Varma data as seen in Fig. 1.

The Breber et al. map was verified with data that included water but this map does not distinguish between stratified and stratified-wavy regimes and hence is not useful for the present correlation. The Tandon et al. [7] map was verified only with refrigerant data. A possible choice for water at higher pressures may be the map of Taitel and Dukler [13] as it was derived analytically. However, that analytical derivation was for adiabatic condition.

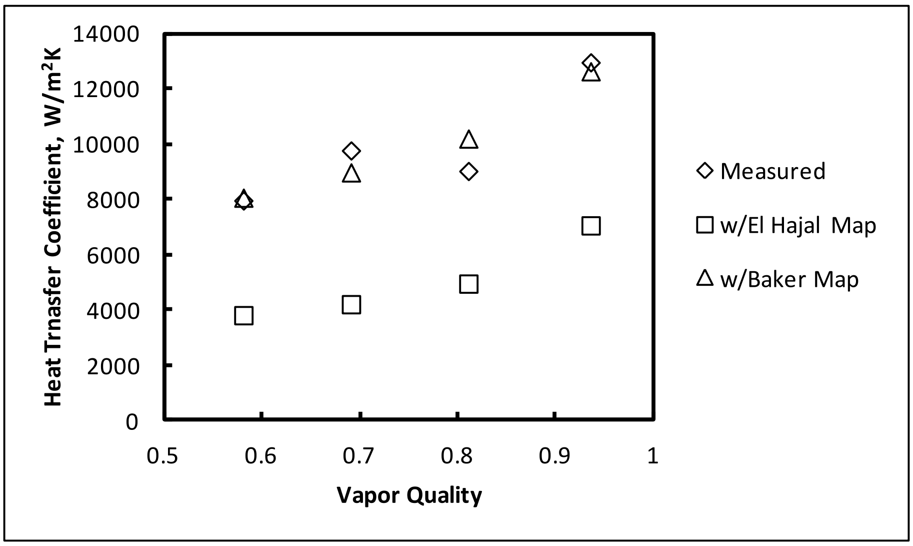

Fig. 1 Predictions of the present correlation using the flow pattern maps of El Hajal et al. and Baker. Data of Varma [10] for water. T_{SAT} = 82 °C, p_r = 0.0023, $\dot{m}$ = 12.6 kg/m^{2}s.

4. NEW FLOW PATTERN BASED CORRELATION

Based on the results of the above described data analysis, the following flow pattern based correlation is proposed:

If flow pattern is intermittent, annular, or mist:

$$h_{TP} = h_I \tag{11}$$

If flow pattern is stratified-wavy:

$$h_{TP} = h_I + h_{Nu} \tag{12}$$

If flow pattern is stratified:

$$h_{TP} = h_{Nu} \tag{13}$$

To determine flow patterns, it is recommended to use the Baker map for low pressure water and the El Hajal et al. map for other fluids. Applicability of other flow pattern maps is unknown.

5. COMPARISON WITH TEST DATA

5.1 Data Search and Collection

A wide ranging database was available from the author's earlier researches, Shah [2, 3]. Recent literature was searched to obtain data for wider range of parameters and for fluids not included in that database. This resulted in procurement of data for butane, R-236ea, R-1234yf, and R-1234ze. The new database thus contains 25 fluids. The complete range of data analyzed is listed in Tables 1 and 2. Data for different fluids or of different diameters were considered separate data sets even if they are from the same source. For refrigerants, only oil-free data was considered as oil can have profound effect on heat transfer. Further, data for mixtures with glide more than 1 degree C were not included as heat transfer of mixtures with large glide is reduced due to mass transfer effects.

Table 1 Complete range of parameters in the data analyzed.

Fluids	Water, R-11, R-12, R-22, R-32, R-113, R-123, R-125, R-134a, R-142b,R-236ea, R-404A, R-410A, R-502, R-507, R1234ze, R-1234yf, benzene, butane, isobutane, propylene, propane, benzene, DME, CO_2
Tube dia., mm	2 to 49
Reduced pressure	0.002 to 0.946
$\dot{m}$, kg/m^{2}s	13 to 820
Re_{LT}	1012 to 84827
Re_{GT}	15892 to 599510
x	0.01 to 0.99
Number of data points	1528
Number of data sources	38
Number of data sets	88

Data for tubes of diameters smaller than 2 mm were excluded from consideration as these are generally regarded as mini/micro channels and their heat transfer behavior is considered to be different from that of larger tubes.

5.2 Correlations Tested

To put the performance of the new correlation into perspective, it is desirable that other leading correlations be also tested along with it. Only a few correlations are available which have been verified with data covering the entire range from very low flow rates to very high flow rates. Perhaps the most verified among these is that of Cavallini et al. [14]. This correlation has two heat transfer regimes called the heat flux independent and the heat flux dependent regimes and there are different formulas for the two regimes. To analyze the data in the heat flux dependent regime with this correlation, heat flux must be known. Most of the data sets analyzed do not report heat flux. Hence only the data in their heat flux independent regime can be compared to the Cavallini et al. correlation. Similar is the situation with the other correlations which have been demonstrated applicable to extreme range of data such as that of Dobson and Chato [15] and Thome et al. [9].

Many other correlations have been proposed which have had considerable verification and their authors have not given any limits for their applicability. Among such correlations are those Akers et al. [16], Ananiev et al. [17], and Moser et al. [18]. These correlations and the correlation of Shah [2, 3] and the new flow pattern based correlation were compared to the entire database.

5.3 Calculation Method

The entire database was compared to all correlations except the Cavallini et al. correlation which was compared only to those data which were in its heat flux independent regime. A run was also made in which all correlations were compared only with those data which were in heat flux independent regime of Cavallini et al. Flow patterns were determined using the Baker map for water and the El Hajal et al. map for all other fluids. Fluid properties were calculated with REFPROP 9.1 [19]. Single phase heat transfer coefficient for the present and Shah correlations was calculated by Eq. (6) for all data except those of Son & Lee [20] for which the following equation was used:

$$h_{LS} = 0.034\,\mathrm{Re}_{LS}^{0.8}\,\mathrm{Pr}_l^{0.3}\,k_l / D \qquad (14)$$

The reason is that these authors' single-phase measurements were higher than Eq. (6) and they fitted Eq. (14) to their data.

The results of calculations are given in Tables 2 and 3.

Table 2 Salient features of data for horizontal tubes and results of comparison with the Shah Correlation [3] and present correlation using flow patterns as criteria.

Source	Dia., mm	Fluid	p_r	$\dot{m}$ Kg/m^{2}s	x	Re_{LT}	Re_{GT}	No. of Data	Deviation, Percent Mean Absolute Average	
									Shah [3]	Present
Wilson et al. [26]	3.72^{**}	R-410A	0.435	75 400	0.80 0.10	2698 14390	19322 103052	12	10.7 7.8	13.7 10.7
		R-134a	0.218	75 400	0.79 0.10	1619 8635	23010 122718	13	14.7 -0.1	17.0 2.2
Zilly [27]	6.1	CO2	0.227 0.309	200 400	0.80 0.10	8046 18973	95529 191058	16	28.7 28.7	28.7 28.7
		R-22	0.049	400	0.78 0.20	9031 12575	206932 231699	7	15.1 15.1	15.1 15.1
Shao et al. [28]	9.4	R-134a	0.249	100 400	0.80 0.10	5811 23245	76018 304071	20	6.4 -3.0	9.5 -2.8
Iqbal & Bansal [29]	6.52	CO2	0.309 0.470	50 200	0.98 0.02	2535 13085	24216 96862	83	27.6 5.1	24.2 -5.7
Kondou & Hrnjak [30]	6.1	CO2	0.810 0.946	100 200	0.98 0.10	9687 19374	32472 64945	31	13.5 -9.1	13.6 -12.1
Afroz & Miyara [25]	4.35	DME	0.127	200 500	0.97 0.02	7081 17703	91698 229244	29	12.5 -11.4	11.8 -10.5
Wen, Ho, & Hsieh [31]	2.46	Butane (R-600)	0.099	205 510	0.84 0.12	3661 9107	64805 161202	18	15.1 -14.4	15.1 -14.4
		R-134a	0.249	205 510	0.84 0.12	3118 7556	40783 101459	18	9.9 2.6	11.9 4.6
		Propane	0.321	205 510	0.80 0.13	6077 15119	56760 141207	18	10.8 -8.5	10.8 -8.5
Dalkilic & Agra [32]	4.0	Isobutane	0.127	57 92	0.90 0.05	1671 2698	29362 47392	17	7.9 -6.3	17.9 17.9
Son & Lee [33]	5.35	R-134a	0.249	400	0.88 0.08	13230	173062	5	12.0 11.9	12.0 11.9
		R-22	0.306	300	0.88 0.12	11554	120231	6	4.0 0.8	4.3 3.4
	3.36	R-134a	0.249	200 400	0.90 0.10	4154 8309	54345 108689	15	8.4 -5.3	9.3 -1.0
		R-22	0.306	200 400	0.88 0.09	7256 9675	75510 100679	12	9.6 -1.2	9.6 -1.2
Lee & Son [34]	5.8	Propane	0.321	49 170	0.85 0.05	3443 11882	32248 110976	13	19.3 -19.3	24.4 -24.3
	6.54	Propane	0.321	56 133	0.85 0.06	4445 10482	41515 97900	12	9.1 1.2	13.9 -1.2
	7.73	Propane	0.321	62 100	0.83 0.05	5813 9336	54289 87002	12	16.4 1.4	24.5 7.3
	10.07	Propane	0.321	47	0.80 0.05	5704	53270	9	20.1 20.1	28.5 6.7
	5.8	Isobutane	0.146	49 170	085 0.05	2211 7609	36231 124681	13	25.0 -25.0	22.2 -20.3
	6.54	Iso-butane	0.146	52 152	0.85 0.05	2609 7671	42756 125703	12	17.4 -17.4	9.8 -8.7
	7.73	Iso-butane	0.146	51	0.86 0.06	3054	50046	10	16.7 3.7	16.8 6.6
	10.07	Isobutane	0.146	49 115	0.87 0.05	3889 8936	62904 146437	12	12.0 10.0	19.7 1.5

	5.8	R-134a	0.146	42	0.86 0.06	1510	19747	10	42.0 -42.0	42.0 -42.0
	6.54	R-134a	0.249	74 160	0.85 0.05	2106 6449	39138 84622	12	15.7 12.2	28.0 -0.3
	7.73	R-134a	0.249	52 165	0.80 0.05	2509 7885	32819 103146	11	29.0 16.6	26.3 11.7
	10.07	R-134a	0.249	52 112	0.84 0.05	3268 6972	42754 91281	10	20.7 -8.6	38.8 35.2
	5.8	R-22	0.306	50 152	0.85 0.06	2100 6346	21854 66041	11	14.6 12.9	26.6 -0.8
	6.54	R-22	0.306	56 210	0.85 0.06	2636 9886	27435 102882	12	42.8 42.7	34.5 28.6
	7.73	R-22	0.306	52 190	0.89 0.05	2921 10572	30400 110021	12	14.8 -14.8	31.9 14.2
	10.07	R-22	0.306	50 150	0.85 0.06	3632 10872	37793 113152	11	19.1 7.1	37.8 37.0
Hossain et al.[35]	0.306	R-32	0.427	300	0.90 0.08	13713	94445	7	24.6 -24.6	24.6 -24.6
	0.306	R-1234ze	0.210	191 375	0.96 0.10	4966 9750	64295 126233	29	27.0 -27.0	24.4 -24.4
Varma [10]	49.0	water	0.002	12.6	0.95 0.58	1808	54415	4	31.1 -24.6	6.2 0.9
Tang et al. [36]	8.8	R-134a	0.25	260 820	0.81 0.09	11573 36500	181808 573395	24	12.2 7.4	13.3 9.7
		R-410A	0.495	320 720	0.81 0.09	29822 73624	191929 473824	16	11.6 8.8	11.6 8.8
		R-22	0.308	270 790	0.91 0.09	11591 33914	165849 485263	28	5.7 -0.4	5.3 0.1
Bae et al. [37]	12.5	R-22	0.235 0.325	210 634	0.90 0.09	12579 38430	193612 569436	27	16.4 4.0	16.0 4.4
Bae et al. [38]		R-12	0.197 0.211	344 634	0.91 0.03	17721 32932	327303 599510	29	14.2 -7.9	13.8 -7.5
Powell [39]	12.8	R-11	0.035	258	0.24	8689	283628	1	2.0 2.0	2.0 2.0
Lambrecht et al. [40]	8.1	R-22	0.308	300 800	0.5	11854 31611	169619 452317	6	31.1 31.1	31.1 31.1
Jung et al. [41]	8.0	R-32	0.428	100 300		8430 25290	55402 166205	17	13.2 1.1	12.6 2.2
		R-12	0.127	100 300	0.93 0.10	4253 12759	63431 190294	14	12.3 1.2	12.1 2.4
		R-125	0.559	100 300	0.90 0.15	7306 21918	42781 128342	13	8.3 -8.3	8.3 -8.3
		R-123	0.042	100 300	0.90 0.15	2675 8024	70573 211720	15	12.1 6.4	15.1 12.3
		R-142b	0.128	100 300	0.92 0.2	4073 12220	72727 218182	17	9.4 -1.4	9.7 6.7
Infante-Ferreira et al. [42]	8.0	R-404A	0.491	250 600	0.88 0.14	19605 47053	150036 360086	16	13.5 -10.3	13.5 -10.3
Park et al. [43]	8.8	Propylene	0.354	100 300	0.91 0.10	10784 32355	90072 270215	28	32.5 32.5	37.9 37.9
		Isobutane	0.146	100 300	0.89 0.10	6882 20646	110913 332739	21	10.8 9.6	16.4 15.9
		Propane	0.322	100 300	0.88 0.1	10643 31930	93739 281217	27	18.8 18.8	22.2 22.2

		R-22	0.308	100 300	0.90 0.10	4293 12879	61426 184277	27	7.6 1.6	10.8 2.1
Jiang & Garimella [44]	9.4	R-404A	0.805 0.907	200 500	0.88 0.20	28415 84827	96507 275264	40	8.7 -4.1	9.2 -4.5
Lee et al. [45]	10.9	Propylene	0.354	150	0.88 0.01	20074	167656	10	17.2 -17.2	15.3 -14.1
		Isobutane	0.146	150	0.88 0.01	12810	206450	10	14.1 -14.1	11.6 -11.6
		Propane	0.32	150	0.90 0.01	19811	174483	10	13.5 -13.5	12.5 -12.1
		R-22	0.308	150	0.91 0.01	7991	114336	10	18.0 -18.0	22.6 -22.6
Jung et al. [46]	8.8	R-134a	0.250	100 300	0.98 0.05	4461 13384	70085 210255	27	10.6 -7.7	9.2 -4.5
		R-410A	0.495	100 300	0.94 0.03	9341 28022	60114 180342	27	9.3 -9.3	8.1 -6.0
		R-22	0.308	100 300	0.96 0.08	4303 12908	61565 184696	26	15.5 -12.7	13.6 -8.7
Eckels & Tesene [47]	8.0	R-507	0.505	251 599	0.80 0.10	19844 47455	147434 352565	23	14.3 5.4	15.2 6.3
		R-502	0.411	600	0.75 0.13	38989	342547	8	21.4 21.4	21.4 21.4
Eckels et al. [48]	8.0	R-12	0.233	134 374	0.47* 0.43	4560 12726	79488 221742	5	12.8 12.1	16.1 16.1
	8.0	R-134a	0.245	87 368	0.50*	3511 14851	55531 234889	7	8.6 8.5	8.6 8.5
	11.0	R-134a	0.249	84 280	0.51* 0.47	5712 19041	74724 249080	5	4. 1.5	7.6 5.3
Nan & Infante-Fereira [49]	8.8	Propane	0.286	150 250	0.59 0.10	15132 25220	144510 240849	6	9.6 -8.1	11.9 -4.8
Dobson & Chato [15]	7.0	R-410A	0.438	75 650	0.90 0.09	5172 44827	37258 322900	18	11.7 -10.2	13.0 -11.5
		R-22	0.272	75 650	0.90 0.16	2558 22171	37768 327323	18	11.0 -8.5	13.2 -10.6
		R-134a	0.219	75 650	0.9 0.09	2622 22725	42961 372331	19	12.5 -11.5	12.5 -11.5
Wijaya & Spatz [50]	7.7	R-22	0.272 0.405	481 495	0.80 0.21	18138 18587	245041 274408	18	7.7 -4.6	7.7 -4.6
		R-410A	0.573 0.652	481	0.79 0.25	43405 47297	231147 242447	13	14.0 -14.0	14.0 -14.0
Shao & Granyrd [51]	6.0	R-134a	0.189 0.191	183 269	0.92 0.10	6030 8797	92064 135629	10	15.3 10.1	20.4 17.8
Cavallini et al. [52]	8.0	R-134a	0.250	65 750	0.80 0.28	2630 30349	41320 476769	37	8.3 -2.0	9.3 -2.0
		R-410A	0.495	750	0.75 0.20	63542	408939	7	20.9 20.9	20.9 20.9
		R-125	0.559	100 750	0.80 0.23	7306 54795	42781 320856	23	10.7 0.2	10.6 1.1
		R-32	0.429	100 600	0.80 0.24	8430 50580	55402 332410	24	11.1 6.8	10.4 8.6
		R-22	0.308	100 750	0.85 0.20	3903 29270	55842 418812	31	9.8 -3.4	8.7 -2.2
		R236ea	0.098	100 650	0.840 .20	2554 15323	70555 423333	28	12.3 -12.1	5.4 -4.2

Altman et al. [53]	8.7	R-22	0.268 0.441	300 618	0.92 0.23	12725 26166	184687 379779	15	8.4 -7.4	6.4 -5.3
Azer et al. [54]	12.7	R-12	0.219 0.296	210 446	0.99 0.35	115362 4690	195269 411239	39	29.2 22.3	31.4 26.7
Chitti & Anand [55]	8.0	R-22	0.272 0.356	149 437	0.75 0.20	5793 17124	84608 236958	12	13.4 -12.2	10.3 -9.1
Berrada et al. [56]	8.9	R-134a	0.278	170 214	0.79 0.25	7765 9774	117866 148373	14	23.7 23.7	32.4 32.4
		R-22	0.312	114 214	0.80 0.12	4963 9317	70769 132846	12	11.9 5.8	14.9 9.2
Jassim et al. [57]	8.9	R-134a	0.164	100 300	0.94 0.04	75125 12663	75125 225375	25	20.0 -20.0	18.0 -18.0
Akers et al. [16]	15.7	R-12	0.662	78 418	0.94* 0.63	6786 36356	67301 360575	33	24.4 20.9	20.4 20.4
		Propane	0.657	13 162	0.83* 0.51	3899 48103	17473 215578	15	16.9 6.9	18.2 12.8
Tepe & Mueller [58]	18.5	Benzene	0.021	54 82	0.57* 0.51	3264 4991	106965 163546	6	10.2 -2.8	5.7 5.7
Yan and Lin [59]	2.0	R-134a	0.16 0.32	100 200.	0.94 0.10	1012 2076	15892 33764	31	14.3 -3.2	19.3 19.0
Wang et al. [60]	4.0	R-1234yf	0.12 0.92	101 401	0.300 0.384	3163 14023	32141 13916	40	31.3 -31.3	21.5 -21.4
All data	2.0 49.0		0.002 0.946	13 820	0.98 0.01	1012 84827	15892 599510	1568	16.1 -0.9	16.7 1.2

*Mean quality for the tube length

**Hydraulic equivalent diameter of flattened tube

Table 3 Results of data analysis for all tested correlations

Correlation	Deviation, Percent Mean Absolute Average	
	Heat Flux Independent Regime* (675 data points)	All Data (1568 data points)
Ananiev et al. [17]	19.5 -16.2	27.0 -24.8
Moser et al. [18]	19.4 8.9	22.8 3.4
Cavallini et al. [14]	15.0 -8.5	Not applied to heat flux dependent regime data
Akers et al. [16]	37.8 -37.6	43.3 -43.2
Shah [3]	14.1 0.4	16.1 -0.9
Present	14.2 2.4	16.7 1.2

*Regime according to Cavallini et al. (2006) correlation.

Mean absolute deviation is defined as:

$$\delta_m = \frac{1}{N}\sum_{1}^{N} ABS\left((h_{predicted} - h_{measured}) / h_{measured}\right) \tag{15}$$

Average deviation is defined as:

$$\delta_{avg} = \frac{1}{N}\sum_{1}^{N}\left((h_{predicted} - h_{measured}) / h_{measured}\right) \tag{16}$$

6. DISCUSSION OF RESULTS

Detailed results of data analysis for the present correlation and the Shah [3] correlation are listed in Table 2. The present correlation has a mean absolute deviation of 16.7 % while the Shah correlation has a mean absolute deviation of 16.1 %. Of the 89 data sets analyzed, 21 show better agreement with the present correlation while 25 show better agreement with the Shah correlation, the mean deviations of the remaining 43 being unchanged. If more data sets are analyzed, the balance may well change. Thus the accuracy of the present flow pattern based correlation is perhaps a little less than that of the Shah correlation which uses heat transfer regimes without any physical meaning. This small loss of accuracy may be acceptable in exchange for the physical clarity.

Table 3 lists the results for all correlations and Figs. 2 to 6 show some of the results in graphical form. Considering all data, it is seen that all correlations have considerably larger deviations than the present and the Shah correlations. The next best is the correlation of Moser et al. with 22.8 % deviation. Considering only those data which are in the heat flux independent regime of Cavallini et al. [14] correlation, the deviations of the present and the Shah correlation are almost equal at 14.2 and 14.1 % respectively. The performance of the Cavallini et al. correlation is also good with a mean deviation of 15.0 %. Notably poor is the performance of the Akers et al. [16] correlation with a mean deviation of 43.3 % and average deviation of -43.2 %. The other correlations give fairly good performance. Figs. 2 to 6 show comparison of data with the present and other correlations.

As seen in Table 2, agreement of the present correlation with near azeotropic mixtures R-410A and R-404A is good. Heat transfer of fluids with large glides is considerably diminished due to effects of sensible heat transfer and mass transfer as the mixture composition and the temperature of components changes along the tube. Shah et al. [21] analyzed an extensive database of mixtures with glides upto 35 ^{O}C. They found that the Shah [2] correlation gave good agreement when used with the correction factors given by Bell and Ghaly [22] and McNaught [23]. Good agreement is also expected with the present correlation in the same way as the El Hajal et al. map was also verified with data for mixtures.

Data for tubes with diameters smaller than 2 mm were not included in the present data analysis. Shah [24] had compared a large database for mini-channels with his correlation [2] and found that many of those data sets were in good agreement while others showed large deviations. That correlation does not consider flow patterns. It will be interesting to compare those data with the present correlation using flow pattern maps applicable to mini-channels. It will also be interesting to compare this correlation to data for non-circular channels using flow pattern maps applicable to them.

In evaluating the results of this data analysis, knowing the accuracy of the test data could be helpful in understanding the deviations from the correlation. Most authors have given only the accuracy of the test instruments used and it is always 2 % or better. A few have done the error propagation analysis to determine the uncertainty in heat transfer coefficients; the reported uncertainties are in the range of 2.3 to 9.5 percent except that Lambrecht et al. [40] estimate it as upto 14.7 %; their data show mean deviation of 31 % which suggests that it may be due to data inaccuracy. Some researchers tested several fluids on the same test rig, for example Park et al. [43]. The deviations of their data for two fluids are low but are high for propylene. Data of Lee et al. [45] for propylene at comparable conditions show good agreement. Thus researchers' own estimates of uncertainty of data are not always helpful. Using data from many sources is probably the best way to identify doubtful data.

The correlation is recommended in the verified range of p_r. Therefore for water it is recommended only at p_r near 0.002 as the data analyzed are only at this pressure and because properties of water differ significantly from other fluids. For other fluids, the verified range of p_r is 0.02 to 0.95. Further, it is recommended only in the verified range of Re_{LT} (1,012 to 84,827) and Re_{GT} (15,892 to 599,510).

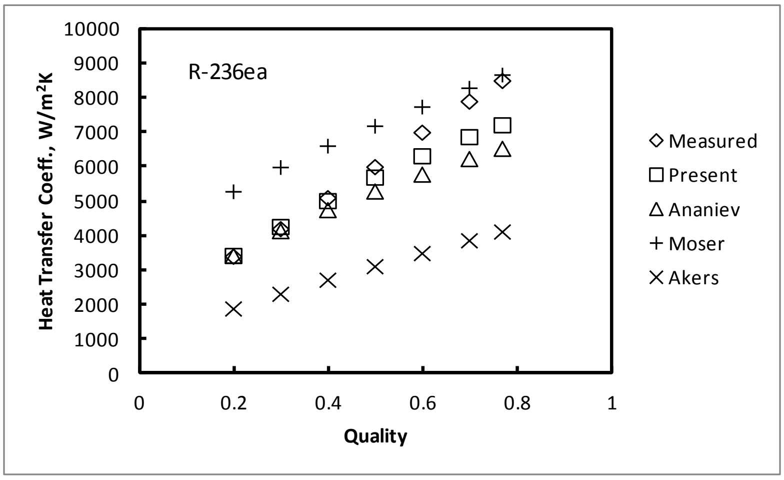

Fig. 2 Comparison of test data of Cavallini et al. [52] with various correlations. T_{SAT} = 40 °C, ṁ = 600 kg/m^{2}s.

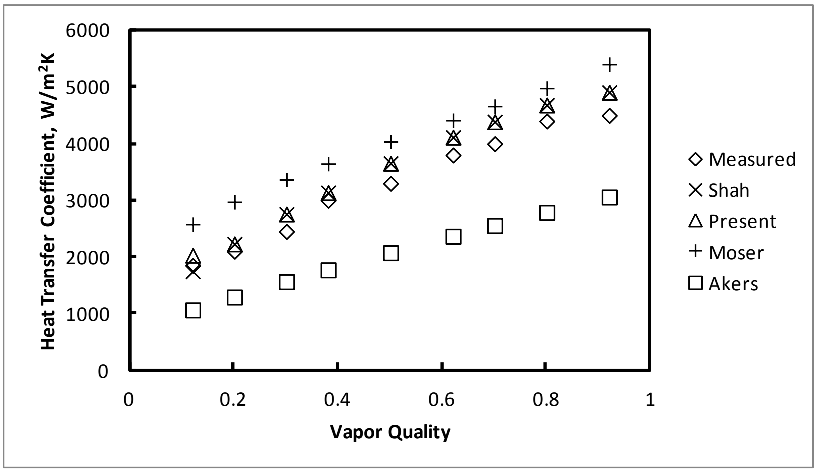

Fig. 3 Comparison of the data of Jung et al. [41] for R-142b with various correlations. T_{SAT} = 40 °C, ṁ = 300 kg/m^{2}s.

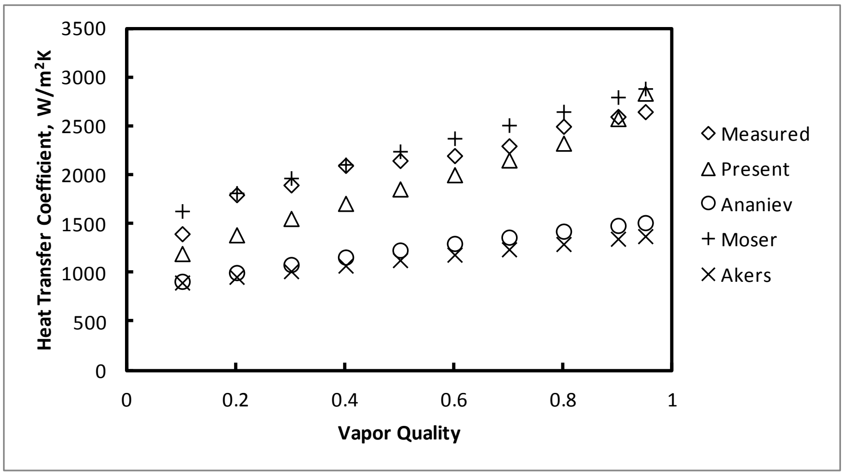

Fig. 4 Comparison of various correlations with the data of Kondou & Hrnjak [30] for CO_2, ṁ = 100 kg/m^{2}s, p_r = 0.81.

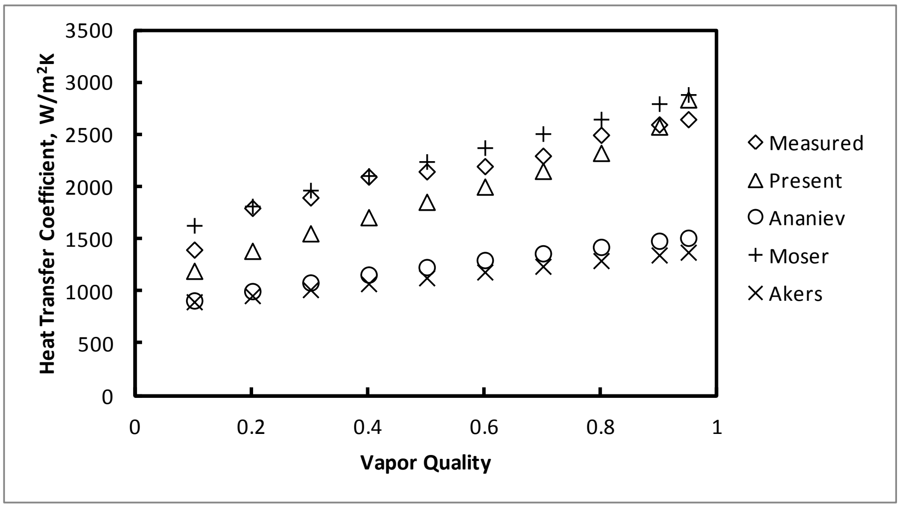

Fig. 5 Comparison of various correlations with the data of Lee & Son [34] for propane. D = 6.54 mm, T_{SAT} = 40 °C, ṁ= 56 kg/m^{2}s.

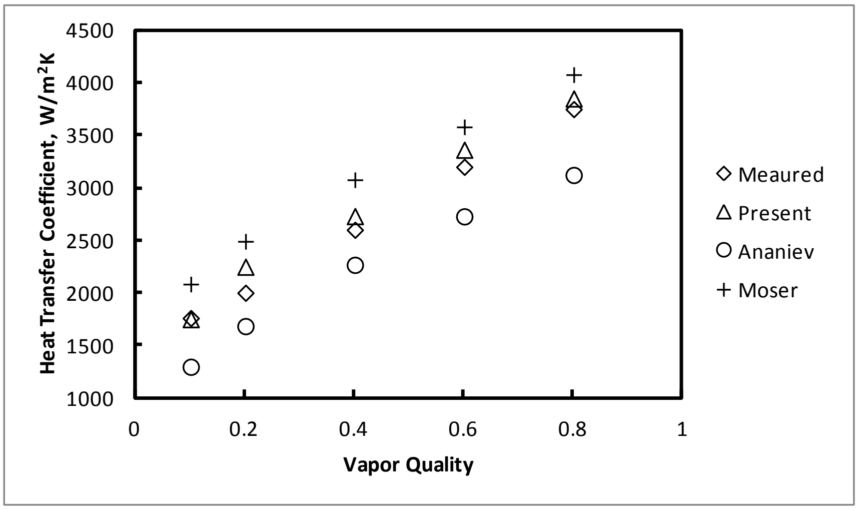

Fig. 6 Comparison of various correlations with the data of Shao et al. [28] for R-134a. ṁ = 300 kg/m^{2}s. T_{SAT} = 40 °C.

7. CONCLUSION

1. A flow pattern based correlation for heat transfer during condensation inside plain tubes has been presented which shows good agreement with data for 25 fluids over an extreme range of parameters including tube diameters from 2 to 49 mm, reduced pressures from 0.002 to 0.94, and mass flow rates from 13 to 820 kg/m^{2}s.

2. A number of other general correlations were also compared to the same data base. The accuracy of the new flow pattern based is slightly lower than that of the Shah [3] correlation but it is more clearly related to the physical phenomena involved. Its accuracy compares favorably with other correlations.

3. For water, there were only a few data points at low pressure and all from one source. While use of the Baker map resulted in good agreement with data, analysis of water data at higher pressures and more varied conditions is needed.

4. Based on the results of data analysis in Table 2, the present correlation is recommended for pure fluids other than water in the following range: p_r = 0.02 to 0.095, Re_{LT} = 1,012 to 84,827 , Re_{GT} = 15,800 to 599,510 . For water, application should be further restricted to p_r near 0.002 till verification with higher and lower pressure data is done.

5. The present correlation is likely to be applicable to mixtures when used with the correction factors of Bell and Ghaly [22] and McNaught [23].

NOMENCLATURE

D	Inside diameter of tube	(m)
$\dot{m}$	Total mass flux (liquid + vapor)	(kg/m^2s)
g	Acceleration due to gravity	(m/s^2)
h	Heat transfer coefficient	(W/m^2K)
h_I	Heat transfer coefficient given by Eq. (1)	(W/m^2K)
h_{LS}	Heat transfer coefficient assuming liquid phase flowing alone in the tube	(W/m^2K)
h_{LT}	Heat transfer coefficient assuming all mass flowing as liquid	(W/m^2K)
h_{Nu}	Heat transfer coefficient given by Eq. (2), the Nusselt relation	(W/m^2K)
h_{TP}	Two-phase heat transfer coefficient	(W/m^2K)
J_g	Dimensionless vapor velocity defined by Eq. (10)	(-)
N	Number of data points	(-)
p_r	Reduced pressure	(-)
Re_{GT}	Reynolds number assuming total mass flowing as vapor, = $\dot{m}D/\mu_g$	(-)
Re_{LS}	Reynolds number assuming liquid phase flowing alone, = $\dot{m}(1-x)D/\mu_l$	(-)
Re_{LT}	Reynolds number assuming total mass flowing as liquid, = $\dot{m}D/\mu_l$	(-)
T_{SAT}	Saturation temperature	(C)
x	Vapor quality	(-)
Z	Shah’s correlating parameter, defined by Eq. (7)	(-)

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