CHAPTER 1

INTRODUCTION

The hydrochlorofluorocarbons refrigerants (HCFCs), especially the refrigerant R-22, have been employed as the working fluids in many refrigeration systems for many years because of their excellent thermal properties and compatibility with various tubing materials. However, evidences have shown the destruction of the ozone layer in the arctic area and the global warming by the use of the traditional chlorofluorocarbons (CFCs) and HCFC refrigerants such as refrigerants R-12 and R-22. Refrigerant R-12 has been phased out and replaced by the hydrofluorocarbons refrigerant R-134a. As for refrigerant R-22, it will be phased out within the next two decades according to the Montreal Protocol amendments. Various non-chlorine alternative refrigerants such as R-134a, R-407C and R-410A were recently proposed for various applications to replace R-22. In order to properly use these new refrigerants in the air conditioning and refrigeration systems, we need to know their thermophysical and heat transfer properties. Especially, the detailed understanding of the two-phase heat transfer and associated bubble characteristics for these new refrigerants is very important in the design of evaporators and condensers used in many current refrigeration and air conditioning systems. In view of the possible enhancement of heat transfer in small channels, we require to develop smaller and more compact evaporators and condensers. Despite the great effort has been paid to the investigation of single and two phase heat transfer in small channels from the heat transfer research community, many unknowns still exist and the detailed heat transfer mechanisms in the small channel flow remain controversial. Specifically, the detailed heat transfer and associated bubble characteristics in small channels need to be understood in order to delineate the associated heat transfer mechanisms. The main purpose of this study is to unveil the detailed subcooled and saturated flow boiling heat transfer characteristics for new refrigerants in an annular duct with a small gap. More specifically, the bubble dynamics associated with the flow boiling of R-134a in the horizontal narrow annular duct with the inner pipe heated will be explored by visualizing the motion of the bubbles in the boiling flow. The relations between the bubble dynamics and heat transfer characteristics are then delineated. General comments on the new refrigerants and flow boiling in channels are made in the following along with a review of the literature relevant to the present study.

1.1 New Refrigerants - Ozone Friendly Refrigerants to Substitute for R-22

Over the past decades refrigerant R-22 ($CHClF_2$) has been the most extensively used working fluid in air conditioning and refrigeration systems. Its principal advantages include thermal and chemical stability, thermodynamic suitability, non-toxicity, non-flammability and non-explosiveness etc. But it will be phased out in a short period of time (before 2020) since the chlorine it contains has an ozone depletion potential (ODP) of 0.055 and comparatively high global warming potential GWP of 1500 based on the time horizon of 100 years [1,2]. As a result, the search for a replacement for R-22 has been intensified in recent years.

Owing to the fact that there are no single-component hydrofluorocarbons (HFCs) that have thermodynamic properties close to those of R-22, binary or ternary refrigerant mixtures have been introduced. The technical committee for the Alternative Refrigerants Evaluation Program (AREP) has proposed an updated list of the potential alternatives to R-22. Some of the alternatives on the AREP's list are R-410A, R-410B, R-407C and R-507. Among these alternatives, R-407C, R-410A and R-410B are gaining most favorable support depending on the particular applications and system design [3]. Meyer [4] has evaluated five refrigerants, including R-290, R-134a, R-404A, R-407C and R-410A, as replacement for R-22 by comparing the cooling capacity, coefficient of performance, compressor discharge temperature, input power, refrigerant mass flow, pressure ratio, and volumetric refrigeration capacity. Besides, alternatives to R-22 for air conditioners were assessed by Devotta et al. [5].

Many long-term alternative refrigerants are mixtures of two or more HFCs and fall into two major groups, zeotropes and azeotropes. More specifically, R-407C is a ternary zeotropic mixture consisting of 23 wt% of R-32, 25 wt% of R-125, and 52 wt% of R-134a. One important feature of the zeotropic mixtures is the temperature glide during the phase change at a constant pressure. Due to the vapor pressure of R-407C is only slightly higher than R-22, the air conditioning system conversion from those using R-22 to R-407C can be fulfilled by simply changing the lubricant. R-410A is a near-azeotropic binary mixture consisting of 50 wt% of R-32 and 50 wt% of R-125. This near-azeotropic mixture has a very small temperature glide (0.1 ^{o}C) and behaves like a single component refrigerant. Currently R-134a, which is a single-component HFC refrigerant and has similar thermophysical properties to R-12, has been extensively used in many systems to substitute for R-12 and R-22. A number of investigations have been reported in the literature dealing with the two-phase (subcooled and saturated boiling, evaporation and condensation) heat transfer of R-134a in ducts of various geometries and dimensions. However, the subcooled and saturated flow boiling heat transfer characteristics for R-410A and R-407C are less studied. Some characteristics of the selected traditional and new refrigerants are compared in Table 1.1 including the ODP and GWP. The operating conditions of refrigerants R-134a, R-410A and R-407C are given in Table 1.2.

1.2 Flow Boiling – Brief Description

Boiling is a phase change phenomenon associated with heat transfer to a liquid and formation of vapor bubbles. If boiling nuclei are at a solid-liquid interface, the boiling mechanism is called heterogeneous boiling. While it is called homogeneous boiling if the nuclei are inside the liquid. The amount that the liquid temperature exceeds the saturation temperature of liquid corresponding to the local pressure is termed "superheat". Usually the superheat required for the homogeneous nucleation is much higher than that for the heterogeneous nucleation. If heat transfer induced density changes and boiling activities are the only causes of fluid motion, the process is called "pool boiling". If there is an imposed coolant flow over the heated boiling surface acting by an external circulatory force, it is called "forced convection (or flow) boiling". Saturated boiling means the bulk liquid is at the saturation temperature, corresponding to the system pressure, and subcooled boiling is named when the bulk liquid temperature is lower than the saturation temperature. In this case, the difference between the bulk liquid temperature and saturation temperature is called the subcooling. The present study is limited to the heterogeneous flow boiling.

According to Kandlikar [6], the subcooled flow boiling on a heated wall covers the region beginning from the location where the wall temperature exceeds the local liquid saturation temperature to the location where the thermodynamic quality of the flow reaches zero, corresponding to the saturated liquid. Figure 1.1 is a schematic diagram to illustrate the boiling of a subcooled liquid refrigerant flow in an annular duct with a constant heat flux imposed at the outside surface of the inner pipe [6,7]. The subcooled liquid refrigerant enters the annular duct at point A in the entry section of the duct at given flow rate and temperature, and the wall temperature of the pipe surface is below the local saturated temperature of the refrigerant. Since the single-phase convection heat transfer coefficient depends very weekly on the wall temperature, both the wall and bulk liquid temperatures increase linearly along the length of the duct until the wall temperature reaches the local saturated temperature of the liquid at point B. However, nucleate boiling does not commence immediately until a certain wall superheat is reached. A certain amount of wall superheat is needed to activate nucleation cavities existing on the pipe surface. This boiling incipient wall superheat depends on the heated wall surface and flow conditions. The liquid gets heated as it moves along the heated wall and the liquid temperature distribution adjacent to the hot surface may result in local boiling at point C while the bulk of the flow is still subcooled. The location C at which the first bubble appears on the surface is identified as the onset of nucleate boiling (ONB). The bubbles form on the cavities or scratches on the heated surface. Meanwhile, the heated wall temperature may drop immediately to a noticeable degree due to more nucleation sites are activated. Thus there is a significant temperature undershoot during the onset of nucleate boiling (ONB). This interesting phenomenon is known as the boiling hysteresis. This is due to the fact that a sudden activation of a large number of cavities at a higher wall superheat, causing a reduction in the surface temperature while the imposed wall heat flux remains constant. Beyond the ONB a small rise in the wall superheat causes a large increase in the heat transfer rate from the wall to the liquid. The wall and bulk temperatures rise linearly and are almost parallel with each other until point D.

After the inception of the boiling, the density of the active nucleation sites and the frequency of the bubble generation increase with the wall superheat, resulting in a marked improvement in heat transfer. Further downstream, as more nucleation sites are activated on the heating surface, both the single-phase convection and phase change heat transfer contribute to the total heat transfer rate. From the viewpoint of the heat transfer characteristics, the subcooled boiling process can be divided into the partial nucleate boiling and the fully developed nucleated boiling. The location E is a transition point from the partial nucleate boiling to the fully developed nucleated boiling. The contribution of heat transfer from the nucleate boiling continues to rise while the single-phase convection contribution diminishes in the partial boiling region. In this partial nucleate boiling region, the bubbles cannot continually grow due to the condensation occurring at the liquid -bubble interface exposed to the subcooled liquid flow, and a thin layer of bubbles is formed on the heated surface. As the refrigerant bulk temperature increases along the flow direction, the layer becomes populated with more bubbles, whose size also increases with decreasing liquid subcooling. At E point the single-phase convection contribution becomes insignificant and the fully developed boiling is established. The fluid velocity and subcooling have little or no effect on the surface temperature. Then the saturated flow boiling occurs at F point at which the bulk liquid flow is at saturated condition. In the fully developed nucleate boiling, bubble coalescence occurs at the heated surface.

A boiling curve is a characteristic curve describing the relationship between the heat flux removed from a hot surface (or wall) and the superheat of the surface for given (1) fluid/surface combination (roughness, surface micro geometry, wet ability, dissolved non-condensable gas content, surface contamination, etc.), (2) thermophysical properties (density, heat capacitance, thermal conductivity, etc.) of the fluid and the wall, and (3) ambient conditions (e.g. gravity, surface orientation, subcooling, pressure, surface shape, channel dimensions, velocity, curvature, etc.). A typical forced-convection boiling curve is sketched in Fig. 1.2. From point A to point B or B' the heat transfer is caused by single-phase forced convection. The point B or B' is called the onset of nucleate boiling (ONB) where boiling activity begins. Generally speaking, a smooth surface/highly wetting fluid combination tends to generate a curve such as AB'BC when the heat flux is the controlled parameter (or AB'BH if the surface temperature is the controlled parameter), while a rough surface/low wetting fluid combination tends to give a path like AB'C. The wall temperature or superheat difference between points B and C is called the temperature undershoot (or called the incipience undershoot). From point C to point D' is the fully-developed nucleate boiling. It is characterized by large slopes of high heat transfer coefficients. A smooth transition from the single-phase forced-convection to fully-developed nucleate boiling, curve B'C, is caused by the partial boiling. Finally, point D, critical heat flux (CHF) (or dry out, or the first crisis), will be reached. At that point, local vapor-film patches will more frequently form on the heated surface, causing degradation of the heat transfer coefficient [8].

Hsu [9] was the first to postulate the criteria for the boiling inception. According to his criteria, for an embryo to evolve into a bubble the minimum temperature surrounding the bubble (the temperature at the tip of the bubble) should be at least equal to the saturation temperature corresponding to the pressure inside the bubble. The pressure inside the bubble is higher than the surrounding liquid, and the pressure difference can be expressed in terms of the Young-Laplace equation for a spherical bubble. The corresponding saturation temperature inside the bubble can be approximately found from the Clausius-Clapeyron equation, assuming a linear temperature drop in the thermal boundary layer (or assuming constant heat flux at wall), which lead us to obtain the incipience heat flux (q_{ONB}) and wall superheat($\triangle T_{SAT,ONB}$). Several studies have been conducted on boiling inception for refrigerants. Hahne et al. [10] studied incipience in subcooled flow boiling for a well wetting liquid (R-12) and came up with a model also applicable for other refrigerants. For well wetting liquids, they stated that the vapor nuclei in the cavities even in the size corresponding to the minimum wall superheat for inception may be displaced or diminished. As such, the correlation from Hsu[9] may not be applicable to the well wetting liquids. They assumed that for such liquids, a nucleus is necessary for the boiling incipience and that is given by the largest of the remaining nuclei on the surface. They developed a correlation for the prediction of the heat flux and wall superheat required for the incipience based on this radius r*, which is the largest of all the nuclei present on the surface. They applied their correlation successfully to data available in the literature for different refrigerants like R-113, R-11, and R-12, covering a wide range of fluid velocities, subcooling, and pressures. Literature review on ONB shows that most of the correlations are based on the minimum superheat criteria from Hsu's postulation. These correlations generally underpredict the actual superheat required for inception. Inception will occur at this superheat only when the corresponding cavity size is available on the surface. For well wetting liquids, the available cavity size is reduced according to Hahne et al.[10]

As mentioned above, at the beginning of the boiling processes the cavities are flooded with liquid and a higher degree of wall superheat is requires. Once the boiling is initiated, the required superheat to sustain the bubble activity becomes lower due to presence of vapor inside the cavities. The behavior is known as the hysteresis effect. The phenomenon of a sudden drop in the wall temperature at the ONB depends on the fluid properties (such as wettability, contact angle and subcooling) and cavity geometry (roughness, coating and cleanliness). The possibility of the cavity flooding is more likely for low-surface-tension and highly wetting fluids such as refrigerants. This is because the low-surface-tension fluids typically have smaller contact angles. However, the cavity geometry and the existence of dissolved gas should have significant effects on the boiling hysteresis [7]. Subcooled flow boiling of R-113 inside a vertical concentric annulus with the inner tube heated was examined by Hino and Ueda [11]. They ascribed the boiling hysteresis to the variation in size of active nucleation cavities on the wall. It is especially important in electronic cooling industry where the maximum chip surface temperature must be well-controlled. The hysteresis will threaten the cooling of electronic devices because the temperature undershoot causes the thermal shock to the devices.

1.3 Literature Review - Flow Boiling Heat Transfer

It is now well known that boiling heat transfer for flow inside channels is a combination of the convective heat transfer from the wall to the liquid and nucleate boiling at the wall. In other words, convective boiling is characterized by the conduction and convection heat transfer through the liquid and the vaporization at the liquid/vapor interface. Moreover, the nucleate boiling is characterized by the formation of vapor bubbles at a heated wall when nucleation conditions are met. For reasons mentioned above, in convection-dominated flow boiling, the heat transfer coefficient is independent of the wall heat flux (or wall superheat) and increases with increasing mass flux and vapor quality. On the other hand, in nucleation-dominated flow boiling the heat transfer coefficient is independent of the mass flux and vapor quality. But it increases with the heat flux (or wall superheat) and is sensitive to the saturation pressure level (the heat transfer coefficient increases with the pressure).

In the following the relevant literature on the flow boiling heat transfer characteristics is briefly reviewed. Subcooled flow boiling of heptane on an internally heated rod and resistance-heated coiled wire in an annular duct was examined by Müller-Steinhagen et al. [12]. Their results indicated that the boiling heat transfer coefficient increased with increasing heat flux but decreased with increasing system pressure and liquid subcooling, while independent of the mass velocity in the nucleate boiling regime. Moreover, the boiling hysteresis was only found at low mass velocity. Hasan et al. [13] investigated the subcooled nucleate boiling of R-113 flow through a vertical annular channel with an electrically heated inner pipe and a thermally insulated outer pipe. They found that the boiling heat transfer coefficient was lower for higher pressure and subcooling. Moreover, the heat transfer coefficient increased with the mass velocity of the refrigerant flow. Besides, the boiling hysteresis was revealed by a sudden drop in the wall temperature in the boiling curve, and the hysteresis was more severe at lower refrigerant mass velocity and pressure. Later, Hino and Ueda [11] studied the incipient boiling superheat and hysteresis by measuring the wall temperature profile and by observing the subcooled boiling flow of R-113 in a pipe. Their results indicated that the wall superheat for the incipient boiling was little affected by the mass velocity and liquid subcooling. In addition, the boiling hysteresis was ascribed to the differences in the size of active nucleation cavities on the wall subject to the increasing and decreasing heat fluxes. Sivagnanam et al. [14] studied subcooled flow boiling of binary mixtures on a long platinum wire and proposed correlations for the partial boiling and fully developed boiling regions incorporating the effects of the subcooling, liquid velocity and binary composition. Subcooled flow boiling of water at a high heat flux was experimentally investigated by Del Valle M. and Kenning [15]. They found that the heat transfer coefficient increased with the subcooling and heated wall thickness. The subcooled flow boiling and the associated bubble characteristics of R-134a in an annular channel were examined recently by Yin et al. [16]. They showed that the subcooled boiling heat transfer was not significantly affected by the refrigerant mass flux, imposed heat flux and saturation temperature. But an increase in the inlet subcooling resulted in much better heat transfer. The subcooled film boiling for a vertical up-flow in a directly heated tube using refrigerants R-12, R-22 and R-134a as test fluids was investigated experimentally by Hammouda et al. [17]. Their results showed that the heat transfer coefficient was very sensitive to the flow parameters such as the mass flux, inlet subcooling and pressure.

Due to the high thermal efficiencies, small size, low weight, design flexibility and energy savings, compact heat exchangers have been used more and more widely in applications involving phase changes. Recently there has been a growing awareness of the benefits from the process intensification and the reduction in plant size for a given capacity. This has led to a requirement for smaller evaporators which are widely used in current energy saving air conditioning and refrigeration systems [18,19,20]. The size of the channels in a compact heat exchanger can significantly affect the performance of the exchanger. Mehendale et al. [18] suggested to use the hydraulic diameter D_h to classify the size of heat exchangers: (1) micro-heat exchanger for D_h =1 ~ 100μm, (2) meso heat exchanger for D_h=100μm ~ 1mm, (3) compact heat exchanger for D_h=1 ~ 6mm, and (4) conventional heat exchanger for D_h>6mm. Another classification from Kandlikar [21,22] proposed that D_h >3mm for the conventional channels, 200μm< D_h <3mm for the mini-channels, 10μm < D_h <200μm for the micro-channels, 0.1μm < D_h <10μm for the transitional channels, 1μm < D_h <10μm for the transitional micro-channels, 0.1μm < D_h <1μm for the transitional nano-channels, $D_h \leq$ 0.1μm for the molecular nano-channels. The boiling heat transfer mechanisms occurring in compact heat exchangers have been examined by many research groups [23-43]. Most authors examine the boiling characteristics in single, small, circular and rectangular channels as a part of a study for narrow compact two-phase heat exchangers [23-29,31,37]. Other authors investigated boiling in the a narrow concentric duct to understand the boiling activities [38-40]. Besides a few groups directly use heat exchanger test sections characterized by small multi-channel passages in parallel to unveil the boiling characteristics [30,41-43].

As the channel size decreases below certain critical value, the two-phase flow regimes and the associated heat transfer differ from those in conventional systems. Which heat transfer mechanism is more important or even prevalent is the main issue of many investigations. In general, convective boiling dominates for low values of heat flux and wall superheat and high vapor qualities while nucleate boiling dominates for high values of heat flux and wall superheat and for lower vapor qualities. A number of experimental studies have been conducted on flow boiling in small channels where the heat transfer is dominated by the nucleate boiling or forced convective boiling. This is ascertained by checking whether the boiling heat transfer coefficient was a strong function of heat flux and only weakly dependent on mass flux and vapor quality, which implied a nucleate boiling controlled process [23-25,28-29,35,38-40,42]. Some scholars indicated that both the nucleate and convective boiling mechanisms were important in the flow boiling heat transfer of the small pipe [33,36,41,43]. It should be mentioned that reducing the channel dimension can have a negative effect on the heat transfer coefficient in the channel.[27,40,41] Some authors observed that boiling heat transfer was much higher in small channels [32,39,40]. The higher boiling heat transfer in the small channels is attributed to three reasons. First, in the small channels the two-phase flow progressively passes from an isolated bubble to a confined bubble regime. The heat transfer in the confined bubble regime is considered to very effective [27]. Secondly, because the space limitation in the small channels the bubbles are squeezed and deformed and the effects of the surface tension and friction shear stress might be stronger. Besides, the cavities for nucleation might be more easily wetted [39]. Thirdly, the bubble departing frequency increased inversely with the cross-sectional area of the channel. This in turn enhances the turbulence level in the flow [40].

1.4 Literature Review - Flow patterns and bubble characteristics

To elucidate flow boiling heat transfer mechanisms in small channels, we require to delineate the prevailing flow regimes. Base on visualization of the flow and measurement of the heat transfer, three flow regimes have been suggested, namely, the isolated bubble, confined bubble and annular-slug flows [27,41,44]. However, Bubble behavior such as bubble generation frequency, growth, sliding and departure size plays an important role in flow boiling heat transfer. The bubble characteristics in the boiling flow have been examined by a number of research groups. For instance, Sheng and Palm[44] visualized the flow pattern and bubble shape for water in a single glass tube with small tube diameters (D_h = 1.0, 1.6, 2.0, 4.0 mm). They indicated the bubble departure diameter was dependent much on the mass flow rate but was slightly affected by the imposed heat flux. Recently, Lee et al. [45] and Li et al. [46] examined the bubble dynamics in a micro channel (D_h = 41.3 & 47.7 μm). The bubble departure radius was correlated by the modified form of the Levy equation. The behavior of near-wall bubbles in subcooled flow boiling for water and R-134a in vertical rectangular channel (D_h = 6.1 mm) was investigated photographically by Bang et al.[47]. They described the coalescence of the bubbles and showed that the bubbles were smaller at a higher mass flux. Similar study for water in a vertical annular channel conducted by Situ et al. [48] indicated that the bubble departure frequency increased with the heat flux. Bibeau and Salcudean [49] visualized the bubble cycling of water flow in a vertical annular pipe (D_h = 10.0 mm) with a high speed photography. They noted that the maximum bubble diameter varied from 0.8 to 0.3 mm and at ejection the bubble was smaller than the maximum diameter, since the bubble condensed on the wall while sliding. The subcooled flow boiling and the associated bubble characteristics of R-134a in a horizontal annular channel (D_h = 10.3 mm) were examined recently by Yin et al. [16]. Results from their flow visualization indicated that the bubble generation was suppressed by raising the mass flux and subcooling, and only the liquid subcooling showed a significant effect on the bubble size. Finally, an empirical correlation for the bubble departure diameter was provided.

Thorncroft et al. [50] experimentally investigated upflow and downflow boiling of FC-87 in vertical rectangular channel ($D_h = 12.7$ mm). They indicated that both bubble growth and bubble departure rates increased with the Jacob number, but decreased with the mass flux. Besides, the bubble waiting time decreased with an increase in the heat flux. This increase in the heat transfer was directly attributed to the sliding vapor bubbles, which remained attached to the wall during the upflow and lift off from the wall during the downflow. The sliding of the bubbles on the boiling surface was found to enhance heat transfer in forced convection boiling of FC-87 in a vertical upflow and downflow by Thorncroft and Klausner[51]. An experimental investigation of low pressure subcooled flow boiling inside a vertical concentric annulus($D_h = 13.0$ mm) from Zeitoun and Shoukri [52] confirmed that the bubble departure was not the reason for the net vapor generation (NVG). However, the mean size and lift duration of the bubbles increased at decreasing liquid subcooling. Moreover, a new correlation for the mean bubble diameter in terms of the Reynolds number, boiling number, local Jacob number, and fluid properties was proposed. Klausner et al. [53] developed a criterion for the bubble departure from the heated surface in the forced convection boiling. The study was carried out for a saturated two-phase mixture of refrigerant R-113 flowing through a 25×25 mm^2($D_h = 25.0$ mm) visual boiling section. They found that the mean bubble departure diameter decreased with increasing mass flux and with decreasing heat flux. Their analytical prediction further showed the strong influences of the liquid velocity and wall superheat on the bubble departure diameter. They also noted that before lifting off from the heated wall, the bubbles would slide a finite distance along the surface. They concluded that not only the surface tension force but also the asymmetrical bubble growth acting in the direction opposite to the fluid motion were important in holding the bubbles at the nucleation sites before departure. Chien and Webb [54] studied the bubble dynamics for pool boiling on an enhanced tubular surface, which consists of an integral-fin tube having a copper foil wrapped over the fin tips. They showed that the mean bubble diameter was smaller for a higher heat flux and the bubble growth period was shorter for smaller bubbles and higher heat flux.

Yang and Kim [55] attempted to quantitatively predict the active nucleation sites from knowing the size and cone angle β of the cavities actually present on the surface. Using an electron microscope and a differential interference contrast microscope, they obtained the cavity probability density function involving cavity size (ranging from 0.65 to 6.2 μm) and β (cone half angle). The size distribution was found to fit a Poisson distribution while a normal distribution was used for β. Gaertner [56] observed that active nucleation sites were randomly located and could be expressed in terms of Poisson's distribution function. Sultan and Judd [57] reached the same conclusion from their observations. Zeng and Klausner [58] obtained experimental data for the active nucleation site density N_{ac} during flow boiling of R-113 on a horizontal 25 mm×325 mm test section with a nichrome heating strip. Their experiments were performed for varying vapor quality at inlet, system pressure and wall heat flux. They examined the effects of vapor velocity, liquid velocity, liquid film thickness, system pressure, and wall heat flux on N_{ac}. They concluded that even if N_{ac} was dependent on the critical radius of the nucleus r_c, their data were not sufficient for correlating N_{ac}. From their data, they further concluded that the vapor velocity, heat flux, and system pressure had strong effects on N_{ac}. Kocamustafaogullari and Ishii [59] developed a relation for active nucleation site density in pool boiling from the data available in the literature. They also applied the correlation to the few available forced convection nucleate boiling data. Their correlation expressed the active nucleation site density in dimensionless form as a function of dimensionless minimum cavity size and density ratio. The correlation was valid for the system pressure ranging from 1.0 to 198.0 bar. Basu et al [60] proposed an empirical correlation including the effect of the contact angle on the active nucleation site density during forced convective boiling of water on a vertical surface based on their experimental data. They performed subcooled boiling experiment at the atmospheric pressure. In the experiments, they utilized mirror-finished copper surfaces prepared by a well-defined procedure. They varied the wettability of the surface by controlling the degree of oxidation of the surface.

1.5 Literature Review – Correlation Equations for Two-phase Flow

Based on the available experimental data from the open literature, some correlating equations for flow boiling heat transfer were proposed [61-67]. An early general correlation model for the two-phase flow boiling, which is still widely quoted, is that of Chen [61]. He divided the boiling heat transfer coefficient into two parts: a microconvective (nucleate boiling) contribution estimated by the pool boiling correlations and a macro convective (non-boiling forced convection) contribution estimated by the single-phase correlation such as the Dittus-Boelter equation [62]. In order to account for the diminished contribution of nucleate boiling, as the convective boiling effects increased at a higher vapor quality he introduced the enhanced factor E and suppression factor S to respectively accommodate the forced convective and nucleate convective contributions. Gungor and Winterton [63] modified the Chen's correlation and proposed the correlations for the enhanced and suppression factors. An enhanced model based on the ratio of two-phase heat transfer coefficient to single-phase heat transfer coefficient was developed by Shah [64]. The ratio was correlated in terms of a series of flow parameters, including convection number Co and boiling number Bo. The other enhanced model was developed by Kandlikar [65] to predict the saturated boiling heat transfer coefficients for refrigerants inside horizontal and vertical tubes. A new correlation from Liu and Winterton [66] introduced an asymptotic function to predict the heat transfer coefficient for vertical and horizontal flows in tubes and annuli. A general subcooled flow boiling correlation based on a large amount of data from annuli was developed by Shah [67]. The data include water, R-113 and methanol for heat transfer in the inner, outer, and both tubes of the annuli. Kandlikar [6] divided the subcooled flow boiling into the partial boiling, fully developed boiling and significant void flow regions. Meanwhile, appropriate correlations were presented to predict the heat transfer in each region. A correlation for boiling heat transfer in small diameter channels was proposed by Cornwell and Kew [41]. They introduced a confinement number in the correlation. Table 1.3 lists some of these correlations for two-phase flow boiling heat transfer in conventional tube. Some empirical correlation equations proposed in the literature for flow boiling heat transfer coefficients in the small channels were summarized in Table 1.4.

1.6 Objective of The Present Study

In recent years, environmental concerns over the use of CFCs as working fluids in refrigeration and air-conditioning systems have led to the development of alternative fluids. Among these alternatives, R-134a, R-407C and R-410A are often used as substitutes for the HCFC-22. Moreover, considerable effort has recently been devoted to improve the design of more compact and efficient evaporators for the process and refrigeration industries. While a great number of technical papers have been written on the flow boiling heat transfer, only several of them consider the associated bubble characteristics for the widely used refrigerant R-134a particularly in small channels. In this study, the saturated and subcooled flow boiling of refrigerant R-134a in an annular duct with a small gap between the inner and outer ducts are investigated by measuring the boiling heat transfer coefficient and by visualizing the bubble behavior. The effects of the imposed heat flux, gap size, mass flux, inlet subcooling and saturation temperature of refrigerant R-134a on the boiling heat transfer characteristics will be examined in detail. The results will be presented in terms of the boiling curves and the heat transfer coefficients. Particularly, flow visualization is conducted here to examine some bubble characteristics associated with the flow boiling such as the mean bubble departure diameter, generation frequency, active nucleation site density and velocity of big bubbles in slug flow to improve our understanding of the flow boiling processes in the narrow channel.

The experimental apparatus, data reduction and the results obtained in this study are presented and discussed in the following chapters:

(1). The experimental apparatus and instruments for the present experiment will be described in Chapter 2.

(2). The procedures adopted for reducing the measured raw data will be discussed in Chapter 3.

(3). Saturated flow boiling and associated bubble characteristics for R-134a flowing in a horizontal narrow annular duct are addressed in Chapter 4.

(4). Subcooled flow boiling and associated bubble characteristics for R-134a flowing in a horizontal narrow annular duct are examined in Chapter 5.

(5). Some concluding remarks from the results presented in Chapters 4 and 5 and recommendation for future works are discussed in Chapter 6.