Proceedings of HT2005
2005 ASME Summer Heat Transfer Conference
July 17-22, 2005, San Francisco, California, USA

HT2005-72025

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

M. Mohammed Shah
Engineering Research & Consultation
8I Talcott Forest Road
Farmington, CT 06032
mmshahpe@hotmail.com
860-869-1328

ABSTRACT

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 (1986), Liu & Winterton (1991), Kandlikar (1990), and Steiner and Taborek (1992). The database used to evaluate these correlations included 29 fluids: water, refrigerants, cryogens, organic and inorganic chemicals. The data cover reduced pressures from 0.005 to 0.783, mass flux from 28 to 11071 kg/m2s, vapor quality from 0 to 0.95, and boiling number from 0.000026 to 0.00742. The correlations of Shah and Gungor & Winterton gave the best agreement with data with a mean deviation of about 17.5%, only a couple of data sets showing large deviations. The paper presents and discusses the results of this study. Included are tables giving the range of dimensional and non-dimensional parameters covered by each experimental study.

Keywords: boiling, heat transfer, evaporation, tubes, correlations

.

INTRODUCTION

Hundreds of correlations have been proposed for the calculation of heat transfer during boiling of saturated liquids inside tubes and annuli. Most of them have been compared to only a limited amount of data. However, some of them have been shown to agree with a wide range of data with many fluids and are therefore considered as general correlations. It is desirable to know their comparative accuracy and limitations so that the most reliable ones 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 29 fluids. Included are tables giving the range of dimensional and non-dimensional parameters covered by each experimental study.

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 & Taborek correlation
Fr_L	Froude number, $=G^2/\left(\rho_L{}^2 gD\right)$
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

Greek

μ	Viscosity of liquid
$_L$	Density of liquid
$_g$	Density of vapor

AVAILABLE CORRELATIONS

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

The first general correlation was published by Chen [1]. It was based entirely on data for vertical channels. The correlation is:

$$h_{TP} = F_{chen} h_{LO} + S h_{pb} \quad (1)$$

It showed excellent agreement with the data analyzed by Chen. However, many later researchers compared it to large data bases and reported that its agreement was not satisfactory either with horizontal or vertical channels. Examples of such studies are Kandlikar [2], Gungor and Winterton [3], Liu and Winterton [4], Gungor and Winterton [5], and Steiner & Taborek [6].

Hundreds of correlations of the form of Eq. (1) have been proposed, most of them based only on one data set.

The present author, Shah [7, 8], presented a correlation whose functional form is:

$$h_{TP} / h_{LO} = f(Co, Bo, Fr_L) \quad (2)$$

The Froude number Fr_L accounts for stratification in horizontal channels; it is not used for vertical channels. The correlation is given in the Appendix. This was the first correlation applicable to both horizontal and vertical tubes. It has been tested with large databases by many researchers [2, 3, 4, 5] with mostly satisfactory results.

Kandlikar [2] has given 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 have been given only for 10 fluids. Hence it is applicable to only those 10 fluids.

Gungor and Winterton [3] presented a correlation similar to Eq. (1) but incorporated the Froude number for horizontal channels in the same way as in the Shah correlation. Liu and Winterton [4] also presented a similar correlation and showed it to be more accurate than the Gungor and Winterton correlation [3].

Gungor and Winterton [5] presented a correlation similar to the Shah correlation and showed it to agree with a wide range of data.

Steiner and Taborek (6) have given a correlation which is based on a large and varied database for vertical channels. It has the form:

$$h_{TP} = \left((F_{st} h_{LT})^3 + h_{pb}{}^3 \right)^{1/3} \quad (3)$$

CORRELATIONS TESTED

The following correlations were tested:

Chen [1] with pool boiling component calculated by the Cooper correlation [9]; Steiner and Taborek [6]; Shah [8]; Kandlikar [2]; Liu and Winterton [4]; Gungor & Winterton [5].

The reason for using the Cooper pool boiling correlation with the Chen correlation is that the Cooper correlation has been verified with an extremely wide range of data while the pool boiling correlation originally used by Chen has had very little verification. It was felt that this change will improve the accuracy of the Chen correlation. Henceforth, the Chen correlation with this change is called the Chen-Cooper correlation. Note that the Cooper correlation has been used without the factor 1.7 for copper tubes which Cooper stated to be a possibility and assuming tube roughness to be 1 μm.

The Gungor & Winterton correlation [3] was not tested as Liu & Winterton (4) has been tested and they showed that their correlation gave better agreement with data.

All of the above correlations require the calculation of single-phase liquid heat transfer coefficient. For use with the Steiner and Taborek correlation, the formula of Pethukov and Krillov [10] was used in accordance with their recommendation. For all other tested correlations, liquid convective heat transfer was calculated by the McAdams equation [12]:

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

Ogata and Sato [17] had compared their non-boiling helium data with Eq.(4) and found that the constant should be changed to 0.015 to fit their data. Therefore in analyzing their data , the constant in Eq. (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 28 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, pentane, nitrogen, argon, neon, hydrogen, nitrogen, and helium. Data for carbon dioxide from several sources were also analyzed but none of them agreed with any of the tested correlations. It was concluded that carbon dioxide 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 have 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 [17] for helium showed strong hysterisis. The mean of the heat transfer coefficients for ascending and descending heat fluxes were 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 [13], fluid properties used were those listed by him. For helium, properties used were from McCarty [14]. Properties of iso-butane, propane, ammonia, R-32, R-502, hydrogen, argon, and Neon were from ASHRAE Handbook [15]. Properties of other fluids (carbon tetrachloride, n-butanol) , were from Beaton and Hewitt [16]

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 for a data point is defined as:

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

The average deviation $_{avg}$ of a data set is defined as:

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

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

$$\delta_{mean} = \Sigma Abs.(\delta) / N \quad (7)$$

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, 2, and 3 that the correlations of Shah [8] and Gungor & Winterton [5] are the most reliable with a man deviation of about 17.5% for all 1859 data points. The Shah correlation is more consistent as only 5 of the 67 data sets have deviation more than 30% while the Gungor & Winterton correlation has 9 data sets exceeding 30% mean devaiation.

The correlations of Shah and Gungor & Winterton show reasonable agreement with almost all data sets. One notable exception is the data of Mohr and Runge [18] 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 [19] gave a correlation of their subcooled data for nitrogen and neon for subcooling starting from 2 degree C. The predictions of this correlation at 1 degree subcooled neon agree satisfactorily with the Shah correlation and are lower than the Shah correlation at 2 degree subcooling.. This suggests that the Mohr and Runge data may be unusually high.

The other notable exception is the data of Steiner and Schlunder [20] for nitrogen; these are much higher than the Shah correlation. However, nitrogen data from three other sources [19, 21, 22] agree well with this correlation. The Steiner & Schlunder data are also much higher than the Gungor-Winterton and Liu-Winterton correlations. Hence these data are apparently unique.

The Liu-Winterton correlation's performance is erratic. While it agrees well with many data sets, it shows large deviations with many data sets, for example the data of Muller for Argon [23]. cyclohexane data of Talty [13], data of Piret and Isbin [24] for water, CCl_4, n-butanol, and iso-propanol.

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

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

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. If the data for these three fluids are deleted, the mean deviation of Kandlikar correlation becomes 16.8% instead of 32.2% if data for these three fluids are included. The apparent reason is that the nucleate boiling multiplying factors for these fluids were determined by Kandlikar from abnormally high data. Those data might have been high because of the surfaces of those test sections having unusually favorable microstructure as discussed later in this paper. The effect of Kandlikar's multipyling factor is highest at zero vapor quality; hence the +436% deviation with the nitrogen data of Pappel and Hendricks which is at zero vapor quality, the multiplying factor for nitrogen being 4.7 (it is 1 for water).

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 [32]. There is no indication that the accuracy of the correlations is affected by the type of material.

Tube Surface Characteristics

It is generally accepted that the intensity of nucleate boiling depends on the shape snd population densities of cavities in the surface. This has been demonstrated by pool boiling tests on surfaces with artificially made cavities. Information on cavity size and cavity population density is not available for any of the test data evaluated here. The fact that almost all data sets are in reasonable agreement with the correlations of Shah and Gungor & Winterton (which do not have any factor for surface microstructure) indicates that the variations in microstructures of commercial tubes are normally small. It may be noted that the most successful general pool boiling correlations (Cooper [9], Stephan and Abdeksalam [62]) do not have any factor for surface microstructure. It is possible that some commercial tubes may have a microstructure very favorable to nucleate boiling. This may be the explanation for the data of Steiner & Schlunder and Mohr and Runge being much higher than predictions of almost all tested correlations.

It should be noted that the designer of heat exchanger has no way of knowing the microstructure of the tubes that will be used in 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 correlations of Shah and Gungor & Winterton.

Type of Fluid

The Shah and Gungor-Winterton correlations show good agreement with 28 of the 29 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 [19] appear to be in agreement with the Shah correlation.

CO_2 data from several sources were analyzed but none of the correlations tested here was found to agree with them. Among such data are those of Bredsen et al [59], Yoon et al. [60] and Knudsen and Jensen [61]. These authors also compared their data with well-known general correlations with poor results. Thome and Hejal [26] compared carbon dioxide data from six sources with their correlation which was based on data for several refrigerants but foumd poor agreement. They concluded that carbon dioxide is a unique fluid and developed a correlation specifically for CO_2.

Thus the correlations of Shah and Gungor & Winterton appear to be suitable for all Newtonian, non-metallic fluids except carbon dioxide

Variation of Heat Transfer With Vapor Quality

For correct design of an evaporator, it is important that a correlation correctly predict variation with quality. All the authors of the correlation tested have shown by comparison with data, in the papers presenting those correlations, that they predict the correct trend. Kandlikar [63] showed that his correlation agrees with the data of Jallouk [64] in vertical tube which show decreasing heat transfer with increasing quality. Shah [8] showed that his correlation predicts decreasing heat transfer with increasing quality at higher Bo and/or higher reduced pressures.

During the present data analysis it was seen that in most cases low mean deviation with a data set was accompanied by correct prediction of the variation of heat transfer with quality.

SUMMARY AND CONCLUSION

1. Six of the best known general correlations were tested with data for 29 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 [8] and Gungor & Winterton [5] gave good agreement with data, mean deviation being about 17.5%. The Shah correlation was somewhat more consistent. The range of data satisfactorily predicted is given in Table 4. The other four correlations had mean deviations from 22 to 46%.
3. The results indicate that the correlations of Shah and Gungor & Winterton can be used with confidence with all Newtonian non-metallic fluids (except CO_2).

REFERENCES

[1] Chen, J. C., 1966, “A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow,”. Ind. Eng. Chem. Process Design and Development, **5**, pp. 322-329

[2] Kandlikar, S. G.,1990, “A General Correlation for Saturated Two-Phase Flow Boiling Heat Transfer Inside Horizontal and Vertical Tubes,” ASME J. Heat Transfer, **112**, pp. 219-228

[3] Gungor, K. E. and Winterton, R. H. S., 1986,”A General Correlation for Fow Boiling in Tubes and Annuli,” Int. J. Heat Mass Transfer, **29**, pp. 351-358.

[4] Liu, Z. and Winterton, R. H. S. 1991, “A General Correlation for Saturated and Subcooled Flow Boiling in Tubes and Annuli Based on a Nucleate Pool Boiling Equation,” Int. J. Heat Mass Transfer , **34**, pp. 2759-2766

[5] Gungor. K. E. and Winterton, R. H. S., 1987, “Simplified General Correlation for Saturated Flow Boiling and Comparisons of Correlations with Data,” Chem. Eng. Res Des., **65**, pp. 148-156.

[6] Steiner, D. and Taborek, J., 1992, “Flow Boiling Heat Transfer in Vertical Tubes Correlated by an Asymptotic Model,” Heat Transfer Engineering **13**: 43-68

[7] Shah, M. M., 1976, “A New Correlation for Heat Transfer During Boiling Flow Through Pipes,” ASHRAE Transactions, **82**, Part 2, pp. 66-86.

[8] Shah, M. M., 1982, “Chart Correlation for Saturated Boiling Heat Transfer : Equations and Further Study,” ASHRAE Trans. **88**, Part 1, pp.185-196.

[9] Cooper, M. G., 1984, “Heat Flow Rates in Saturated Nucleate Pool Boiling – A Wide Ranging Examination Using Reduced Properties,” In “Advances in Heat Transfer,” , Academic Press , New York
Vol. 16, pp. 157-239

[10] Pethukov, B. S. and Kirillov, V. V. 1958, “The Problem of Heat Exchange in the Turbulent Flow of Liquids in Tubes,” Teploenergetica, **4**, pp. 63-68. Quoted in Bhatti and Shah [11]

[11] Bhatti, M. S. and Shah, R. K. 1987, “Turbulent and Transition Flow Convective Heat Transfer in Ducts,” In “Handbook of Single Phase Heat Transfer,” edited by S. Kacak, R. K. Shah, and W. Aung, John Wiley, New York.

[12] McAdams, W. H., 1954, *Heat Transmission*. 3rd Edition, McGraw-Hill, New York.

[13] Talty, R. D. 1953. A Study of Heat Transfer to Organic Liquids in a Natural Circulation Vertical Tube Boiler, PhD Thesis, University of Delaware.

[14] McCarty, R. D., 1972, “Thermophsical Properties of Helium-4 From 2 to 1500 K with Pressures to 1000 Atmospheres” Report NBS-TN-631.

[15] ASHRAE Handbook Fundamentals 1997. ASHRAE, Atlanta

[16] Beaton, C. F. and Hewitt, G. F. (editors), 1989, “Physical Property Data for thr Chemical and Mechanical Engineer,” Hemisphere Publishing Corp., New York.

[17] Ogata, H., and Sato, S. 1974, “Forced Convection Heat Transfer to Boiling Helium in a Tube,” Cryogenics. **14**, pp. 375-380

[18] Mohr, V. and Runge, R., 1977 ,”Forced Convection Boiling of Neon in Horizontal Tubes,” In “Heat Transfer in Boiling,” edited by E. Hahne and U. Grigull, Hemisphere, Washington, pp. 307-344

[19] Pappel, S. S. and Hendricks, R. C. 1978, ”Boiling Incipience and Convective Boiling of Neon and Nitrogen. Advances in Cryogenic Engineering 23: 284- 294

[20] Steiner, D. and Schlunder, E. U. 1977, “Heat Transfer and Pressure Drop for Boiling Nitrogen Flowing in Horizontal Tube. In “Heat Transfer in Boiling,” edited by E. Hahne and U. Grigull, Hemisphere, Washington, pp. 263-306

[21] Klein, G. 1976, “Heat Transfer for Evaporating Nitrogen Streaming in a Horizontal Tube,” *Proc. Sixth Int. Cryogenic Engineering Conference*,,IPC Science & Technology Press, pp. 314- 318.

[22] Klimenko, V. V. and Sudarchikov, A. M., 1983, “Investigation of Forced Flow Boiling of Nitrogen in a Long Vertical Tube,” Cryogenics **23**, pp. 379 – 385.

[23] Muller, H., Bonn, W. and Steiner, D., 1983, “Heat Transfer and Critical Heat Flux at Flow Boiling of Nitrogen and Argon within a Horizontal Tube,” in “Heat Exchangers Theory and Practice,” edited by J. Taborek, G. F. Hewitt, and N. Afgan, Hemisphere, Washington, pp. 230- 250.

[24] Piret, E. L. and Isbin, H. S. 1954, “Natural Circulation Evaporation Two Phase Heat Transfer,” Chem. Eng. Prog. **50**, pp. 305-311.

[25] Adorni, N. et al., 1961, “Results of Wet Steam Cooling Experiments Pressure Drop Heat Transfer and Burnout Measurements in Annular Tubes with Internal and Bilateral Heating,.” C.I.S.E. Report R 31, TID 12459.

[26] Thome, J. R. and Hajal, J. E., 2004, “Flow Boiling Heat Transfer to Carbon Dioxide: General Prediction Method,” Int. J. Refrigeration **27**, pp. 294-301.

[27] Chaddock, J. and Buzzard, G. 1986, “Film Coefficients for In-Tube Evaporation with and without Small Percentages of Mineral Oil,” ASHRAE Trans. **92(1A),** :paper no. 2935, pp. 22-40.

[28].Chaddock, J. B. and Noerager, J. A., 1966, “Evaporation of Refrigerant 12 in Horizontal Tube with Constant Heat Flux,” ASHRAE Trans. **72**, part 1, pp. 99-103.

[29] Chawla, J. M., 1967, “Warmeubergang und Druckabfall in Wagrechten Rohren bei der Stromung von verdampfenden Kaltmitteln,” VDI Forschungsheft: 523-

[30] Dengler, C. E. and Addoms, J. N., 1956, “Heat Transfer Mechanism for Vaporization of Water in Vertical Tubes,” Chem. Eng. Prog. Symp. Ser. **52**(18), pp. 95-103

[31] Ebisu, T. and Torikoshi, K. 1998, “Heat Transfer Characteristics and Correlations for R-410A Flowing inside a Horizontal Smooth Tube,” ASHRAE Trans. **104**(2). Paper TO-98-3-4

[32] Gouse. S. W. and Coumo,, K. G., 1965, ”Heat Transfer and Fluid Flow Inside a Horizontal Tube Evaporator,” ASHRAE Trans. **71**(2), pp.152-160.

[33] Hambreaus, K., 1995, “Heat Transfer of Oil-Contaminated HFC134a in a Horizontal Evaporator,” Int. J. Refrig. **18**, pp. 87-99.

[34] Haynes, B. S. and Fletcher, D. F., 2003. “Subcooled Flow Boiling Heat Transfer in Narrow Passages,” Int. J. Heat Mass Transfer, **46**, 3673-3682.

[35] Johannes C., 1972, “Studies of Forced Convection Heat Transfer to Helium I,” Advances in Cryogenic Engng. **15**, pp.352-380.

[36] Johnston, R. C. and Chaddock, J. B., 1964, “Heat Transfer and Pressure Drop of Refrigerants Evaporating in Horizontal Tubes,” ASHRAE Trans. **70**, pp. 163-172.

[37] Jung, D. S., McLinden, M., Radermacher, and Didion, R. S., 1989, “Horizontal Flow Boiling Heat Transfer Experiments with a Mixture of R22/R114,” Int. J. Heat Mass Transfer, **32**, pp. 131-145.

[38] Jung, D. S., McLinden, M., Radermacher, R., S. Didion 1989,. “A Study of Flow Boiling Heat Transfer with Refrigerant Mixtures,” Int. J. Heat Mass Transfer **32**, pp**.** 1751-1764.

[39] Kattan, N., Thome, J. R., and Favrat, D., 1998, “Flow Boiling in Horizontal Tubes: Part 2 – New Heat Transfer Data for Five Refrigerants,” ASME J. Heat Transfer ,**120**, pp. 148-155.

[40] Keilin, V. E., Kovalev, I. A., Likov, V. V. 1975, “Forced Convection Heat Transfer to Liquid Helium I in the Nucleate Boiling Region,” Cryogenics, **15**, pp. 141-145.

[41] Lahey, R. T. (editor), 1992, “*Boiling Heat Transfer*.” Elsevier Science Publishers, Amsterdam.

[42] Lazarek, G. M. and Black, S. H., 1982, "Evaporative Heat Transfer, Pressure Drop and Critical Heat Flux in a Small Vertical Tube with R-113," Int. J. Heat Mass Transfer, **25**, pp. 945-959.

.[43] Mathur, A. P., 1976, "Heat Transfer to Oil-Refrigerant Mixtures Evaporating in Tubes," PhD Thesis, Department of Mechanical Engineering, Duke University, Durham, NC, USA.

[44] Morozov, V. G., 1969, "Heat Transfer During Boiling of Water in Tubes," In "Convective Heat Transfer in Two-Phase and One-Phase Flow," edited by V. M. Borishanskii and I. I. Paleev, Israel Program for Scientific Translation Inc.

[45] Mumm, J. F., 1954, "Heat Transfer to Boiling Water Forced Through a Uniformly Heated Tube," Argonne National Laboratory Report ANL-5276

[46] Murata, K. and Hashizume, K., 1990, "An Investigation of Forced Convection Boiling of Non-Azeotropic Mixtures," Heat Transfer Japanese Research. **19**, pp. 95-109.

[47] Muzzio, A., Niro A., and Arosio, S., 1998, "Heat Transfer and Pressure Drop During Evaporation and Condensation of R22 Inside 9.52-mm O.D. Microfin Tubes of Different Geometries," Enhanced Heat Transfer, **5**, pp. 39-52.

[48] Naitoh, M. 1974. Dryout in Helically Coiled Tube of Sodium Heated Generator. ASME Paper 74-WA/HT-48, ASME, New York

[49] Pierre, B., 1957, "Varmeovergongen vid Kokande Koldmedier I Horisontella ror," Kylteknisk Tidskrift No. 3 (May), pp. 129-137.

[50] Reid, R. S., Pate, M. B., and Bergles, A. E. 1987. ASME Paper no. 87-HT-51, ASME, New York. Quoted in Lahey [41]

[51] Robertson, J. M. and Wadekar, V. V., 1988,"Vertical Upflow Boiling of Ethanol in a 10 mm Tube," *Trans. 2nd UK National Heat Transfer Conf.*, **1**, pp. 67-77. Quoted in Steiner and Taborek [9].

[52] Shin, J. Y., Kim, M. S., and Roe, S. T., 1997, "Experimental Study on Forced Convective Boiling Heat Transfer of Pure Refrigerants and Refrigerant Mixtures in a Horizontal Tube," Int. J. Refrig. **20**, pp. 267-275

[53] Staub, F. W. and Zuber, N., "Void Fraction Profiles Flow Mechanism and Heat Transfer Coefficients in Refrigerant 22 Evaporating in Vertical Tube," ASHRAE Trans., **66**(1), pp.130-146.

[54] Uchida, H. and Yamaguchi, S. 1966, "Heat Transfer in Two-Phase Flow of Refrigerant 12 Through Horizontal Tube," *Proc. 3rd International Heat Transfer Conference*, Chicago.

[55] Wattelet, J. P., Chato J. C., Souza, A. L. and Christofferson, B. R., 1994, "Evaporative Characteristics of R-12, R-134a, and a Mixture at Low Mass Fluxes," ASHRAE Trans. **100**, Paper 94-2-1, pp. 603-615.

[56] Wright, R. M. 1961, "Downflow Forced Convection Boiling of Water in Uniformly Heated Tube," Report UCRL 9744, University of California, Berkley

[57] Wright, C. C. and Walters, H. H., 1959, "Single Tube Heat Transfer Tests Gaseous and Liquid Hydrogen," WADC Technical Report 59-423

[58] Zurcher, O. Thome, J. R., Farvat, D., 1998, "Evaporation of Ammonia in Smooth Horizontal Tube: Heat Transfer Measurements and Predictions," ASME J. Heat Transfer, **12**, :pp. 89-101

[59] Bredsen, A. M.. Hafner, A. Petterson, J., Neksa, P., Aflekt, K. 1997, "Heat Transfer and Pressure Drop for In-Tube Evaporation of CO_2," *Proceedings of the Conf. Of Commission B1 with E1*, Paris,International Institute of Refrigeration.

[60] Yoon, S. H., Cho, E. S., Hwang, Y. W., Kim, M. S., Min, K, and Kim, Y,. 2004, "Charecteristics of Evaporative heat Transfer and Pressure Drop of Carbon Dioxide and Correlation Development," International J. Refrigeration, **27**, pp. 111-119

[61] Knudsen, H. J. H and Jensen, P. H., 1997, "Heat Transfer Coefficients for Boiling Carbon Dioxide," In *Workshop Proceedings – Carbon Dioxide Technology in Refrigeration, Heat Pump and Air Conditioning Systems*. Trondheim, Norway, pp. 319-328

[62] Stephan, K. and Abdelsalam, M., 1980, "Heat Transfer Correlations for Natural Convection Boiling,"Int. J. Heat Mass Transfer, **23**, pp. 73-87

[63] Kandlikar, S. G., 1991, "Development of Flow Boiling Map for Subcooled and Saturated Flow Boiling of Saturated Fluids in Circular Tubes," ASME. J. Heat Transfer, **113**, pp. 190-200

[64] Jallouk, P.A., 1974., "Two-Phase Flow Pressure Drop and Heat Transfer Characteristics of Refrigerants in Vertical Tubes," PhD Dissertation, Univ. of Tennessee, Knoxville, USA. Quoted in Kandlikar [63]

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 x 10^4	Co	Fr	No. of data	Deviation, % Mean Average					
												Shah 1982	G-W	L-W	Kand-likar	S- T	Chen-Cooper
Mumm [45]	11.8	SS (Electr.)	Water	0.014 0.0624	345 1382	157 788	0.00 52.0	0.53 11.0	0.04 1000	1.1 20.0	184	11.4 -5.6	10.9 -0.2	13.2 -6.1	13.3 -10.1	31.8 -31.1	32.2 -30.9
Chawla [29]	6.0	Copper (Electr.)	R-11	0.0135	40 252	2.3 69.9	10.0 90.0	2.0 26.7	0.02 0.28	0.025 0.46	57	14.8 -14.8	19.9 -15.1	28.3 -28.3	13.9 -7.6	36.1 -34.1	21.2 -20.7
	14.0			0.0135	25 130	1.2 23.3	10.0 90.0	0.51 24.3	0.01 0.28	0.002 0.045	29	11.7 8.2	14.6 -4.7	19.0 -3.4	12.0 10.9	58.7 51.4	30.0 24.7
	25.0			0.0089 0.0198	22 74	1.8 11.6	10 90	1.3 28.0	0.01 0.34	8E-4 0.099	52	18.8 15.8	12.5 1.2	17.3 -0.9	17.9 13.2	105.4 103.6	54.8 54.8
Haynes & Fletcher [34]	1.95	Copper (Elect.)	R-11	0.0987	150 420	53.0	0.00 17.0	7.75 21.7	0.46 1000	0.63 4.93	6	27.0 -23.1	13.2 -5.2	35.3 -35.3	19.2 10.6	73.8 -73.8	25.1 -25.1
Wattalet et al. [55]	7.0	Copper (Electr.)	R-12	0.088	50 300	2.0 20.0	10.0 92.0	1.1 6.7	0.01 0.72	0.019 0.62	50	12.9 -12.3	15.5 -12.8	16.2 -10.4	11.8 -2.7	20.2 2.4	8.5 -3.7
			R-134a	0.086	300	50 300	5.0 90.0	0.85 5.1	0.02 1.2	0.022 0.80	52	16.3 -8.5	13.3 -12.0	13.5 -7.2	NA	25.1 14.5	12.7 -3.4
Uchida et al. [54]	6.4	SS (Electr.)	R-12	0.097	345 518	14.4 27.9	0.00 95.0	1.9 5.7	0.01 1000	0.25 2.5	40	21.8 -21.5	20.8 -19.9	15.6 -11.7	15.7 =10.4	18.3 -19.2	18.3 -18.1
Chaddock & Noerager, [28]*	11.7	SS (Elect.)	R-12	0.1098	122 585	3.5 35.2	26.1 54.5	0.99 7.94	0.16 0.36	0.071 1.63	19	16.4 -13.6	13.0 -5.5	15.6 2.3	12.8 -2.4	11.6 -7.9	21.7 -17.1
Ebisu, & Torikoshi [31]	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 [45]	9.5	Copper (Electr.)	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 & Chaddock, [36] *	11.6	Copper (Electr.)	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. [47]*	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 [49]*	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. [37, 38]	9.0	Copper (Electr.)	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

Data of	Dia. mm	Material (Heating By)	Fluid	p_r	G $Kg/m^2 s$	q kW/m^2	x, %	Bo x 10^4	Co	Fr	No. of data	Deviation, % Mean Average					
												Shah 1982	G-W	L-W	Kand-likar	S- T	Chen-Cooper
Reid et al. [50]	8.7	(Electr.)	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
Shin et al. [52]	7.7	SS (Electr.)	R-22	0.145	424 742	18 30	10 79	0.69 3.64	0.05 0.91	1.54 4.74	35	8.5 -4.7	13.4 4.9	12.7 9.0	51.5 50.9	23.4 17.9	6.5 -6.2
			R-32	0.20	424 583	30.0	5.0 50.0	1.7 2.4	0.18 1.9	2.3 4.4	12	9.6 -9.4	9.0 3.0	13.6 10.6	NA	22.7 1.2	8.3 -8.3
			R-134a	0.109	424 583	30.0	10.0 79.0	2.7 3.7	0.05 0.6	1.52 2.9	16	8.5 1.2	14.3 7.3	14.2 9.9	NA	28.4 20.3	7.3 -7.1
			Propane	0.158	424 583	30.0	10.0 68.0	1.44 1.98	0.09 0.98	9.1 17.1	12	5.9 3.8	16.3 14.2	26.9 26.9	NA	32.6 32.5	1.9 0.8
			Iso-Butane	0.065	424 583	30.0	1.0 68.0	1.5 2.1	0.06 4.1	7.4 14.0	13	16.8 16.8	20.2 18.4	33.2 33.2	NA	46.5 43.5	3.7 3.2
Gouse & Coumo [32]	10.9	Glass, Ni -coated (electr.)	R-113	0.031 0.035	517 699	12.9 22.1	2.2 36.6	1.3 2.9	2.2 36.6	1.05 1.91	10	8.4 7.6	18.8 18.8	41.4 41.4	23.6 23.6	24.6 21.4	9.2 -9.2
Murata & Hashizume [46]	10.3	Copper	R-114	0.061	300	30.0	20.0 80.0	4.1	0.08 0.66	0.39	3	13.0 -13.0	9.1 -9.1	14.1 -14.1	9.2 -9.2	18.6 -13.4	27.7 -27.7
			R-123	0.0546	100 300	10.0 30.0	20.0 92.0	2.1 18.5	0.01 0.28	0.05 0.45	26	13.0 -12.3	14.0 -11.2	11.1 -4.1	NA	16.1 -1.4	17.1 -17.1
Hambreaus [33]	12.0	Copper (elect.)	R-134a	0.049	137	6.0	30.0 90.0	2.1	0.02 0.17	0.09	21	18.9 11.5	17.3 1.3	20.6 14.2	NA	40.3 40.2	12.3 2.3
Chaddock & Buzzard [27]	7.7	Copper (electr.)	R-502	0.0085 0.059	45 358	3.8 23.7	20 70	4.2 5.2	0.04 0.36	0.008 0.567	26	12.3 5.4	15.2 6.1	16.3 4.7	NA	29.4 28.5	9.7 3.3
Kattan et al , [39]	12.0	Copper (liquid)	R-502	0.15	100 300	8.0 10.0	3.0 54.0	2.1 6.2	0.14 2.61	0.049 0.442	15	19.0 -17.1	15.5 -7.0	26.5 -9.8	NA	32.7 -22.2	8.7 -7.0
Zurcher et al [58]	14.0	SS (liquid)	NH_3	0.044	10 140	8.0 71.6	0.03 0.90	0.76 6.5	0.01 1.36	0.0024 0.473	106	21.9 1.7	23.4 -4.7	25.5 -9.7	NA	29.8 17.9	27.5 13.5
Steiner & Schlunder [20]	14.0	Copper (elect.)	Nitrogen	0.186 0.461	44 460	0.5 34.6	5.0 75.0	1.0 9.2	0.05 2.2	0.031 3.3	42	58.6 -58.6	52.2 -52.2	44.4 -42.1	51.4 45.8	26.0 -6.8	46.6 -44.9
Klein [21]	12.0	Copper (electr.)	Nitrogen	0.0873	154 209	1.0 50.0	10 90	0.26 17.4	0.02 0.74	0.35 0.61	21	29.3 -19.7	33.8 -17.5	29.2 --16.1	120.2 106.1	23.0 6.4	29.0 -29.0
Mohr & Runge[18]	4.0	Copper (electr.)	Neon	0.0564	78 125	1.0 20.0	13.0 70.0	6.0 34.7	0.05 0.49	0.11 00.28	15	48.4 -48.4	40.4 -40.4	63.4 -63.4	52.4 43.6	56.8 -56.8	60.0 -60.0
Wright & Walters[57]	6.3	Copper (elect.)	Para H_2	0.0175	412 1180	10.0 99.7	2.6 5.2	0.42 2.5	1.88 4.15	587 4822	18	17.6 2.0	18.5 11.5	27.0 -27.0	NA	13.2 -4.3	45.7 -46.7
Muller et al. [23]	14.0	Copper (Elect.)	Argon	0.036 0.413	120 460	1.8 97.0	0.1 0.9	0.36 74.2	0.05 1.79	0.064 1.35	33	23.4 -0.3	38.4 24.5	116.2 114.9	NA	169.7 164.7	38.0 28.5
All data	1.95 25.0			0.0134 0.413	10 1382	1.0 788	0.0 95.0	0.26 74.2	0.01 1000	0.0008 4822	1086	17.5 -6.4	18.9 -4.9	26.0 -4.9	27.8 +6.6	36.8 +9.8	23.7 -7.5

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

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 x 10^4	Co	No. of data points	Deviation, % Mean Average					
											Shah	G-W	L-W	Kand-likar	S- T	Chen-Cooper
Naitoh [48]	16.5	SS (Liquid)	Water	0.783	1250	100 523	0.0 60.0	0.96 5.02	0.34 1000	7	8.8 -8.8	8.0 -0.2	110.8 110.8	15.9 -15.2	28.8 -28.8	38.4 -38.4
Wright [56]	18.2	SS (Electr.)	Water	0.0053 0.0078	434 796	99 154	1.0 11.8	0.56 1.5	0.15 1.0	71	10.1 1.4	11.4 -8.6	14.5 11.2	8.7 -6.6	25.0 23.0	12.6 12.3
	12.0			0.0068 0.014	666 2437	118 274	1.4 10.0	0.52 1.07	0.18 6.4	37	21.5 19.8	24.0 21.9	37.1 36.8	15.1 12.3	43.9 42.8	10.8 0.0
Dengler & Addoms [30]	25.4	Copper (Steam)	Water	0.011	721	95 448	1.7 13.5	0.6 2.83	0.15 0.98	5	11.5 8.8	21.3 21.3	34.7 34.7	13.1 9.9	40.1 40.1	12.2 12.2
Piret & Isbin [24]*	27.1	Copper (Electr.)	Water	0.0046	394 822	19.4 165	0.19 0.45	0.22 0.84	1.27 3.4	4	9.7 9.7	40.9 40.9	88.3 88.3	10.2 10.2	53.4 53.4	6.4 -3.6
			CCl_4	0.022	347 943	5.9 55.3	0.64 2.4	0.29 0.99	1.17 3.43	4	9.1 -8.5	13.5 13.5	80.8 80.8	NA	26.9 26.9	5.6 0.2
			n-butanol	0.0204	555 706	16.9 70.0	0.4 1.5	0.51 1.73	1.62 4.6	4	7.8 -7.8	3.7 -1.5	47.9 47.9	NA	13.0 -12.2	22.8 -22.8
			Isopropyl Alcohol	0.011	681 779	10.8 85.7	0.26 1.6	0.29 1.8	1.02 4.43	4	6.5 -6.5	7.8 7.8	90.7 90.7	NA	10.3 8.0	12.9 -12.9
Adorni et al [25]	3.2 a	SS (Electr.)	Water	0.32	980 3000	420 1250	14.0 69.6	0.66 5.9	0.18 1.68	39	22.2 -14.7	15.0 -4.2	15.4 -5.5	24.5 -15.2	29.3 -22.2	32.2 -27.4
	3.2 b			0.32	980 3800	91 688	7.4 70.1	0.65 4.5	0.11 1.68	38	18.1 -11.2	14.9 5.9	19.5 -0.2	19.5 -13.8	22.7 -0.5	17.0 -11.7
	8.5 c			0.32	1010 2954	137 812	21.0 70.1	0.9 2.34	0.11 0.63	8	46.8 -46.8	42.3 -42.3	41.7 -40.6	50.3 -50.3	38.9 -38.9	45.4 -45.4
Morozov [44]	13.8 d	SS (Electr.)	water	0.228	6085 11071	261 375	0.0 20.0	0.24 0.26	0.55 1000	6	20.9 4.4	28.6 25.5	16.7 9.6	30.5 -17.5	58.5 32.0	35.9 11.8
Robertson & Wadekar [51]	10.0	Copper (Electr.)	Ethanol	0.0244	145 290	25.5 104. 6	3.0 56.0	2.1 7.0	0.05 0.90	51	21.3 -21.3	17.7 -17.7	23.3 23.3	NA	20.6 -19.6	9.4 -6.6
Staub & Zuber [53]	10.0	Copper (Electr.)	R-22	0.121	153 896	12.1 70.7	4.0 21.0	3.95 3.98	0.41 1.12	8	40.0 -40.0	33.8 -33.8	34.8 -34.8	33.5 33.4	57.5 -57.7	45.2 -45.2
Lazarek & Black [42]	3.15	SS (Electr.)	R-113		502	64.0	4.0 60.0	16.1 25.2	0.06 1.14	10	10.4 5.4	32.5 32.5	23.1 -23.1	38.2 37.6	54.5 -54.5	24.4 -24.4
Johannes [35]	2.1	Monel (Electr.)	Helium	0.477	130	0.5 1.5	3.2 25.0	2.0 5.8	0.92 5.86	7	27.2 19.2	35.6 31.6	35.1 -35.1	NA	25.9 -25.9	51.5 -51.5
Keilin [40]	2.0	Copper (Electr.)	Helium	0.57 0.68	28 96	0.1 3.0	1.3 39.4	1.3 40.3	0.49 11.0	15	28.5 9.5	41.1 41.1	24.8 -24.8	NA	19.5 -13.5	39.7 -39.7
Ogata & Sato [17]	1.1	SS (Electr.)	Helium	0.477	87	0.2 1.4	2.0 40.0	0.9 8.1	0.53 8.62	14	11.2 -5.5	12.3 9.1	15.1 -14.1	NA	14.7 11.3	29.5 -29.4

Data of	Dia. mm	Material (Heating by)	Fluid	p_r	G Kg/m^{2}s	q kW/m^2	x, %	Bo x 10^4	Co	No. of data points	Deviation, % Mean Average					
											Shah	G-W	L-W	Kand-likar	S- T	Chen-Cooper
Pappel & Hendricks [19]	2.0	SS (Electr)	Nitrogen	0.64	2210	212	0.00	9.2	1000	1	0.10 -0.10	19.6 19.6	14.3 -14.3	436.3 436.3	12.5 12.5	52.0 -52.5
Klimenko & Sudar-chikov [22]	9.0	SS (Electr.)	Nitrogen	0.14 0.26	220	9.0 27.0	2.0 70.0	2.35 7.05	0.09 7.05	20	13.9 -3.7	19.7 6.8	16.1 7.8	269.8 269.8	32.3 31.3	14.7 -7.2
Talty [15]	19	Brass (Liquid)	Heptane	0.037	231 454	7.7 31.7	0.14 8.1	0.99 1.73	0.53 6.9	33	18.6 0.8	18.6 8.9	19.7 17.4	NA	13.6 -9.1	27 -27
	25.3				266 391	13.6 35.6	0.20 5.00	0.69 1.59	0.77 3.98	28	16.9 -15.5	10.5 -6.8	17.1 7.9	NA	18.9 -16.1	34.3 34.3
	19.0		Pentane	0.030	251 408	9.1 22.9	0.28 8.3	0.85 2.16	0.48 16.6	51	13.1 -0.9	11.4 9.1	24.5 24.0	NA	12.2 -1.8	20.5 -20.0
	25.3				266 399	13.6 38.4	0.61 11.7	1.11 3.74	0.35 16.7	54	11.3 -10.6	5.4 -2.1	10.9 7.5	NA	17.4 -16.5	36.4 -36.4
	19.0		Methanol	0.0156	280 459	26.2 49.7	0.12 4.3	0.85 1.40	0.48 7.3	22	25.9 -25.9	16.7 -16.7	38.8 38.8	NA	18.7 -17.0	13.3 -1.4
	25.3				314 553	20.3 53.5	0.19 4.3	0.60 1.09	0.65 5.5	54	35.2 -35.2	21.9 -21.9	33.6 33.6	NA	12.1 -10.7	22.2 -22.2
	25.4		Cyclo-hexane	0.025	335 488	10.1 41.6	0.5 10.0	0.58 3.02	0.37 4.46	52	15.9 -15.9	6.8 -6.4	24.0 24.0	NA	16.8 -15.6	26.0 -26.0
	19.0				390 482	7.9 24.1	0.36 6.1	0.46 1.86	0.57 5.71	23	8.9 -5.2	9.8 9.1	51.4 51.4	NA	15.4 6.0	9.6 -9.2
	25.4		Benzene	.0203	347 600	12.7 41.4	0.20 8.5	0.59 2.58	0.39 8.4	55	13.7 -11.2	9.3 -0.3	24.7 24.6	NA	9.9 -3.6	28.0 -28.0
	19.0				293 521	16.5 43.1	0.26 8.7	1.34 2.75	0.4 6.8	48	11.7 -5.9	8.2 1.2	17.2 16.8	NA	16.6 -16.3	22.0 -21.3
All data	1.1 27.1			0.0053 0.783	28 11071	0.2 1250	0.00 70.1	0.22 40.3	0.09 1000	773	17.6 -9.2	14.9 +20.5	25.2	47.4	20.4	22.7

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

Table 3: Summary of results for horizontal & vertical channels

	Mean Dev. %	
Correlation of	a	b
Shah	17.5	17.3
Gungor & Winterton	17.3	18.6
Chen-Cooper	23.2	22.4
Liu & Winterton	25.7	37.5
Steiner & Taborek	30.0	36.5
Kandlikar	32.2 c	46.0

a. giving equal weight to each data point
b. giving equal weight to each data set
c. 16.8 % if the data for neon, N_2, & R-22 are deleted.

Table 4: Complete range of data satisfactorily predicted by the correlation of Shah [8]

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, nitrogen, argon, hydrogen, nitrogen, and helium
Test channels	Tubes and annuli (heated on inside, outside, and bilateral). Horizontal and vertical
Heating method	Electric, steam, liquid
Diameter, mm	1.1 to 27.1
Reduced pressure	0.0053 to 0.78
G, kg/m^2s	10 to 11,071
q, kW/m^2	0.2 to 1,250
x, percent	0 to 95
$Bo x 10^4$	0.22 to 74.2

APPENDIX

The Shah Correlation

The Shah correlation is given by the following equations:

$$h_{TP} = 230 Bo^{0.5} h_{LO} \qquad \text{(A1)}$$

$$h_{TP} = 1.8\left[Co\left(0.38 Fr_L^{-0.3}\right)^n\right]^{-0.8} h_{LO} \qquad \text{(A2)}$$

$$h_{TP} = F Bo^{0.5} \exp\left[2.47\left(Co\left(0.38 Fr_L^{-0.3}\right)^n\right)^{-0.15}\right] h_{LO} \qquad \text{(A3)}$$

$$h_{TP} = F Bo^{0.5} \exp\left[2.74\left(Co\left(0.38 Fr_L^{-0.3}\right)^n\right)^{-0.1}\right] h_{LO} \qquad \text{(A4)}$$

$$h_{TP} = h_{LT} \qquad \text{(A5)}$$

The predicted h_{TP} is the largest of the values given by the above equations. n = 0 for horizontal tubes with $Fr_L > 0.04$ and for vertical tubes at all values of Fr_L, n = 1 for horizontal tubes with $Fr_L < 0.04$. F = 14.7 for $B_o > 0.0011$, else F = 15.43. The above equations are the same as in the published Shah correlation (1982) but have been rearranged for ease of computer programming.