CHAPTER 2

BACKGROUND LITERATURE

The boiling of single component liquids and binary mixtures with thermally induced flow in vertical tubes has received considerable interest as is evident from the rapid growth of literature on the subject. In almost all the investigations, attempts have been made to gain an insight of the process—namely hydrodynamics, heat transfer and stability with a view to provide reliable methods for the design of thermosiphon reboilers on industrial scale. The studies reported in the literature are mostly experimental and have resulted in a number of empirical and semi-empirical correlations. A survey of the existing literature is presented in the following sections.

2.1 Hydrodynamics and Stability

A full hydrodynamic description of the flow patterns requires a knowledge of void distribution, velocity and shear distribution in the flow field. A great deal of understanding has been gained from visualization studies. Griffith and Wallis [83], Govier et al. [82] and Collier [55] presented charts for identification of flow patterns existing in the pipe for the given flow conditions. Orkiszewki [143] based on the results of Griffith and Wallis [83], Duns et al. [64] and Nicklin et al. [147] formulated some useful correlations for the identification of flow regimes. The majority of the correlations proposed are based on the experimental data obtained under isothermal conditions of two-phase two-component systems. Hosler [96] based on his comparison of high pressure water tests examined the maps of Baker [20] and Quandt [152], and found that none predicts flow regimes in boiling two-phase flow accurately. Baker's plot predicted annular flow reasonably well while Quandt's predicted the largest fraction of data.
Manhane carried out a systematic study of flow pattern maps. He developed earlier and suggested a new map. Manhane’s map was valid for low-pressure systems without large changes in the gas density.

Dynamic hold up of vapor and liquid in the heated zone of the reboiler tube create problems in estimating static head effects. Initial studies to this effect assumed that the gas and liquid flow at the same velocity (No slip) but actually the gas flows faster than the liquid. Martinelli et al. [136] conducted the hold up measurements in a small horizontal pipe and presented a graphical correlation for the calculation of hold up assuming homogeneous flow conditions. Chisholm and Laird [47] put the above correlation in the form of an equation. Hughmark [100] developed a hold up correlation valid for hold ups approximately between 0.1 to 1.0 and was considered satisfactory by Duckler et al. [62,63]. Duckler et al. [62,63] based on his experimental data analyzed and tested the hold up correlations over a wide range of values. He found that the Martinelli’s and Hughmark’s correlations were more accurate than others. DeGance and Atherton [58,59] presented the approximate ranges for the applicability of hold up correlations. Takeda [174] conducted experimental studies in natural circulation vertical annular spaces and proposed a correlation with major parameters as heat flux, length of boiling region and modified terminal velocity of a single bubble. Badger et al. [21] recommended an empirical correlation for the prediction of liquid velocities in terms of specific volumes of liquid and vapor and submergence ratio. Johnson [111] proposed a model predicting recirculation rates, modifying Kern’s method [120] by including the existence of a liquid zone and using the two-phase pressure drop correlation of Martinelli and Lockhart [133] for vaporization zone. Hughmark [102, 103] considered the prediction of circulation rate in conjunction with two-phase pressure drop. He proposed a polynomial equation in terms of Froude number and volume fraction of liquid.

Kreith and Summerfield [124] studied the effect of heat flux on frictional pressure drop using Aniline and N-butyl alcohol flowing upward in S.S. tube. They found that
friction loss is a strong function of heat flux. Jicha and Frank [109] proposed a correlation wherein they incorporated the effect of heat flux by using colburn (J) factor. They suggested that the true void should be used to calculate both the frictional pressure drop and the momentum pressure drop due to flow acceleration in the evaporative two-phase flow. Duckler et al. [62,63] developed methods for the calculation of frictional pressure drop and acceleration terms considering slip and no slip between the phases. Thom's [176] empirical method is similar to Martinelli and Nelson [137]. He based his correlation on a large body of high pressure (15-3000 psia) data for boiling water systems. Baroczy [23] took data for water-air, water-steam, Hg-N₂ and constructed a set of correlation curves. He found very strong dependence of the two-phase pressure drop on the flow rate as well as the quality. Recently, Lazarek and Black [130] measured pressure drop for saturated boiling of R-113 in a round tube. Correlations were proposed for two-phase frictional, spatial acceleration and bend loss from pressure drop data.

Ramadevi et al. [153] analyzed the pressure drop in a vertical thermosiphon by using various existing correlations with C₆H₆ and water as working fluids. The correlation of Hughmark et al. gave better results. The assumption of constant heat flux is not correct, but good result are obtained by considering constant temperature.

Hydrodynamic instabilities in natural circulation boiling systems are usually due to feedback between flow rates, vapor volume and pressure drop, the intercoupling between these magnitudes becoming instables under certain conditions [36].

Bergles et al. [32] carried out experiments on water at low pressure to investigate the effects of tube length, inlet temperature, tube diameter and pressure on the CHF.

The results were related to the instabilities of the slug-flow regime. Shellene et al. [165] carried out plant tests on a highly instrumented reboiler. The pressure was slightly above atmospheric of particular interest in the work was the exploration of the onset of unstable operation. It was found that the addition of flow resistance to the inlet line extended the
stable operating range, and the allowable pressure drop across the tubes decreases as the heat flux increases. Adding flow resistance to the vapor return line results in a decrease in a maximum flux. The authors recommended to keep the return line flow area at least equal to the total flow area of the tubes. Maximum heat fluxes were tabulated for the various fluids with accompanying temperature differences and percent vaporization. Other data were presented as heat flux versus log mean temperature difference and mass velocity versus pressure drop.

Blumenkrantz and Taborek [36] developed a two-phase flow stability computer program based on Boure's density effect model and used in conjunction with steady state prediction by the H.T.R.I., thermosiphon program for calculation of stability limit in natural circulation boiling systems. Comparison of the model prediction with available experimental data at various pressures showed good agreement. Becker et al. [26] studied experimentally the hydrodynamic instability and dynamic burn out in natural circulation two-phase flow. He observed that the other operation parameters being given, an increase of subcooling had a destabilizing influence for low values of subcooling and a stabilizing influence for high values of subcooling. Berenson [30] investigated experimentally the flow stability for a five-tube Freon-113 system. He made a photographic study and showed that insertion of a variable restriction at each boiling tube could stabilize the flow. The pressure drop in the restriction required to damp out oscillation was found to be in the range of 20 to 160 percent of the two phase pressure drop. He also found that the flow tended to be more stable if entrance subcooling was increased and the density ratio $S_L/S_V$ was decreased. Chexal and Bergles [46] studied the stability characteristics of a single-channel vertical thermosiphon reboiler. Seven steady and fluctuating flow modes were observed for a wide range of inlet subcooling and heat flux. Fukuda and Kobori [71] conducted experimental study on two-phase flow instabilities in parallel channels under forced and natural circulation using water. Two types of flow oscillations were observed, one occurs at nearly zero steam quality, the other at relatively high steam quality.
The analysis done showed that gravitational pressure drop was the governing factor in type I oscillations and frictional pressure drop was dominant in type II oscillations. Dogan [61] developed a numerical model to predict both the steady state and transient behaviour of forced convection, boiling two-phase flow systems. The study involved also experimental work with a forced boiling Freon-11 loop for comparison purposes. Steady state operating characteristics and stable and unstable regions are determined for various ranges of heat flux, inlet subcooling and mass flow rates. Different modes of oscillations and their characteristics are identified.

2.2 Boiling Incipience

The onset of nucleation along the tube length and its required superheat depends upon a number of operating parameters. Numerous studies to this effect, on predicting superheat through semi-empirical approach for forced convection boiling in tubes have been reported in literature. These studies include the effect of various physical parameters - surface roughness by Corty and Foust [53], size and geometry of nucleation sites by Griffith and Wallis [83], Howell and Siegel [97], Schultz et al. [161] and Jemison et al. [107] and the role of surface tension and wettability by Harrison and Levine [90] and Lorentz et al. [134]. Some of the experimental studies have also been reported on the influence of prior boiling and effect of dissolved gases by Murphy and Bergles [142]. Hodgson [94] and Yin and Abdelmessih [195] have shown through experimental studies the presence of two boiling incipience points, depending upon the direction (increasing or decreasing) of heat flux changes.

The analysis established for the prediction of incipient boiling are either empirical in nature or based on solutions derived from approximate theories [195]. The widely accepted approach for the prediction of incipient boiling has been one which is based on the Gibb’s equilibrium theory of bubble in a uniformly superheated liquid and the one dimensional steady or transient heat conduction equation. It was postulated that in
the liquid film adjacent to the heating surface, the super-heated layer, \( \delta^* \), must attain a threshold value so that the critical bubble nuclei with radius \( r_c \) can further growth to the point of detachment.

Hsu [98] and Hsu and Graham [99] developed analytical expressions for the size range of active nucleation sites for constant heat flux at the wall. Bergles and Rohsenow [31] developed a criterion of incipient boiling for systems that have a wide range of cavity sizes which should be applicable to commercially finished surfaces. They concluded that only a small additional increase in wall temperature is necessary to activate a considerable range of cavity sizes when bubbles originating from cavities of a particular radius start to grow. Sato and Matsumura [158] proposed an analytical expression equivalent to that of Hsu's for the prediction of incipient nucleate boiling of water at atmospheric pressure. Based on the analysis of Hsu, Bergles and Rohsenow and Anderson and Davis they derived an equation for the prediction of subcooled incipient boiling of water in forced convection. They concluded that the criterion used in their analysis appears satisfactory for determining an upper limit of the liquid superheat required to initiate nucleate boiling when a wide range of cavity sizes exist. Fiore and Ricque [68] made an analysis for the prediction of the incipient of nucleation under forced convection conditions of high boiling point multi-component organic liquids. The analysis was also extended to the condition of degassing. Tong [186] studied the existing nucleate and film boiling correlations and recommended the Davis and Anderson equation for the prediction of incipient nucleate boiling in subcooled flow boiling of water. Frost and Dzakovic [70] extended the analysis of Davis and Anderson and derived an equation for the prediction of boiling incipience for a variety of different liquids. They considered their equation to be applicable to both forced and natural convection system.

Murphy and Bergles [142] obtained a relation for the prediction of incipient flow boiling of Freon-113 under chemical potential equilibrium. They noted that their analysis satisfactorily predicted the point where nucleation dies and that
it is not capable of predicting the traverse nucleation behaviour encountered on the increasing heat flux traverse.

Unal [191] considered the effect of pressure on the boiling incipience under sub-cooled flow boiling of water in a vertical tube. Maximum bubble diameters at this point were observed experimentally and correlated.

Unal [192] determined the incipient point of boiling for subcooled nucleate flow boiling of water with high speed photography. He correlated his data and those available in literature covering ranges of pressure, mass velocity, hydraulic radius, heat flux, subcooling for plate, circular tube and annulus with S.S. and nickel surfaces. He also modified his own equation developed earlier for maximum bubble diameter at the incipient point of boiling. Maximum bubble diameter at the incipient point of boiling were measured and correlated along with the data of Abdelmessih et al. [1, 2].

Yin and Abdelmessih [195] investigated the phenomenon of liquid superheat during incipient boiling in a uniformly heated forced convection channel. Experimental data were obtained using Freon-11 as the test medium.

Based on certain assumptions and existing theories, an analytical method predicting both points of boiling incipience, was developed in the form of the following equation:

\[
\frac{\sigma^*}{r_c} = \frac{(T_w - T_s)^2 k_L \lambda \rho_v}{2 q \sigma T_s} \quad \ldots (2.1)
\]

Using the generated experimental data, they computed the values of \((\sigma^*/r_c)\) for both incipient conditions and finally correlated them as linear functions of heat flux. In view of the basic assumptions involved in the analysis, the applicability of \((\sigma^*/r_c)\) have been extended to water and other organic liquids of surface tension in both pool and flow boiling systems.

Golovchenko and Fokin [78] derived an equation to calculate the height of convective heat transfer zone in evaporators with a natural circulation and boiling of a solution in pipes, taking
into account the pressure drop in the two-phase flow. The relation was verified experimentally in an evaporator with a heat transfer area of 2.9 m² using water and aqueous solution of glycerine and MgCl₂ at various concentrations and pressure.

Agrawal [4] developed the following equation to determine the length of heated tube required for the onset of fully developed boiling

\[ Z_{OB} \times 100 = C_4 (Pe_B) (K_{sub}) (S) \quad \ldots \quad (2.2) \]

The values of indices and constant in above equation were determined, system wise, by regression analysis. Experimentally measured values of \( Z_{OB} \) and those predicted by using equation (2.2) were compared. Majority of the data points were found to lie within ±40 percent error lines.

Butterworth and Shock [39] found that the Davis and Anderson [58] equation did not predict the subcooled boiling incipience satisfactorily for higher values of \( r_c \) for some fluids and conditions. They recommended Bergles and Rohsenow [31] equation for water at 0.1 x 10⁶ to 13.6 x 10⁶ Pa and Davis and Anderson equation for water at pressure less than 0.1 x 10⁶ Pa, organic liquids including refrigerants and cryogenic liquids for \( r_c \) less than 0.5 um.

Hino and Joda [92,93] performed measurements of wall temperature profile and photographic observation with R-113 in subcooled boiling flow through a channel with heat fluxes up to the CHF (critical heat flux). The incipient boiling superheats measured are little affected by mass velocity and liquid subcooling. Their observation of hysteresis in boiling by increasing and decreasing heat flux seems to be ascribed to variation in size of active nucleation cavities on the wall. By increasing heat flux up to the CHF, the bubble density on the
Heated surface: Remarkably large coalescent bubbles appear periodically near the heated section outlet.

Ali [12] and Ali and Alam [16] developed the following correlation for predicting the length of the heated tube required for the onset of fully developed boiling.

\[
Z_{OB} = \left( \frac{n_1}{n_2 n_3 n_4} \right) \gamma_L \gamma_V
\]

(\(\gamma_L \times 100\)) = \(C_1 (P_B) (K_{sub}) (S)\) ... (2.3)

The values of indices, \(n_1, n_2, n_3, n_4\) and constant \(C_1\) in equation (2.3) were determined by regression analysis for various test liquids. Experimentally measured values of \(Z_{OB}/L\) and those predicted by using equation (2.3) were compared. Majority of the data points were found to lie within ±30 per cent error lines.

Ali and Alam [14] carried out an experimental study to identify the boiling incipience conditions in a vertical tube thermosiphon reboiler. Three binary systems: acetone-water, ethanol-water and water-ethylene glycol were based with various concentrations. They proposed correlations for the prediction of maximum superheat attained around boiling incipience and the heated length required for onset of fully developed boiling.

Marsh and Mudawar [135] performed experimental study to develop a fundamental understanding of boiling incipience in wavy free-falling turbulent liquid films. Incipience conditions were measured and correlated for water and a fluorocarbon (FC-72) liquid. They found that incipience in water films is influenced by turbulent eddies and, to a larger extent, by interfacial waves. They presented a new approach for predicting incipience in water and other, non-wetting fluids. This new approach utilizes physical parameters of commonly accepted incipience models and provides a means of correcting these models for the effects of turbulent eddies and roll waves. It also demonstrates some unique incipience characteristics of fluorocarbon films. The water surface tension forces of FC-72 allow droplets and liquid streams to break off the crests of incoming roll waves prior to, and during nucleate boiling. The low contact angle of FC-72
allows the liquid to remain deep inside wall cavities. Thus incipience from these flooded cavities require much higher wall superheat than predicted from incipience models. Ahmad, Ali and Alam [17] carried out an experimental study to identify the boiling incipience conditions in a vertical tube thermosiphon reboiler with water and cyclohexane as test liquids. They proposed an empirical equation for the prediction of minimum wall superheat required for onset of boiling in a reboiler tube.

2.3 Circulation Rate

Piret and Isbin [149] reported a study on a single, electrically heated 1-in. schedule-40 pipe 46.5 in long. They recorded circulation rates for six systems, three of which were aqueous. They correlated their data by an empirical equation similar to the Dittus-Boelter equation but involving a surface-tension correction and also utilizing the logarithmic mean of the inlet and outlet velocities.

Johnson [112] carried out an experimental study to measure circulation rates in a steam-heated vertical thermosiphon reboiler of standard design. The tube bundle contained 96, 1.0 in, 12-BWG carbon steel tubes, 8 ft long. The circulation rates were predicted fairly successfully by a modification of Kern's method including the existence of a liquid zone and use of the two-phase pressure-drop correlation of Martinelli and Lockhart for the vaporization zone. Fair [65] presented a general method for the estimation of circulation rate. This method involved a nestle series of trial and error calculations, starting with a rough estimate as a preliminary design. Hughmark [102,103] discussed the problems in estimating the circulation rate with the utilization of a length wise temperature profile. He developed an equation for its prediction in which the two-phase pressure drop was related by means of a polynomial in terms of the Froude number and volume fraction of liquid. Beaver and Hughmark [25] obtained circulating rate data for a single tube thermosiphon reboiler under vacuum and atmospheric pressure and compared with those calculated from a computer program based upon
gas-liquid two-phase flow correlations developed by Hughmark. Experimental data showed that there was nothing unusual about vacuum operating conditions. Shellene et al. [165] used an industrial reboiler having a 14-in shell, containing 70 3/4 in, 14 gauge, and 3 7/8 in, 12 gauge, 8-ft long tubes, providing 110 sq.ft. of area. The reboiler was connected to an existing distillation column and, except for instrumentation, was identical to a typical commercial unit. They studied experimentally the effect of heat flux on the relationship between fluid circulation and driving force. It was found that the regulation of the fluid flow to the reboiler is of importance in maintaining stable operation. Recently some studies have been carried out by Smith [168], Shah [162] and Agarwal [4] to see the effect of liquid level in cold leg (submergence) on the performance of thermosiphon reboiler. These studies have indicated, qualitatively, that submergence does influence the location of boiling incipience and circulation rate in the tube. Johnson and Yukawa [112] studied the effect of liquid driving head on the circulation rate for vertical thermosiphon reboilers operating under vacuum conditions. They found that the optimum practical operating conditions for vacuum reboilers are 50 per cent liquid driving head and 50 per cent vaporization. The effect of heat flux on circulating flow was observed by Hallinan and Viskanta [88] in a rectangular natural circulation loop, under natural convection condition for water at atmospheric pressure from a vertical tube bundle, consisting of twenty one tubes 1.65 m long and 9.55 mm in diameter, and a pitch-to-diameter ratio of 1.33. They developed empirical correlations in terms of dimensionless numbers to govern the fluid flow. Recently, Ali and Alam [13,18] studied the effect of heat flux and liquid submergence on circulation rates in a single vertical tube thermosiphon reboiler. As a result of data analysis, they developed an empirical correlation in terms of dimensionless numbers.
2.4 Heat Transfer

Most of the studies on flow boiling heat transfer in vertical tubes were in tube flow mode for correlating purposes. Piret and Isbi [71] investigated six fluids: water, carbon tetrachloride, isopropyl and butyl alcohols, 35 wt% and 50 wt% K$_2$CO$_3$ at atmospheric pressure in a 1 in nominal copper tube with 46.5 in. heated length. They proposed a modified Dittus-Boelter equation to correlate average heat transfer coefficient.

\[
\frac{\Delta H_{20}}{L} = 0.0086 \left( \frac{Re}{Pr} \right)^{0.8} \left( \frac{Pr}{Pr} \right)^{0.6} \left( \frac{\theta}{	heta} \right)^{0.33} \ldots (2.4)
\]

In calculating Re they used log mean velocity assuming a homogenous flow.

Guerrieri and Talty [84] studied heat transfer to boiling of cyclohexane, methyl alcohol, benzene, pentane, and heptane at atmospheric pressure, in two single tube natural-circulation vertical reboilers which were light oil-heated brass tubes 0.75 in. I.D., 6 ft. long and 1 in. I.D., 6.5 ft. long respectively. Inside wall and boiling stream temperatures were measured at 6 in. intervals along the tubes. Film coefficients have been expressed as a function of Lockhart-Martinelli parameter $\chi_{tt}$.

\[
\frac{h_{TP}}{h_{L}} = 3.4 \left( \frac{\chi_{tt}}{\chi_{tt}} \right)^{0.45} \ldots (2.5)
\]

Wall temperatures were found generally to decrease from the bottom to the top of the tube. Stream-temperature distribution displayed the expected maximum at some intermediate point. The boiling film coefficients has also been presented in terms of a nucleate boiling correction factor. Dengler and Addoms [60] stressed convective boiling mechanism by conducting forced convective boiling with 1 in. I.D. and 20 ft. long vertical copper tubes with water as test liquid. Radioactive
Tracers have been used to measure liquid fractions along the tube. They presented the ratio of local two-phase coefficient to the liquid-phase coefficient as a function of the reciprocal of the Lockhart-Martinelli parameter.

\[
\frac{h_{TP}}{h_L} = \frac{1}{3.5 \left( -\frac{1}{X_{tt}} \right)^{0.5}} \quad \text{... (2.6)}
\]

They observed and discussed the suppression of nucleate boiling by forced convection either externally induced or vapor induced. Lee et al. [131] used a reboiler consisting of seven tubes in a bundle. The tubes were of 1 in. O.D., 14 gauge, 10 ft. long mode of admirality metal. The investigation was carried out for seven liquids and data were presented for a pressure range of 2 to 120 psia. Overall coefficients were expressed as functions of overall temperature differences. The average inside-film coefficient and the maximum flux were presented in terms of dimensionless groups graphically. The maximum flux was found for each fluid and system pressure. Vapor locking was reported above maximum flux for each liquid. Recommendations for a maximum overall coefficient of 500 BTU/hr.ft.\(^2\) °F, and the need for giving particular attention to reboiler entrance and exit piping had been given.

Johnson [111] measured circulation rates and overall temperature driving forces for a 15-in shell reboiler containing 96, 1-in., 12 gauge, 8-ft long tubes. One tube was equipped with a temperature probe to obtain local boiling stream temperatures. The system investigated were water and a hydrocarbon having a normal boiling point of 80.8°C. The Lockhart-Martinelli parameter was used to calculate friction and expansion losses for the two phase zone. Overall coefficients, driving forces fluxed, flow, and vaporization rates were tabulated. Typical temperature profiles were shown for six runs on the hydrocarbon.

Bennett et al. [27] carried out experimental studies on heat transfer to two-phase steam-water mixtures in the liquid dispersed region in an annulus. They pointed out that below 15
percent dryness, the mechanism of heat transfer was probably governed by considerations of nucleate boiling whilst at higher steam qualities (upto 55-64%) a forced convective mechanism was suggested. Beyond 65% dryness, the heat transfer rate decreases. In the absence of a fundamental knowledge of the hydrodynamics of the system, attempts were made to correlate the data in the forced convective region by a modified form of the Guerrieri and Talty [84] equation:

\[
\frac{h_{TP}}{h_L} = 0.64 \left(\frac{Q}{A}\right)^{0.11} \left(\frac{X_{tt}}{1}\right)^{0.74}
\] ... (2.7)

where \( \frac{Q}{A} \) is in Btu/hr.ft\(^2\)

Ladiev [127] carried out experiments in three tubes 1500 mm long and 24, 28 and 52 mm diameter. Special attention was given to maintain identical conditions in all tubes. Heat transfer experimental results were correlated graphically for water at atmospheric pressure. The apparent liquid level in the tube had a significant effect on heat transfer, which decreased with an increase in the level. The sharp reduction in heat transfer at boiling in vertical tubes with inherent circulation was associated with inadequate flow in the upper part of the tube. Increase in tube diameter had no significant effect on heat transfer rate but circulation velocity decreased.

Chen [44] developed a correlation from experimental data for nucleation with flow conditions. The data included those for water in the pressure range of 1 to 35 atm. with liquid flow velocities upto 14.7 ft./sec, heat flux upto 760,000 BTU/hr.ft\(^2\), and quality upto 71%. Other fluids included methanol-cyclohexane, pentane, heptane, and benzene, under 1 atm. pressure, liquid velocities of 1 to 3 ft/sec., a heat flux range of 2000 to 17000 BTU/hr.ft\(^2\) and quality upto 12%. The correlation was proposed to account for both the micro convection
due to boiling and macroconvection due to flow

\[ h = h_{mic} + h_{mac} \]  \( ... (2.8) \)

For microconvective heat transfer, Chen developed a correlation from experimental data for nucleation with flow conditions using Forster and Zuber's analysis [69] for nucleate pool boiling. Chen's correlation contains suppression factor 's' to include the suppression effect of the moving fluid on the boiling rate.

\[ h_{mic} = 0.00122 \left( \frac{k_L}{\rho L} \right)^{0.79} C_L^{0.45} L^{0.49} g_C^{0.25} \]

\[ (T_w - T_s)^{0.24} (\Delta P)^{0.75} S \]

\[ \sigma^{0.5} \mu_L^{0.29} \rho_{24}^{0.24} \]

\[ ........(2.9) \]

where \( \Delta P \) is the saturated vapor pressure difference corresponding to \( \Delta T \).

It was also postulated that 'S' could be represented as a function of the local two-phase Reyonld's number. Hughmark [100] mentioned that experimental heat transfer data did not agree with this postulate and suggested a value of 'S' as 0.25 to better fit the data when nucleation apparently occurred.

Chen suggested that:

- \( S_C \rightarrow 1 \) at low flow rate
- \( S_C \rightarrow 0 \) at high flow rate

For macroconvection, Chen proposed for a two-phase fluid based on the Dittus-Boelter relationship for a liquid flowing alone in a heated conduit.

\[ h_{mac} = 0.023 F_C \left( \frac{G(1-x)}{D} \right)^{0.8} (Pr_L)^{0.4} \left( \frac{k_L}{\mu_L} \right)^{0.4} \]

Hence \( h_{mac} \) can be found if \( F_C \) is known. Chen presumed \( F_C \) to be a purely hydrodynamic function and to depend solely on the Martinelli Parameter \( X_{tt} \).

Claire [49] obtained fundamental information regarding heat transfer in a pilot evaporation plant. The coefficients of heat transfer for brass tubes and stainless steel tubes of different lengths (6 ft. and 4 ft.) and 2.0 in. and 1.5 in. O.D. are
compared. Tests with water boiling at atmospheric pressure indicated that the heat transfer was at maximum when the level of water was maintained at about 1/3 of the tube height. For clean tubes the value of $U$ was always higher for brass tubes than for stainless steel tubes.

Beaver and Hughmark [25] conducted experiments on twelve fluids in a 3/4 in. by 8 ft. long carbon steel tubes, heated electrically, to investigate the reliability of using developed correlations in vacuum operations. It was concluded that for wall minus saturation temperature difference less than 15°F, single phase coefficients dominate and can be predicted by a modified Dittus-Boelter equation (Sieder-Tate modification):

$$\text{Nu} = 0.023 \left(\text{Re}\right)^{0.8} \left(\text{Pr}\right)^{0.4} \left(\frac{\mu}{\mu_w}\right)^{0.14} \quad \ldots \quad (2.11)$$

For temperature differences greater than 15°F nucleation sets in and local inside coefficients can be predicted by existing two-phase correlations.

Gel'perin [75] correlated the experimentally observed heat transfer coefficients for boiling zone with corresponding heat fluxes in the following form:

$$h_B = a \left(\frac{L}{d}\right)^{0.2} \quad \ldots \quad (2.12)$$

where $a = a_1 \left(\frac{L}{d}\right)^{0.2}$ and $a_1$, depends on physico-chemical properties of the liquid.

Takeda et al. [174] measured the axial distribution of vapor hold up and boiling heat transfer coefficient in the annuli of a natural circulation vertical tube evaporator for pure liquids (water, methanol) and liquid mixtures (10 mole percent methanol-water, 50 mole percent methanol-water, $\text{H}_2\text{O-C}_2\text{H}_5$ and $\text{C}_6\text{H}_4-\text{SO}_3\text{Na}$ (1 gm/lit.)). Vapour hold up in the annuli was expressed in terms of heat transfer rate and length of boiling region. The effect of vapor hold up on the boiling heat transfer coefficients was analyzed to give an empirical dimensionless equation.
Calus et al. [40] carried out experimental work on a single tube natural circulation reboiler to investigate heat transfer to single component liquids. One copper and one stainless steel tube each equipped with a single steam jacket, and one stainless steel tube equipped with a six-compartment steam jacket were used. All the tubes had nominal dimensions of 0.5 in. diameter and 48 in. height. Three workers worked independently to obtain the length-mean and point coefficients of heat transfer for water, isopropanol, n-propanol and their azeotropes. Two-phase heat transfer coefficients for all five liquids were correlated by a single equation:

$$h_{TP} = 0.06 \left[ T_s \right] \left[ \frac{\sigma_{H_2O}}{T_L} \right] \left[ \frac{\sigma_{H_2O}}{T_L} \right] 0.9 \ldots (2.13)$$

$$h_L = X_{tt} \Delta T_f \frac{\sigma_{H_2O}}{T_L}$$

All the length-mean coefficients from runs with a two-phase mixture quality of between 0.2 and 0.68 at the tube exit are correlated well within the ± 20 percent accuracy limits. The same equation correlated point heat transfer coefficients from runs with a quality in the range of 12 percent to 50 percent within ± 30 percent accuracy limits. The dimensionless groups

$$T_s \frac{\sigma_{H_2O}}{T_L}$$

(-----) and (---) were powerful correlating factors.

The latter group accounts for the differences in the nucleating properties of the various single component liquids and its correlating effectiveness indicated that nucleation was one of the mechanisms present in the flow boiling.

Smith [168] studied some of the reasons why thermosiphon reboilers sometimes fail to measure up to expected performance levels and suggested that the single most important process parameter affecting the performance is the liquid level in the tube. He suggested that usually about 25 to 50% of the tube length above the bottom tube sheet, the heat transfer rate begins to deteriorate with further reductions in the liquid head.
Mesler [139] made critical analysis of Dengler and Addom's experimental data and found severe inconsistencies. He observed that the analysis by Dengler and Addoms was not correct and his data could not be explained by nucleate boiling mechanism. Based on this finding, he critically examined the similar data of other authors and added support to his analysis. Later, Chaudhari and Mesler [43] proposed analytical linear models relating basic parameters of nucleate boiling as heat flux, q, and ΔT. They included mass velocity also to take into account the effect of convection. Models were also successfully compared with the experimental data of various authors appeared earlier in the literature.

Leong and Cornwell [132] studied the heat transfer characteristics on the shell side of a reboiler tube bundle. The experimental rig consisted of a reboiler section with one side of glass to enable visual and photographic study of flow. Refrigerent-113 is boiled within the section on a simulated tube bundle on 241 electrically heated tubes. Individual heat transfer coefficients for the tubes were measured at various uniform heat fluxes. The magnitudes of these heat transfer coefficients and their variation with height up the tube columns were compared with the theoretical predictions of a flow boiling analysis.

Johnson and Yukawa [112] studied the effect of submergence on the resulting length of boiling and non-boiling zones under vacuum on an industrial reboiler.

Shah [162] explained some trouble shooting methods with respect to the design and operational difficulties generally encountered in thermosiphon reboilers.

Shah [163] presented a general correlation for calculating CHF in vertical tubes during subcooled and saturated boiling. He compared his correlation to 1271 data points from more than 30 sources and found to have a mean deviation of 15% with 90% of data within +30%. Data include water, potassium, freons, benzene, ammonia, parahydrogen, and nitrogen. Reduced pressure range was 0.0012 to 0.94, mass flux from 6 to 24300 kg/m² s, critical quality from -2.6 to +0.96, and inlet quality from -3.0 to positive values.
Agarwal [4,5] carried out an experimental investigation on heat transfer of various liquids with natural convective flow through a vertical tube as encountered in thermosiphon reboiler. The heat transfer section consisted of an electrically heated S.S. tube of 21.44 mm I.D. and 1440 mm long. The wall and liquid temperatures were measured at very low heat fluxes, for a test liquid with different inlet liquid subcooling and submergence. Data were generated for five test liquids - water, acetone, ethyl acetate, propan-2-ol and toluene to cover a wide range of thermophysical properties. The degrees of subcooling at the test section inlet were varied to cover the natural convective as well as boiling regions of heat transfer. The heat transfer coefficients in non-boiling and boiling regions for all the test liquids have been correlated by two separate correlations in terms of dimensionless groups.

\[
(Nu_{NB})_{avg} = 0.0126 \ (Gr.Pr)_{avg}^{0.481} \ (Re)_{avg}^{0.064} \ (----)^{-0.23} \ (2.14)
\]

\[
Nu_B = 6.142 \ (Pe_B)^{0.462} \ (----)^{0.0134} \ (Pr)^{1.014} \ (----)^{1.743} \ (X_{tt})^{V_{H_2O}} \ (2.15)
\]

Stephan and Abdelsalam [170] have applied the methods of regression analysis to the nearly 5000 existing experimental data points for natural convection boiling heat transfer. They demonstrated by analysis that these data can best be represented by subdividing the substances into four groups (water, hydrocarbons, cryogenic fluids and refrigerants) and employed a different set of dimensionless numbers for each group of substances. They suggested that an equation valid for all substances could be built up, but its accuracy would be less than the individual correlations without adding undesirable complexity.
Stephen and Aloni [17] has shown in a recent paper that many existing data of natural convection nucleate boiling are well represented by using a different set of dimensionless numbers for different groups of substances. They built a general correlation valid for all substances considering the influence of forced convection. They found that existing experimental data could be fairly well correlated by introducing the new pool boiling equation into an equation by Chawla.

Lazarek et al. [130] have measured experimentally the local heat transfer coefficient, pressure drop and CHF on tubes with an internal diameter of 0.31 cm, heated lengths of 12.3 and 246 cm. Their experiments include vertical, co-current upflow and down flow configurations. They presented a correlation for the local heat transfer coefficient which expresses the Nusselt number as a function of the liquid Reynolds number and boiling number. Pressure drop data for frictional, spatial acceleration, and 180° band losses were successfully correlated by employing slight modifications to commonly accepted two-phase techniques reported in the literature. A new CHF correlation, applicable to low reduced pressure conditions, is developed which predicts the vapor quality at dryout in terms of mass velocity, inlet-subcooling and heated length. The CHF correlation is accurate within 5% over the range of conditions covered in the experiments.

Bjorge et al. [35] have extended the method of superposition for correlating forced convection boiling heat transfer data to cover subcooled to high quality ranges using single phase and two phase forced convection equations, a pool boiling equation, and an incipient boiling criterion. They found that only one empirically determined coefficient is needed. Agreement with water data was found better than that provided by the Chen correlation.

Bartolini et al. [24] carried out an experimental study on nucleate boiling of water using an annular vertical channel both in upflow and downflow. Heat transfer data are given in different conditions of subcooling and fluid velocity. They found that photographs show different behaviour of heat transfer mechanism.
Tobilevich and Filonenko [187] studied the mechanism of heat transfer in the boiling tubes of natural circulation evaporators. The boundaries of the characteristics heat transfer regimes were determined. Equations were derived describing the heat transfer coefficient during vapor formation, which can be used for predicting the heat transfer coefficients in the boiling tubes of evaporators of different shapes and geometric dimensions.

Kasyanenko et al. [117] investigated the heat transfer to aqueous salt solutions in a concentrator with natural convective circulation through external boiling tubes. In the experimental study, the length of heating tube (L) was varied from 5000 to 7000 mm, the ratio of cross-sectional areas of boiling tubes and heating tubes (n) from 0.81 to 2.49, the useful temperature difference from 10 to 30°C, the viscosity from 1 to 4 C.P., the density from 960 to 1300 kg/m³, the thermal conductivity from 0.44 to 0.6 Kcal/(m)(hr)(°C) and the heat capacity from 0.80 to 1 Kcal/(kg)(°C). From the least squares analysis of the experimental data, the following empirical equation was developed for the prediction of the heat transfer coefficient.

\[
\frac{1}{h} = A \cdot Pr^{0.4} \cdot Ko^{0.43} \cdot (-)^{0.865} \cdot \frac{\mu_w}{\mu_L}^{0.28} \quad \ldots (2.16)
\]

where

\[
A = \sum_{i=1}^{N} E_i M_i
\]

and

\[
Ko = \frac{(t_{ns}-t_{b}) k_L \rho_L}{3600 \lambda \rho_v \mu_L}
\]

The error of reproduction of the experimental data by this equation is not greater than 10%.
Baloh [26] measured experimentally the temperature of the tube wall and vaporator tube. From the experimental data, the local heat transfer coefficients as well as heat transfer in the evaporator tube were calculated and also the apparent level of juice and tube length were determined.

Gungor and Winterton [85] have developed a new general correlation for forced convection boiling with the aid of a large data bank. The data bank consists of over 4300 data points for water, refrigerants and ethylene glycol, covering seven fluids and 28 authors, mostly for saturated boiling in vertical and horizontal tubes, but with significant information also for subcooled boiling and for annuli. The correlations developed are as follows:

For saturated boiling

\[ h_{tp} = h_{1} + Sh_{pool} \]  \hspace{1cm} (2.17)

where

\[ E = 1 + 24000 \beta_{0}^{1.16} + 1.37 (---)^{0.86} \]

\[ S = 1/1 + 1.15 \times 10^{6} E^{2} \beta_{1}^{1.17} \]

\[ h_{1} = 0.023 \beta_{1}^{0.8} \beta_{r}^{0.4} \]

\[ h_{pool} = 55 \beta_{r}^{0.12} (-\log_{10} \beta_{r})^{-0.55} \beta_{p}^{-0.5} \beta_{r}^{0.67} \]

In subcooled boiling:

\[ q = h_{1} (T_{w} - T_{b}) + Sh_{pool} (T_{w} - T_{s}) \]  \hspace{1cm} (2.18)

These correlations give a better fit to the data than existing correlations. The mean deviation for boiling heat transfer coefficient is 21.4% for saturated boiling and 25.0% for subcooled boiling.

Kobertson and Sudek [155] carried out upflow boiling tests on a vertical 10.7 mm bore, electrically heated copper tube with ethanol at various heat fluxes, mass fluxes of 145 and 290 kg/m^2 s and a pressure of 1.5 bar. They have compared boiling heat transfer coefficients and measured local two-phase pressure
gradients with the production of empirical and theoretical models. Heat transfer coefficients for the nucleate boiling region have also been obtained and compared with published pool-boiling correlations.

Klimenko [122] proposed a generalized correlation for forced convection vaporization heat transfer, which is valid for both vertical and horizontal channels with a fully wetted perimeter. The correlation represents experimental data for nine different fluids, with a mean absolute deviation of 12.9%. The ranges of parameters were: pressure 0.61-30.4 bar, mass flow rate 50-2690 kg m\(^{-2}\) s\(^{-1}\), vapor quality 0.017-1.00, channel diameters 1.63-41.3 mm. He found that vaporization heat transfer rate depends on the thermal conductivity of channel wall material. Heat transfer in the region of developed nucleate boiling and convective boiling can be predicted from the following equations:

\[
\text{Nu}_B = 7.4 \times 10^{-3} \, \text{Re}^{0.6} \, \text{Pr}_l^{1/3} \, \frac{k_w}{k_l} \quad (--)^{0.15} \quad (2.19)
\]

\[
\text{Nu}_C = 0.087 \, \text{Re}_m^{0.6} \, \text{Pr}_l^{1/6} \, \frac{\rho_v}{\rho_l} \, \frac{k_w}{k_l} \quad (--)^{0.2} \, (--)^{0.09} \quad (2.20)
\]

He has also suggested a universal criterion for convective boiling which determines the dominant mode of heat transfer of the two main ones; nucleate boiling or evaporation.

Ali [12] carried out an experimental investigation on heat transfer to boiling liquids with natural convective flow through a vertical tube thermosiphon reboiler. The test section consisted of an electrically heated S.S. tube 25.56 mm I.D., 28.85 mm O.D., and 1900 mm long. The wall and liquid temperatures were measured at various heat fluxes, for a test liquid with different inlet liquid subcooling and submergence. Data were generated for test liquids, distilled water, acetone, ethanol and ethylene glycol to cover a wide range of thermo-physical properties. The heat transfer coefficients in the non-boiling and boiling regions for all the test liquids have
been correlated by two separate correlations in terms of dimensionless groups:

$$\text{Nu}_C = 2.62 \ (Gr)^{0.220} \ (Pr)^{0.768} \ (Re)^{0.229} \ (-\ -) 0.375 \ldots (2.21)$$

$$\text{Nu}_B = 7.388 \ (Pe_B)^{0.526} \ (Pr_B)^{0.115} \ (-\ -) 0.085 \ (----) 0.48 \ \ldots (2.22)$$

Ali and Alam [15] carried out an experimental investigation of heat transfer to boiling liquids under natural convective flow to study the effect of heat flux and liquid submergence on heat transfer coefficient. They developed a dimensional correlation for the estimation of heat transfer coefficient in the fully developed boiling region.

Cooper [52] re-examined the nucleate boiling term in the Chen correlation [44] for the heat transfer coefficient in flow boiling. The re-examination employed all available data published for water, and also additional data from flow boiling experiments, in which the 'apparently nucleate' regime can be distinguished with some confidence. It was concluded that a term based on the new pool boiling analysis would probably be better as well as simpler, but, in view of the extremely wide scatter present in these and all other nucleate boiling data, there is no strong case for altering existing calculation methods based on the term derived by Chen.

Hahne and Grigull [86] obtained heat transfer coefficients from experiments on flow boiling with R12 for a wide range of pressure, mass flux, heat flux and flow quality. They compared experimental results with seven different correlations. They found good agreement only for some correlations, but best agreement for the modified Chen correlation using the pool boiling equation by Corenflo [79] and the suppression factor by Bennet and Chen [29].

Kenning and Cooper [119] obtained accurate heat transfer data for saturated flow boiling of water at 160-600 kPa in 9.6
and 14.4 mm bore vertical tubes under conditions dominated by convection or by nucleate boiling. Convection in the annular flow regime is well described by a modified Chen correlation. They found that further modification is required for Plug/Churn flow. Flow nucleate boiling is shown to be sensitive to surface conditions where as convective boiling is not. Saturated convective and nucleate boiling are not additive; the larger of \( \alpha_c \) or \( \alpha_{nb} \) should be used. They discussed the appropriate features of general flow boiling correlations.

Klimenko [123] in his second assessment proposed a generalized correlation for two-phase forced flow heat transfer (nucleate boiling and vaporization) which is valid for vertical and horizontal channels with a fully wetted perimeter. The correlation represents with a mean absolute derivation equal to 14.4\%, experimental data for 21 different liquids (water, organic liquids, freons and cryogens) in the following ranges of the main parameters: pressure, 0.61-196 bar; heat flux density, 10-8\( \times 10^6 \) W/m\(^2\); mass flow rate, 5.6-6240 kg/m\(^2\).s, channel diameter, 0.47-74.7 mm. It has been found that both the nucleate boiling and the vaporization heat transfer intensity depend on the thermal conductivity of the channel wall material. Nucleate boiling heat transfer is described in terms of dimensionless numbers, containing an individual constant for each of the four groups of fluids (water, organic, liquids, freons and cryogens) while vaporization heat transfer is represented by a single equation with a constant universal for all the fluids. He suggested following correlation for two-phase flow heat transfer:

\[
\begin{align*}
\text{Nu}_B & \quad \text{with } N_{CB} < 1.6 \times 10^4 \\
\text{Nu}_C & \quad \text{with } N_{CB} > 1.6 \times 10^4 \\
\end{align*}
\]

where the nucleate boiling heat transfer is found from the formula.

\[
\text{Nu}_B = 7.4 \times 10^{-3} \ \text{Pe}^{0.6} \ \text{Re}^{0.5} \ \text{Pr}^{-1/3} \ \text{Ka}^{0.15} \quad \text{.. (2.23)}
\]
and the forced convection vaporization heat transfer is given by the relation

\[ \text{Nu}_C = 0.087 \, \text{Re}_m^{0.6} \, \text{Pr}_l^{1/6} \left( \frac{\phi_v}{\phi_l} \right)^{0.2} \, K_{\lambda}^{0.09} \]  

(2.24)

Gel'perin et al. [76] studied heat transfer in boiling of cyclohexane, PrOH and BuOH in thermosiphon tubes (diameters 22-38 mm, height 3.0 m). They presented graphically the dependence of heat transfer coefficient on the temperature gradient at various heat fluxes and gave a correlation for this heat transfer coefficient.

Calus et al. [41] obtained heat transfer data from a natural circulation single tube reboiler for binary liquid mixtures of isopropanol, n-propanol and glycerine each with water. Two tubes, one of copper and one of stainless steel, were used to obtain length-mean heat transfer coefficients. Also one stainless steel tube was used to obtain local coefficients. All the three tubes had nominal dimensions of 0.5 in. diameter and 4 ft. length. It was found, in correlating the experimental data, that the single component correlation was adequate, provided that the surface tension used in it is that of the binary liquid of the interfacial concentration, \( \sigma_L \), and that the temperature driving force is the difference between the wall temperature and the saturation temperature of the mixture of interfacial concentration. The latter was found by correcting the apparent temperature difference \( T_f \) with the correction factor \( F \). The length mean coefficients corresponding to a combination of flow boiling regimes, excluding the purely bubbly-nucleate and dry-wall regions, were correlated by the equation:

\[ \frac{h_T}{h_L} = 0.065 \left( \frac{T_s}{X_{tt}} \right) \left( \frac{\sigma_{H20}}{\sigma_L} \right)^{0.9} F^{0.6} \]  

(2.25)
where 

\[ F = 1 - \left( \frac{y^*-x}{\lambda D_M} \right)^{0.5} \]

75 to 95 percent of the data points, depending upon the type of mixture, were within \( \pm 20 \) per cent accuracy limits. The same equation correlated the local coefficients within \( \pm 30 \) percent accuracy limits, if the data points for nucleate boiling or dry wall regimes were rejected. The factor \( F \) was a powerful parameter with binary mixtures having a highly non-ideal vapor liquid equilibrium relationship. In the case of binary mixtures of low relative volatility this factor is very close to unity.

Shock [167] has studied the types of liquid mixtures which exhibit high nucleate boiling heat fluxes. He found that the explanations for the decrease in nucleate boiling heat transfer coefficient which results when a second component is added to a pure liquid are inconsistent. He summarized various mechanisms postulated to account for this behaviour. He showed that the difference in the superheat required to initiate bubble growth was influenced by wetting changes at low organic concentrations for aqueous organic solvent mixtures. He deduced that the diffusion resistance encountered when boiling had commenced played a significant role for aqueous systems and furthermore was probably the controlling factor for non-aqueous systems.

Ponter and Peier [150] re-examined Shock's analysis using total reflux wetting data. The data confirm that small bubble production with accompanying high heat transfer is to be expected.

Bennet and Chen [29] reported over 1000 sets of data for forced convective boiling of distilled water, ethylene glycol and aqueous mixtures of ethylene glycol. Most of these data were taken in the annular flow regime. They observed a significant reduction in the heat transfer coefficient for mixtures attributable to mass transfer effects. They developed an expression which accounts for both of these effects and correlates the experimental data to within a mean deviation of
The correlation reduces to the standard Chen correlation for pure fluids with Nusselt numbers close to unity.

Toral, Kenning and Shock [189] obtained flow boiling heat transfer data for ethanol, cyclohexane and their mixtures in a vertical electrically heated tube. The test section was a copper tube 26.2 mm internal diameter, 0.86 mm average wall thickness. The boiling curves for the pure liquids and their azeotrope have very steep slopes, while other compositions have much smaller slopes. They observed that the present correlation techniques for mixture effects are inconsistent with their findings. They suggested that bubble growth and nucleation may be the possible reasons for the low heat transfer rates in mixtures.

Schlunder [109] derived an equation for predicting heat transfer coefficients for nucleate boiling of mixtures, which contains only one adjustable parameter and the liquid-phase mass transfer coefficient. If the adjustable parameter is put equal to unity, comparison with the most recent data for the SF₆-CF₂-Cl₂ system gives a mass transfer coefficient of $2 \times 10^{-4}$ m/s, which is of the same order of magnitude as the value obtained in physical and chemical absorption and in falling film vaporization. The new equation corresponds particularly well with the experimental observation that the heat transfer coefficient is less dependent on the heat flux density and the pressure for nucleate boiling of mixtures than in the case of the pure components.

Kusumowardhoyo and Hardianto [125] investigated the two-phase heat transfer in saturated flow-boiling region for multi-component mixtures (ethanol-gasoline). The binary heat transfer coefficient where heat transfer of boiling is simply expressed in terms of the boiling number can be predicted as:

$$\text{Nu}_{TP} = 3.2 \left(\text{Re}_L\right)^{0.8} \left(\text{Pr}_L\right)^{0.8} \left(\text{Bo}\right)^{0.6} \ldots \ (2.26)$$

where

$$\text{Bo} = \frac{Q/A}{\rho \cdot \dot{m} \cdot c_p}$$
Ross et al. [156] determined experimental heat transfer coefficients for pure R152a and R13B1 and for four mixtures of these refrigerants. They found that mixtures yielded sharply lower heat transfer coefficients than either pure refrigerant. Correlative evidence suggests that full suppression of nucleate boiling is easier to achieve with mixtures than pure fluids. They compared the existing correlations to the data with success for both pure and mixed fluids.

Ali [11,12] carried out an experimental study to heat transfer to boiling binary liquids with natural convective flow through a vertical tube. The systems used for binary mixtures were acetone-water, ethanol-water and water-ethylene glycol. The heat transfer coefficients in the non-boiling and boiling regions for all systems have been correlated by two separate correlation in terms of dimensionless groups:

\[
\text{Nu}_{CM} = 2.394 \left( \text{Gr} \right)^{0.171} \left( \text{Pr} \right)^{0.3728} \left( \text{Re} \right)^{0.074} \left( \text{Pe} \right)^{-0.04} \quad \text{...(2.27)}
\]

\[
\text{Nu}_{BM} = 0.307 \left( \text{Pe}_B \right)^{0.835} \left( \text{Pr}_B \right)^{1.212} \left( \text{x}_{tt} \right)^{0.169} \left( \text{Pe} \right)^{0.918} \quad \text{...(2.28)}
\]

Thome [182,185] investigated the mixture effect on the nucleate boiling contribution to convective boiling inside of vertical tubes at low vapor qualities. He observed that the effect of mass diffusion on the boiling process reduces the nucleate boiling heat transfer coefficient for mixtures substantially relative to an equivalent pure fluid. Thome tested mixture boiling correlation factors from two published convective boiling mixture correlations against a published set of experimental data for the convective boiling of ethanol/cyclohexane mixtures with partial success. He found that several correlations for the mixture correction factor in
nucleate pool built accurately predict the data's variation with composition and heat flux. He presented one of these correlations for the first time and uses the boiling range with a heat flux dependency to model the mixture boiling process.

Jung et al. [113] carried out an experimental study on horizontal flow boiling heat transfer for pure R22, R114 and their mixtures under uniform heat flux condition. They obtained more than 1200 local heat transfer coefficients for annular flow at a reduced pressure of 0.08. The ranges of heat flux and mass flow rate are 10-45 kW/m² and 16-46 g/s, respectively. Their results indicate a full suppression of nucleate boiling for pure and mixed refrigerants beyond transition qualities and the majority of the data belongs to the convective evaporation region. The heat transfer coefficients of mixtures in this region are as much as 36% lower than the ideal values under the same flow condition. Non-ideal variations in physical properties account for 80% of the heat transfer degradation seen with mixtures and the other 20% (less than 10% of the heat transfer coefficient) is believed to be caused by mass transfer resistance in this region. A composition variation of upto 0.07 mole fraction in the annular liquid film was measured between the top and bottom of the tube, which causes a corresponding circumferential variation of wall temperature with mixtures.

Jung et al. [114] studied mixture effects on horizontal flow boiling heat transfer with both azeotropic and non-azeotropic refrigerant mixtures. They developed an analysis to predict a transition quality by using Hsu's [101] onset of nucleate boiling theory. The prediction agreed well with observed transition qualities for both pure and mixed refrigerants. Correlations based on the supposition of Chen [45] and using only phase equilibrium data to consider mixture effects, were developed with mean deviations of 7.2 and 9.6% for pure and mixed refrigerants.