CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Boiling Heat transfer

Boiling heat transfer is known as a superior mode of heat transfer due to the latent heat transport during the phase-change. It is characterized by high heat transfer which is essential for industrial cooling applications, such as nuclear reactors and fossil fuel boilers. Due to its importance in industry, a large amount of researches have been extensively carried out to study the boiling heat transfer capacity and mechanism.

Boiling is a liquid-to-vapor phase-change process which involves the formation of liquid-vapor interfaces (bubble generation) at discrete sites on the heated surface or in a superheated liquid layer adjacent to the heated surface. Boiling is one of the most efficient heat transfer mechanism as it utilizes the latent heat of vaporization and allows a large amount of heat to be transferred over a small surface area. It is widely used in industries that require the removal of high heat flux, from small electronic chip cooling to large scale power plants.

The phenomena of boiling is classified as pool boiling or flow boiling, depending on the presence of bulk fluid motion. According to the bulk fluid motion, boiling is classified as pool boiling, which is under quiescent fluid conditions, or flow boiling, which is under forced-flow conditions. The different boiling mechanisms include convective boiling, nucleate boiling and film boiling. When bulk liquid temperature is below the saturation temperature, the process is called subcooled boiling, whereas if the liquid is maintained at the saturation temperature the process is known as saturated boiling as shown in Fig. 2.1.

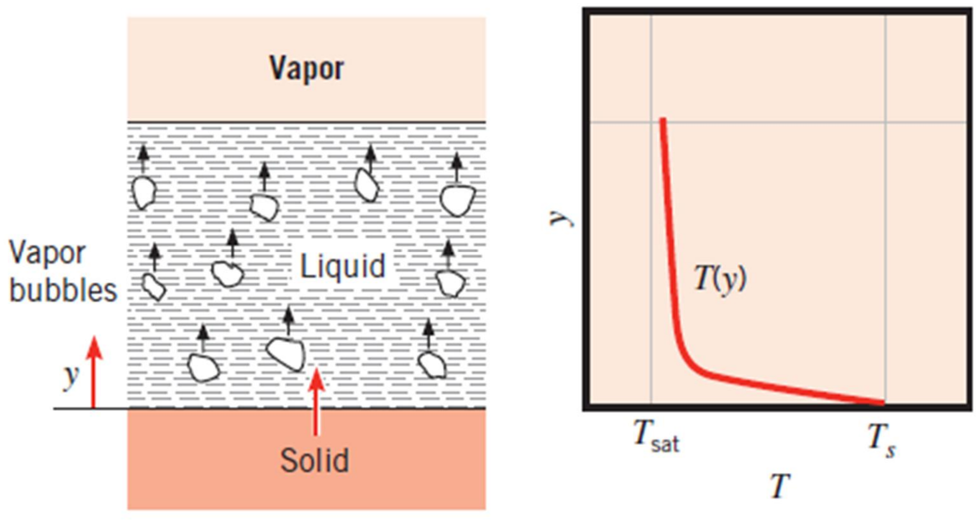


Fig. 2.1 Saturated pool boiling [18]

2.1.1 Pool Boiling

Pool boiling is the process in which the heating surface is submerged in a large body of stagnant liquid. Boiling curve exhibits the relationship between applied heat flux and wall superheat and has been presented for pool boiling phenomenon in Fig. 2.2.

Nukiyama [19] was the first to introduce boiling curves for nucleate boiling in 1934, followed by Bergles[20], Rohsenow et al. [21] Kutateladze [22], Katto [23], Berenson [24], Kandlikar [25] and Dhir [26]. Depending on the applied heat flux and resulting wall superheat, the entire boiling curve is divided into natural convection, nucleate boiling, transition boiling and film boiling. These classifications are based on heat transfer characteristics and bubble behaviour during boiling. Among these boiling regimes, the nucleate boiling regime exhibits the highest heat transfer rate.

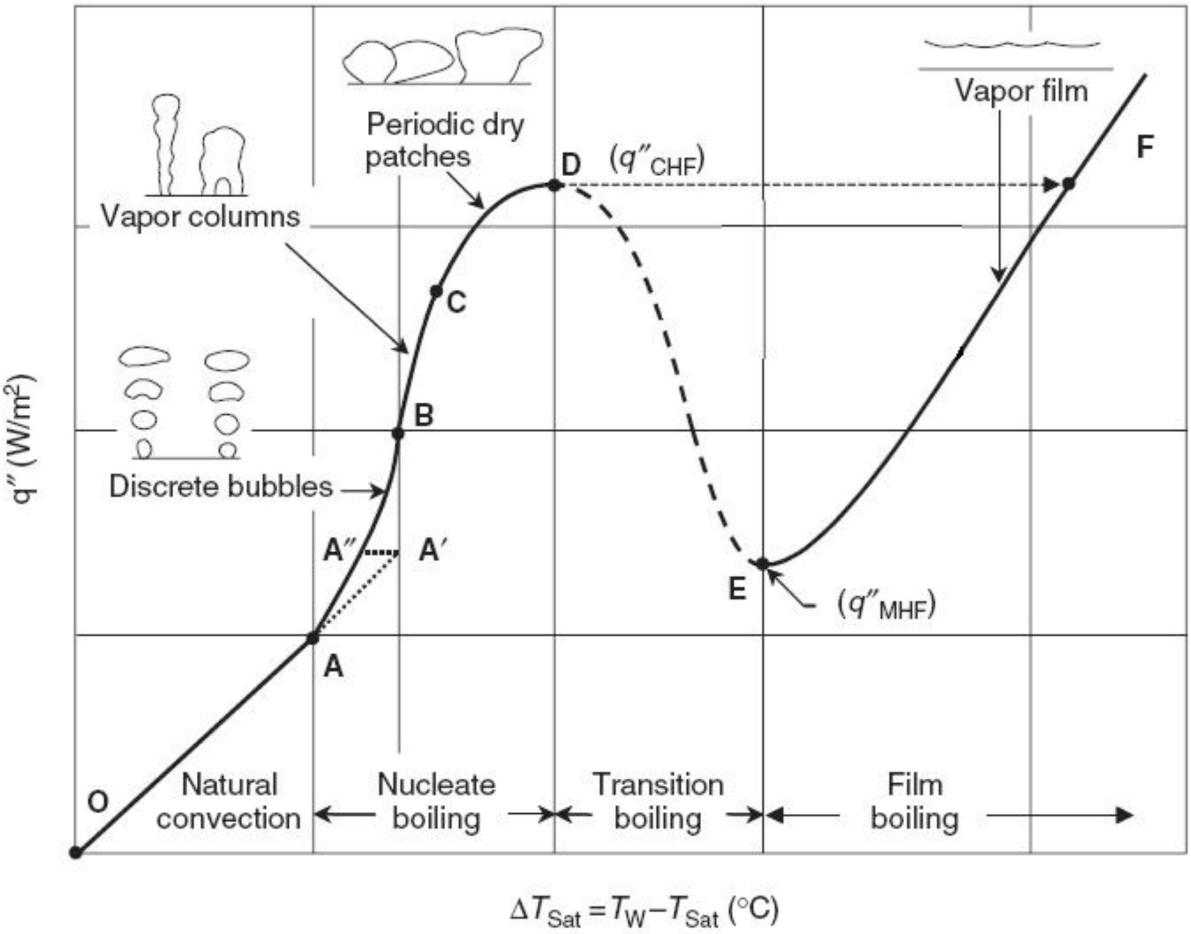


Fig. 2.2 Boiling curve and heat transfer mechanisms in pool boiling [27]

The boiling curve consists of several regimes classified by the bubble conditions. Initially (O-A), heat is transferred by natural convection between the hot surface and the liquid vapor interfaces. When wall superheat reaches a certain value (A), bubbles nucleated at the vicinity of the surface, which is known as the onset of nucleate boiling (ONB).For liquids with higher wettability, this ONB may be delayed(A') [28]. As the applied heat flux increases, the bubble behavior changes from weak boiling to vigorous boiling (B) because of activation of more number of nucleation sites. Later, in the region C to D, the intense evaporation underneath the bubble leads to periodic dry patches on the heater surface. The nucleate boiling at the highest heat flux intensity (point D) is referred to as critical heat flux (CHF). Later, the liquid flow to the heater surface decreases, leading to the formation of hot spots on the heater surface which is known as transition boiling. This phenomenon increase the wall temperature up to point E, where the heat flux reached a minimum called the Leidenfrost point. As the heat flux is further increased, the temperature reaches point F, the film boiling region. The curve E-F represents the film boiling, vapour film covers the surface and the liquid does not contact the solid. The region between D-E is known as the transition boiling region which is very unstable.

Among these boiling regimes, nucleate boiling is the most desirable one in practice because high heat transfer rates can be achieved in this regime with relatively small values of $\Delta Tsup$, typically under 30°C for water [29]. During nucleate boiling, vapor bubbles form at cavities along the heated surface where a gas or vapor phase already exists. Due to the continuous heating and liquid evaporation, the vapor bubbles keep growing and expanding until the buoyancy force is large enough to lift the bubbles from the cavities. During this process, bubbles move and carry away the latent heat of evaporation, while the bulk liquid present in the flow continues to remove heat by natural convection from the surface.

2.1.2 Flow boiling

Flow boiling is the boiling process where the fluid is forced to move in a heated channel (internal flow boiling) or over a surface (external flow boiling) by external means as it undergoes a phase-change process. Since there is no free surface for the vapor to escape during internal flow boiling (two-phase flow), the consequent mixing of the liquid and vapor phase make it more complicated in nature and strongly influence the boiling phenomena. Therefore, flow boiling heat transfer is closely related to the two-phase flow structure of the evaporating fluid. Also, it exhibits characteristics of both convection and pool boiling.

The flow patterns encountered in up flow of liquid and vapor in a vertical tube are shown in Fig. 2.3.

- Bubbly flow: small discrete bubbles in the continuous liquid phase with various shapes and sizes.
- Slug flow: with increasing the gas fraction, larger bubbles formed due to collision and coalescence.
- Churn flow: with increasing the velocity, the flow becomes unstable and the liquid travels up and down in an oscillatory fashion.
- Annular flow: a thin film of liquid on the wall with the gas as the continuous phase in the centre of the tube.

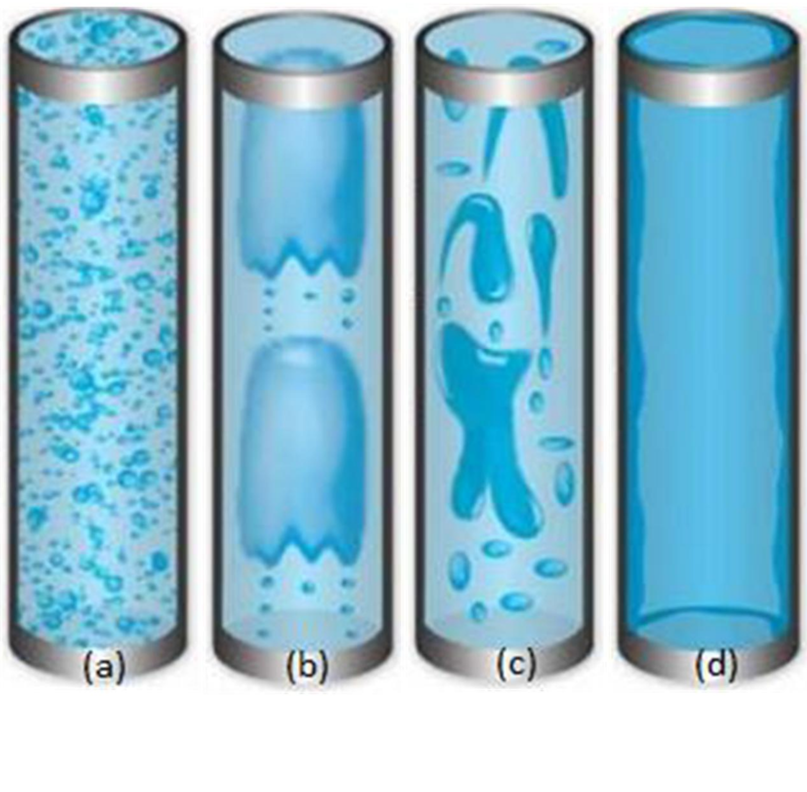


Fig. 2.3 Flow patterns in vertical up flow: (a) bubbly flow; (b) slug flow; (c) churn flow; (d) annular flow [30]

The boiling curve similar to that in pool boiling is obtained when flow occurs inside a heated tube**.** Figure 2.4 shows a picture of forced flow boiling process in which subcooled liquid enters the tube. The flow of liquid is upward and the supplied heat flux is uniform. The flow patterns have been presented along with temperature profile. The flow boiling mechanisms are more complex as compared to pool boiling because of continuous mixing of liquid and vapour along the flow.

The first mode of heat transfer is single-phase convection as subcooled liquid enters the tube. Single phase convection continues until the wall temperature reaches a certain value above the saturation temperature. With increase in heat flux, boiling is initiated with formation of bubbles and only few nucleation sites are found to be active[31], being identified as the onset of nucleate boiling (ONB). As more nucleation sites become activated, nucleate boiling heat transfer increases while the convective heat transfer diminishes. This region is termed as partial boiling. When the surface is entirely covered with active nucleation sites, fully developed nucleate boiling is established. As the wall superheat is increased further, different flow patterns were observed with increasing heat flux. Small discrete bubbles appeared in bubbly flow which developed into larger coalesced bubbles changing the flow pattern to slug flow and eventually dry patches appeared on the heater rod exhibiting departure from nucleate boiling. Further downstream, the addition of vapor leads to complete evaporation of the liquid film. This transition is known as dryout and is accompanied by a rise in the wall temperature.

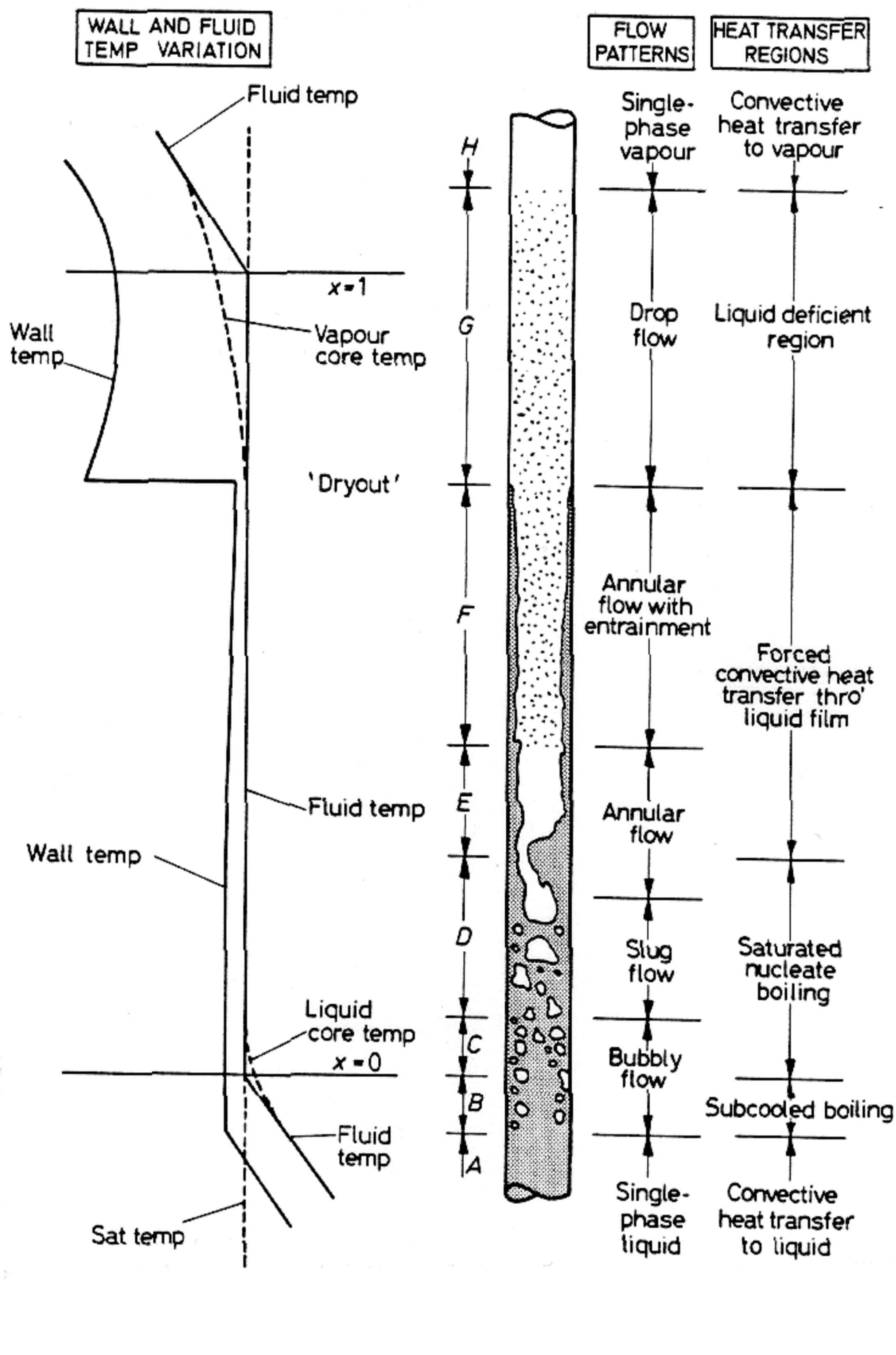


Fig. 2.4 Flow boiling in a uniformly heated circular tube [32].

The critical heat flux (CHF) in water subcooled flow boiling has been studied in relation with the cooling of high heat flux components in nuclear reactors. From a practical point of view, optimum cooling is achieved by maintaining conditions within the nucleate boiling regime, above the onset of boiling, but safely below CHF. Given the great importance of CHF to cooling system design, investigators have studied its mechanisms for decades in pursuit of predictive models and correlations. However, owing to the complexity of the phenomenon of CHF, it is a difficult task for the researchers to explain the mechanism. According to the extensive reviews, a number of hypotheses have been reported which fall into one of the following four categories:

1. Hydrodynamic instability model - This theory proposed by Zuber et al. assumes that CHF occurs when the down flow of fresh liquid to the heated surface is prevented by the rising vapor [33-34]. The velocity of the bubbles increases as the heat flux increases. At a critical velocity, the vapor jets experience Helmholtz Instability. As a result the vapor columns collapse preventing the liquid to flow to the heated surface. This Helmholtz Instability occurs far above the heated surface and hence is also known as "far field theory".

The CHF is calculated as

$$q''_{CHF} = C.h_{fg}\rho_g^{1/2}\sigma^{1/4}g^{1/4}(\rho_f - \rho_g)^{1/4} \qquad (2.1)$$

Where C is an empirical constant depending on the geometry of the heater.

This theory excludes any effect of the heated surface characteristics on CHF and hence has been criticized in recent years.

2. **Macrolayer dryout model** - This model was originally proposed by Katto and Yokoya [23] and later modified by Haramura and Katto [35]. In this model a liquid film is formed, known as macro-layer which separates the heated surface under the bubble mushroom formed during nucleateboiling. This macro-layer is fed with liquid from surround regions while the bubble grows. CHF occurs once this macro-layer dries out which separates the heated surface from the liquid by a vapor film.

CHF is calculated as

$$q''_{CHF} = \rho_f h_{fg} \delta_e (1-\alpha) f_m \quad (2.2)$$

Where$\alpha$the void fraction at the surface is, f_m is the departure frequency of the mushroom bubble. The expression of δ_e was proposed by Sadasivan et al. [36], which includes the effect of the contact angle.

$$\delta_e = 0.5\,(N_A)^{-0.5}\left[\cos\theta - \frac{\pi}{12}(3\cos\theta - cos^3\theta)\right] \quad (2.3)$$

While the macro-layer dryout model deals with the evaporation of liquid film under the vapor mushroom, microlayer model [37] states that the boiling heat transfer is mainly due to the evaporation of a microlayer formed under individual bubbles. As the wall heat flux increases, the microlayer's thickness decreases leading to microlayer dryout and higher rate of evaporation. Hence a vapour film is formed between the liquid and the heated surface and CHF occurs (Fig. 2.5).

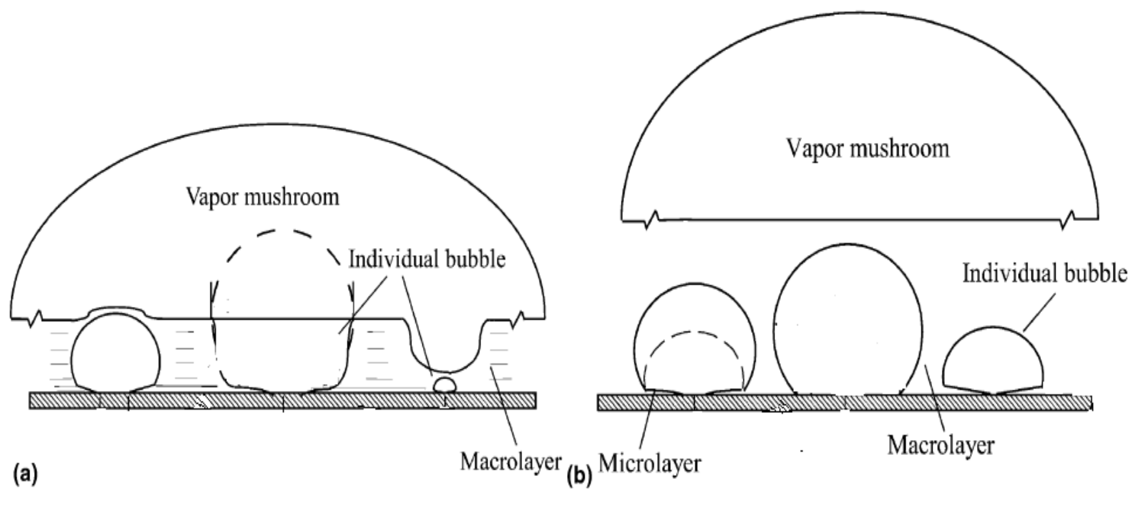


Fig. 2.5 Physical model (a) coalescence into vapour mushroom; (b) coalescence among individual bubbles [37]

3. **Bubble interaction model**

This theory states that at high heat flux the bubble number and departure frequency becomes very high .As a result the bubbles coalesce radially, liquid access to the surface is prevented and CHF occurs [38].

4. **Hot/Dry spot model**

This theory assumes that CHF occurs due to temperature excursions resulting localized hot/dry spots on the surface. Theofanous et al. [39] considered the micro-hydrodynamics of the solid-liquid-vapor line at the boundary of a hot/dry spot and calculated the CHF as:

$$q''_{CHF} = k^{-1/2}. h_{fg}\rho_g^{1/2}\sigma^{1/4}g^{1/4}(\rho_f - \rho_g)^{1/4} \qquad (2.4)$$

According to [39], k is smaller for a well-wetting surface than a poorly-wetting surface. Hence, a well-wetting surface will have a higher CHF than a poorly-wetting surface.

In contrast with pool boiling, which depends primarily on heat flux, the strong parameter of flow boiling is mass flux. At lower quality (vapor fraction), flow boiling is similar to nucleate boiling and depends mostly on heat flux and weakly on mass flux [40]. The mechanistic model and correlations for pressure drop and heat transfer in flow boiling are quite complex. Some semi- empirical flow boiling CHF models have been reported in the literature [41]. Bubble layer separation, near - wall bubble "crowding" and sub-layer dryout have been proposed as CHF mechanisms in the development of these models.

For flow boiling, as previously mentioned, the heat transfer is closely related to the two-phase flow structure of the evaporating fluid. As the use of nanofluids instead of pure liquids can significantly enhance the boiling heat transfer, a detailed and systematic literature review of experimental findings of boiling heat transfer of nanofluids is needed.

2.2 Boiling heat transfer of nanofluids

Boiling of nanofluids has been a vastly explored research topic. Though many researchers have investigated boiling heat transfer in nanofluids, variation of heat transfer coefficient is not clear. Several arguments among researchers on the enhancement and the deterioration of nucleate boiling heat transfer characteristics have been reported.

The presence of nanoparticles and the interaction of both the solid and the liquid phases play a vital role in the boiling phenomena of nanofluids. At high temperatures, during nanofluid boiling, particles agglomerate and deposit on the heating surface. This deposition leads to modification of the heating surface. The deposited nanoparticles change the active nucleation sites, alter the surface wettability and prevent direct contact of liquid with the boiling surface by forming extra thermal resistance on the heating surface. Conversely, the availability of nanoparticles to interact with the bubbles at the heater surface decreases as a result of the deposited nanoparticle layer. Also the boiling performance decreases because of deposited nanoparticles which fill the active micro-cavities [42-46]. The bubble diameter, nucleation site density and bubble frequency are all affected by addition of nanoparticles during boiling. Several researchers [45, 47] have found increased bubble diameters during nanofluid boiling, but decrease in nucleation site density with the addition of nanoparticles to the base fluid. In nanofluid boiling, varying dispersion conditions of nanoparticles alters the heater surface microstructure. These influence the bubble dynamics due to an increase in nucleation site density [48-49]. The complex mechanism of boiling heat transfer in nanofluids [50] might be one of the reasons for the inconsistency found in the literature.

2.2.1 Pool Boiling of Nanofluids

Research on pool boiling with nanofluids was initially conducted by You et al. [47] and Das et al. [42]. Since then, a number of studies have been conducted on pool boiling CHF and HTC. However, the results concerning nanofluid pool boiling remain inconsistent because of many variables such as nanoparticle material, heater surface properties, surfactant use, heater geometry etc. [51]. Nanofluids exhibited enhanced heat transfer performance as compared with boiling of pure fluids [52-55], which however contrasts significantly with others where heat transfer deterioration was reported [42, 44, 56]. Some others have shown both enhancement and degradation [47, 53]. It is difficult to explain such wide differences.

Tu et al. [57] tested Al_2O_3 nanofluids on a smooth heating surface and observed HTC enhancement (up to 64%) and a fourfold increase in nucleation sites. Liu et al. [52] tested CuO/water nanofluids of various concentrations on a copper plate with micro-groove structure and observed significant enhancements at lower value of mass concentration. The enhancement decreased with further increase in nanoparticle concentration. Shi et al. [58] performed experiments with iron and alumina nanofluids on a Cu block. It was found that Fe nanoparticles exhibited more enhancement than Al_2O_3 nanoparticles and the factors responsible for such enhancement were increased thermal conductivity and lowered surface tension. Similar HTC enhancement was also found in the work carried by Wen and Ding [55] where the pool boiling of Al_2O_3/water nanofluids was investigated inside a cylindrical vessel on a stainless steel disc. The pool boiling HTC significantly enhanced with the increasing particle concentration in nanofluids compared to water resulting in 40% enhancement for 1.25 wt%. Truong et al. [59] conducted pool boiling heat transfer experiments with SiO_2 and Al_2O_3/water nanofluids and found very high enhancements. Oxidation of copper heaters (four different roughness) due to boiling using water was investigated by Coursey and Kim [60]. Their results exhibited that the wettability is the main parameter behind the CHF enhancement with nanofluids. The contact angle of the heater surface was reduced after boiling in nanofluids. The largest enhancement of HTC was observed in the experimental study of Wen et al [61], where the pool boiling of 0.001 vol% Al_2O_3/water nanofluids on smooth heater surfaces exhibited a two-fold increase in boiling heat transfer coefficient under low heat flux conditions (Fig. 2.6). To conclude, these studies of dilute nanofluids showed enhancement ranging from 15–68% in nucleate boiling heat transfer.

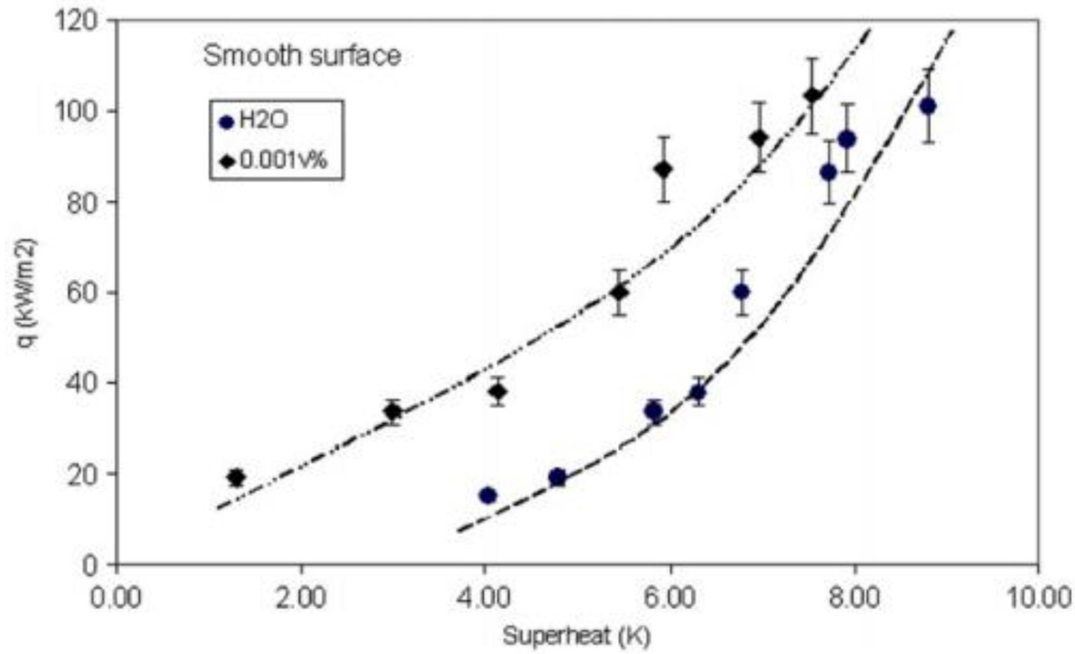


Fig. 2.6 Comparative boiling experiments on the smooth surface [61]

Several arguments among researchers on the deterioration of nucleate boiling heat transfer characteristics in nanofluids pool boiling have been reported. Bang and Chang [44] investigated the pool boiling characteristics of Al_2O_3/water nanofluids (0.5~4 vol%) on horizontal and vertical smooth heaters (R_a=37nm). Their results showed 25-50% deterioration in HTC with the increase in nanoparticle concentration. The authors observed significant change in the surface roughness especially after the occurrence of critical heat flux. Das et al. [42] worked with alumina-water nanofluids and concentrations of 0.1 to 4 vol. %. With increase in nanoparticle concentration, the nucleate boiling curve shifted to higher temperatures. Furthermore, a higher wall temperature was observed for the same heat flux, which corresponds to heat transfer degradation. Kim et al. [56] also tested several nanofluids (Al_2O_3, ZrO_2, SiO_2, 0.001~0.1 vol%) on stainless steel wires and plates. Even though due to the lack of exact data of the temperature curve for stainless steel, degradation of the HTC was found. Also significant deposition of nanoparticles on surface of heater was observed by the authors using scanning electron microscope (SEM) analysis. They attributed the HTC degradation in nanofluids to the deposited nanoparticles. Milanova et al. [62] conducted experiments using various nanofluids such as alumina (Al_2O_3), silica (SiO_2), and ceria (CeO_2). The nucleate boiling heat transfer decreased with changing PH in pool boiling experiments. It was found that the nichrome (NiCr) wires were oxidized due to nanoparticle deposition during the boiling experiments.

Kwark et al. [63] studied boiling mechanisms using a Cu block heater and alumina nanofluid. The SEM results exhibited that nanoparticle deposition occurred due to boiling rather than gravity effect or application of an electric field. The contact angle measurements yielded the smallest value for nanoparticle deposited heaters. They proposed microlayer evaporation mechanism which is responsible for particle deposition as shown in Fig. 2.7.

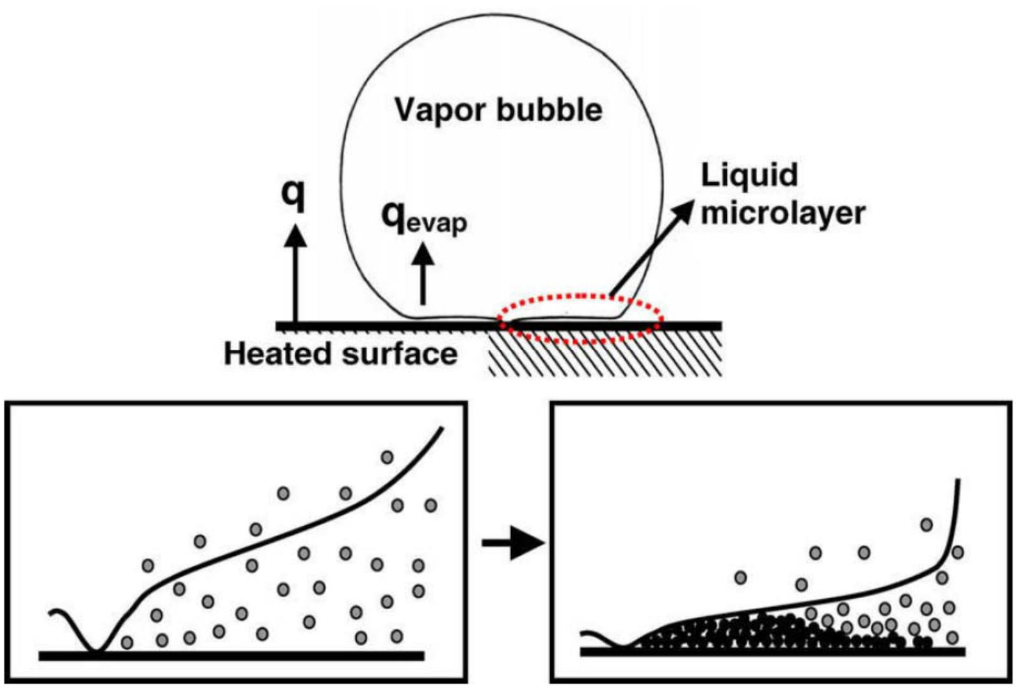


Fig. 2.7 Mechanism of nanoparticle deposition during the boiling process (microlayer evaporation) [63]

Zhou [64] investigated pool boiling phenomena using Cu nanoparticles with acetone as the base fluid in a horizontal Cu tube. Zhou observed convective heat transfer enhancement and degradation in boiling heat transfer. The R141b based TiO_2 suspension was boiled on horizontal cylindrical copper heater by Trisaksri and Wongwises [65]. They reported a degradation of heat transfer for 0.05 and 0.03 vol% TiO_2 concentrations.

There were few papers which reported both increased and decreased heat transfer. Chopkar et al. [66] investigated pool boiling of ZrO_2 based nanofluids using a Cu plate in a glass tube. Boiling heat transfer was enhanced at lower particle concentration, but deteriorated at higher concentrations or with repeated runs. The authors observed smoother surface after nanofluid boiling which was opposite to most experimental works. The authors concluded that, overall, it was too early to say whether heat transfer was enhanced or degraded. Kim et al. [67] investigated critical heat flux phenomena at different heater orientations using alumina nanofluid. They observed increased bubble size and decreased bubble frequency. However, the authors concluded that nucleate boiling heat transfer remain unchanged for nanofluids.

Narayan et al. [68] explained the mechanism of enhancement/deterioration of boiling heat transfer using nanofluids. The authors observed 70% enhancement in heat transfer coefficient with an average roughness of 524 nm heater surface and nanofluids with an average particle size of 47 nm. But when the ratio of the average surface roughness to the average particle size became close to unity, the pool boiling heat transfer deteriorated significantly due to the decrease of the number of nucleation sites. Vassallo et al. [53] used silica nanofluids on NiCr wires in their experimental investigation. The authors found a thin coating on the wires after boiling. No conclusions about enhancement or deterioration could be made because of the results obtained which were on either side of the curve for pure water. You et al. [47] used alumina nanofluid to investigate CHF and reported that bubble departure was decreased but bubble size was increased without any noticeable change in the nucleate boiling regime. Narayan et al. [68] suggested that enhancement or deterioration can be controlled by surface conditions. This group of research presented a variety of results for different nanoparticle material-heater surface conditions.

2.2.2 Flow Boiling of Nanofluids

Flow boiling of nanofluids has more applications in thermal systems than pool boiling, perhaps because of the potential to improve heat transfer and energy efficiency. Flow boiling heat transfer of nanofluids is more complicated than nanofluid pool boiling because flow regimes influence bubble dynamics. Hence, it becomes necessary to review the fundamental works carried out in nanofluid flow boiling heat transfer. Most of the flow boiling heat transfer studies of nanofluids deal with HTC, CHF and pressure drop. In recent years, flow patterns and bubble dynamics of nanofluid flow boiling have been investigated. But the relevant studies are rare. Some important experimental results of the nanofluid flow boiling have been summarized in Table 2.1.

Table 2.1 Some important experimental investigations of nanofluid flow boiling.

Reference	Test Section Geometry	Working Fluid	q"(kW/m^2)	Remarks
Kim et al. [46]	Stainless steel tube	Al_2O_3/water, ZnO/water, diamond/water	100-7500	53%, 53%, and 38% enhancements in CHF for Al_2O_3/water, ZnO/water, and diamond/water nanofluids, respectively
Kim et al. [43]	Stainless steel tube	Al_2O_3/water, ZnO/water, diamond/water	100-7500	Flow boiling CHF was enhanced up to 50% by the presence of the nanoparticles
Lee et al. [69]	1/2 inch Stainless steel (316L) tube	Al_2O_3/water, SiC/water	100-3500	CHF Enhancement of 15% for Al_2O_3/water and 41% for SiC/water
Lee et al. [70]	1/2 inch Stainless steel (316L) tube	GO/water	100-3500	100% CHF enhancement
Abedini et al. [71]	Stainless steel round tube	TiO_2/water	51-102	Heat transfer enhanced with increasing concentration
Sarafraz et al. [14]	Pyrex tube	CuO/water	0-190	Heat transfer deteriorated with concentration
Ahn et al. [72]	Transparent rectangular channel	Water	200-5000	Delayed transition from ONB to the CHF on nanoparticles-coated heater compared with bare heater
Rana et al. [11, 73]	Borosilicate glass tube	ZnO/water	100-550	Increased bubble population with increasing heat flux and decreasing particle volume fraction
Henderson et al. [74]	Horizontal copper tube	SiO_2/R134a CuO/R134a/POE	0.7-3.1	55% deterioration for SiO_2/R134a; more than 100% enhancement for CuO/R134a/POE
Xu and Xu [16]	Single rectangular	Al_2O_3/water	0-1000	For pure water the main flow pattern was

	microchannel			elongated bubbles, while for nanofluid, miniature bubbles were the major flow pattern.
Yu et al. [75]	Circular stainless steel mini-channel	Al_2O_3/water	Up to 406	Oscillation amplitudes of pressure, temperature and mass flux of nanofluids were reduced compared to water.
Edel and Mukherjee [76]	Single trapezoidal microchannel	Al_2O_3/water	130-300	Addition of nanoparticles stabilized bubble nucleation and growth and increased heat transfer in the thin film regions.

2.2.2.1 Heat Transfer Coefficient

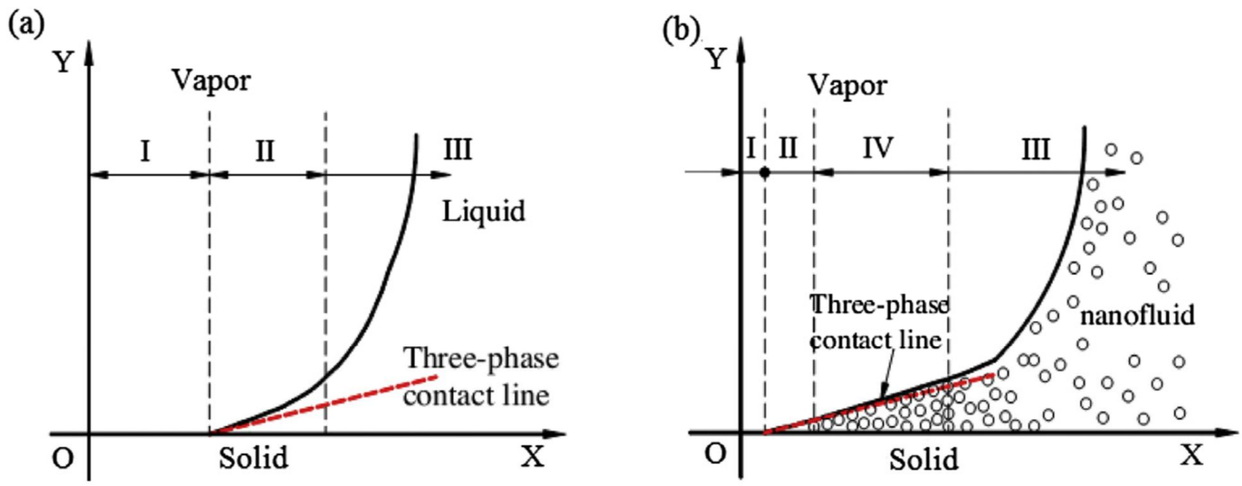
Peng et al. [77] investigated nanofluid flow boiling with CuO/R113 in a smooth horizontal copper tube. From the results, it was found that heat transfer coefficient of CuO/R113 nanofluid was higher than the pure liquid. The authors reported that reduction of the boundary layer height was the main cause behind HTC enhancement. There was formation of molecular adsorption layer on the surface of nanoparticles and the nanoparticles disturbed the boundary layer.

Kim et al. [43] experimentally studied the subcooled flow boiling using dilute alumina, zinc oxide and diamond water-based nanofluids at atmospheric pressure. Three volume concentration of 0.001%, 0.01% and 0.1% for all the nanofluids were used by the authors. Both heat transfer coefficient and critical heat flux were measured and it was found that CHF enhanced with increase in mass flux and nanoparticle concentration for all the three kinds of nanofluids. Nanoparticle deposition was found to be responsible for CHF enhancement as reported by Kim et al. [54]. They concluded that the nanoparticle deposition changes the micro-cavity number and affects surface wettability. The authors measured the contact angle of the fluid on the surface and number of micro-cavities.

However, the heat transfer coefficient remained largely unchanged with enhancement or deterioration of nucleation site density. Boudouh et al. [78] used CuO/water nanofluid for their flow boiling experiments in narrow rectangular cupper channels to study local HTC and local wall temperatures. The distribution of local heat flux, local HTC and local surface temperature varied with nanoparticle concentration and axial location. With increasing concentration of Cu nanoparticles, the local HTC and local vapour quality improved. Henderson et al. [74] investigated flow boiling phenomenon in a horizontal cupper tube using SiO_2/R134a and CuO/R134a/polyolester nanofluids. The HTC was found to decrease with addition of SiO_2 nanoparticles in R134a. They reported that particle agglomeration due to poor suspension degraded heat transfer. For CuO-R134a/polyolester oil nanofluids, heat transfer coefficient was not affected significantly.

Xu and Xu [16] studied flow boiling of water and alumina-water nanofluid in a single microchannel. The HTC of nanofluids was found to be larger than pure water but there was no nanoparticle deposition on the heater surface. The authors explained the heat transfer mechanism in terms of thin liquid film evaporation, interchange of hot and cold liquid during bubble departure and micro convection due to disturbance of the boundary layer during bubble departure (Fig. 2.8). Miniature bubbles suspended in the channel accounted for heat transfer enhancement during nanofluid boiling.

Abedini et al. [71] conducted subcooled flow boiling experiments with TiO_2/water nanofluids in vertical and horizontal stainless tubes. In subcooled zone, the heat transfer coefficient of titania nanofluid was less than water and further decreased with increase in nanoparticle concentration. Results indicated that the heating surface was coated with a porous layer of nanoparticles which increased the wettability during nanofluid boiling. This increasing wettability in turn increased the bubble departure size and decreased the bubble frequency which deteriorated HTC.



(a) Pure water: I -- area between the heater surface and the dry vapor, II -- thin liquid film evaporation heat transfer region, III -- bulk liquid heat transfer region. (b) Nanofluid: I -- area between the heater surface and the dry vapor, II -- thin liquid film heat transfer region without nanoparticles involved, III -- bulk nanofluid region, IV -- thin liquid film evaporation heat transfer region with nano-particles involved.

Fig. 2.8 Solid-liquid-vapor three phase contact line [16]

Rana et al. [11, 73] performed flow boiling experiments using ZnO/water nanofluid in a horizontal annulus at 1 bar inlet pressure and 20°C subcooling. The results indicated increase in HTC with increasing nanoparticle concentration. The reason may be attributed to enhancement in effective thermal conductivity and alteration of boiling surface. Sun and Yang [79]investigated flow boiling characteristics using four nano-refrigerants (Cu, Al, Al_2O_3 and CuO nanoparticles dispersed in R141b) in a horizontal copper tube. With increasing mass fraction, mass velocity and quality, the HTC of the nano-refrigerants increased. The HTC was mainly influenced by nanofluid concentration. Among all the nano-refrigerants, Cu/R141b exhibited highest enhancement in HTC and thermal conductivity of Cu was speculated to be responsible for such enhancement.

Sarafraz and Hormozi [14] conducted flow boiling experiments using CuO/water nanofluid in a vertical annular test section. The results reported two distinct heat transfer regimes, namely forced convective and nucleate boiling. With increasing nanoparticle concentration, HTC decreased in both the regions and the reason may be attributed to deposition of nanoparticles which affected surface wettability.

From the experimental results explained so far, it can be concluded that nanofluids provide a promising technique for flow boiling heat transfer enhancement with proper selection of nanoparticle material, size and concentration. The scope for heat transfer enhancement in flow boiling using nanofluids are more than that in pool boiling.

2.2.2.2 Critical Heat Flux

In flow boiling, Kim et al. [80] reported the potential of nanofluids to improve the CHF for the first time. They used alumina nanofluid in a vertical stainless steel tube to investigate the flow boiling phenomenon. The authors found significant enhancement in CHF with nanofluids as compared to pure water. They speculated that the deposition of nanoparticles might have caused high surface wettability which prohibited the propagation of hotspots. Again, Kim et al. [46] studied flow boiling of alumina/water, zinc oxide/water and diamond/water nanofluids and observed maximum CHF enhancements of 53%, 53% and 38% for Al_2O_3/water, ZnO/water and diamond/water nanofluids respectively. They found that the morphology of the boiling surface was changed due to nanoparticle deposition during boiling which affected surface wettability and contributed to CHF enhancement.

Ahn et al. [72] investigated flow boiling CHF of water based alumina nanofluids in a rectangular horizontal channel and found enhancement in CHF as compared to pure water. The change in surface properties was caused due to deposition of nanoparticles and was found to be the main reason behind CHF enhancement (Fig.2.9). Kim et al. [81] studied flow boiling CHF of alumina nanofluids in a vertical stainless steel tube under atmospheric pressure. The CHF of Al_2O_3/water nanofluids enhanced with increasing mass flux and remained almost unchanged as concentration of nanofluid increased from 0.001 to 0.01 vol%.The deposition of nanoparticles was observed in FE-SEM images on the inner test section surface which was responsible for enhanced CHF. Later, Kim et al.[82] compared flow boiling CHF of NFPT (Al_2O_3 nanofluid with a plain tube) and DWNT (DI water with alumina nanoparticle deposited tube). The authors did not find much change in CHF values between NFPT and DWNT and indicated that enhancement in CHF was due to deposited nanoparticles on the heating surface.

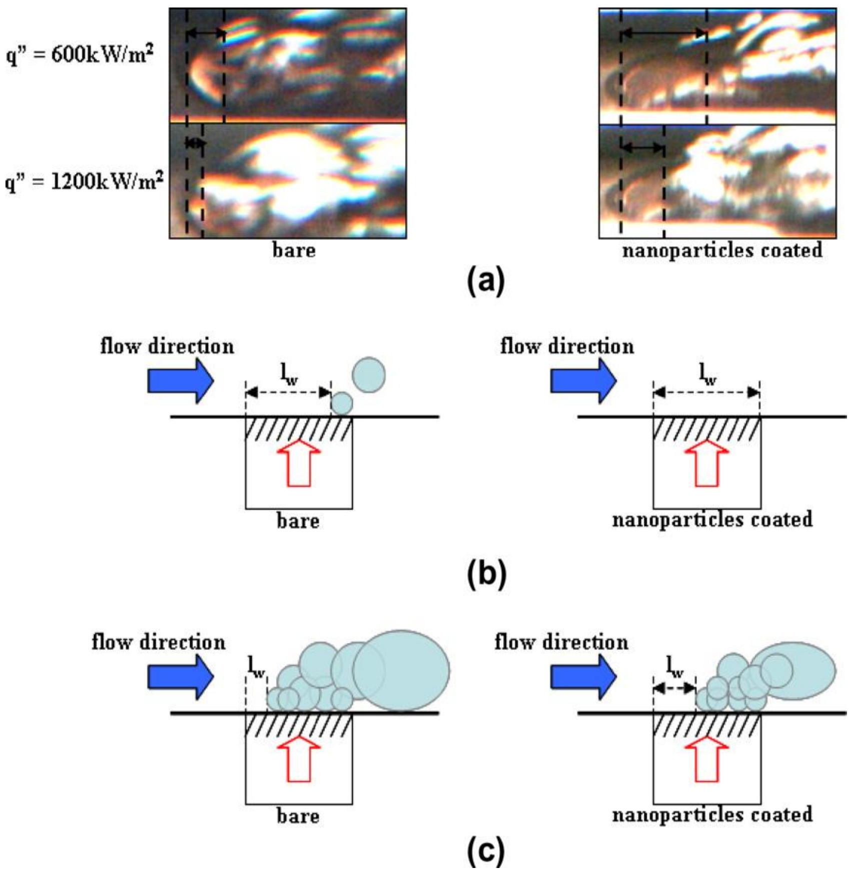


Fig. 2.9 Wetting zone of bare and nanoparticles-coated specimens: (a) photographs of wetting zone (b) q" = 250 kW/m^2,ΔT_{wall} of bare specimen 14 K, ΔT_{wall} of nanoparticles-coated specimen 20 K (c) q"=600 kW/m^2, ΔT_{wall} of bare specimen 22 K, ΔT_{wall} of nanoparticles-coated specimen 32 K [72]

Vafaei and Wen [83] investigated flow boiling CHF of water based alumina nanofluids and reported that CHF was enhanced by about 51% in case of 0.1 vol% nanofluid concentration. They concluded that surface modification due to nanoparticle deposition must be responsible for CHF enhancement. Also, Vafaei and Wen [84] proposed that nanoparticles play double role in enhancing flow boiling CHF: surface modification through nanoparticle deposition and improved bubble dynamics due to suspended nanoparticles in the fluid.

Lee et al. [69] conducted flow boiling CHF experiments using alumina-water and silica-water nanofluids flowing upward in a vertical channel under atmospheric pressure. The CHF was enhanced for all the nanofluids and varied with mass flux and inlet temperature. Nanoparticle deposition on heating surface was confirmed from SEM images. The surface contact angle was reduced due to this deposition and altered the surface wettability. Lee et al. [85-86] conducted CHF experiments in a vertical channel using Fe_3O_4/water and Al_2O_3/water nanofluids. CHF was enhanced in case of both the nanofluids but no significant difference was found. Nanoparticle deposition improved the rewetting characteristics of the heating surface and hence enhanced the flow boiling CHF. Also, the authors observed additional CHF enhancement when external magnetic field was applied at the location of CHF occurrence during flow boiling of Fe_3O_4/water nanofluid.

2.2.2.3 Flow and Heat Transfer Mechanism

The mechanism of flow boiling heat transfer of nanofluids is very complicated and difficult to understand. Many researchers reported that nanoparticles get deposited on the heating surface during boiling and alter the surface wettability. The general belief is that this wettability modification causes CHF enhancement in nanofluid flow boiling. However, contradictory opinions exist among the researchers regarding the other mechanisms of enhanced heat transfer and CHF.

Ahn and Kim [87] and Ahn et al. [88] reported that deposited nanoparticles strongly influence the boiling phenomena by changing the main parameters such as bubble departure diameter, bubble departure frequency, nucleation site density, micro and macro-layer evaporation beneath the bubbles. According to them, further investigations are essential as how far boiling phenomena is getting affected by suspended nanoparticles in the fluid and deposited nanoparticles on the surface.

Wu and Zhao [89] reviewed the flow and heat transfer mechanisms and stated that bubble dynamics (bubble generation, growth and detachment) was affected by many parameters. Surface characteristics due to deposition of nanoparticles play very important role in bubble departure phenomena. According to them, the suspended nanoparticles in the base fluid also influence the bubble generation and growth as well as bubble departure characteristics.

Vafaei and Wen [84] proposed that nanoparticle deposition during boiling alter the heating surface and suspended particles in the base fluid modify bubble dynamics by changing the force balance at the triple line due to variation of surface tension. Bubble dynamics can be varied significantly by varying contact angles, departure bubble volume and frequency with use of nanofluids.

2.2.2.4 Flow patterns and bubble dynamics

Flow patterns and bubble dynamics are important for understanding flow boiling mechanisms. However, the mechanism of heat transfer enhancement due to bubble behavior is not well understood and exploration of the phenomenon still remains a challenge. High-speed visualization techniques may help to investigate two-phase flow during boiling process. Though many experimental studies were carried out to observe bubble behavior of water, research on bubble behavior during nanofluid boiling are rare.

Ahn et al. [72] investigated the flow boiling behavior of water on nanoparticles coated heater and bare heater. The results demonstrated delayed transition from the onset of nucleate boiling (ONB) to CHF in case of nanoparticles-coated heater because of the good surface wettability. Prajapati and Rohatgi [90] conducted flow boiling experiments and studied heat transfer of ZnO-water nanofluids. The addition of nanoparticles enhanced surface roughness and increase in heat transfer coefficient by 126% with respect to its base fluid. Rana et al. [73] measured the effect of heat flux, flow rate and particle concentration of ZnO-water nanofluids on bubble behavior and heat transfer coefficient. They reported that bubble population increased with increasing heat flux and decreasing particle volume fraction (Fig. 2.10). The reason may be attributed to increasing nanofluid concentration which increased convective heat transfer and less energy was available for bubble nucleation due to plugging of nucleation cavities by nanoparticles.

Henderson et al. [74] investigated the flow-boiling heat transfer of R-134a based nanofluids in a horizontal tube. They observed that the heat transfer coefficient decreased as much as 55% with respect to the base R-134a with dispersion of SiO_2 in R-134a. However, the mixture of R-134a and polyolester oil with CuO nanoparticles exhibited higher heat transfer coefficient than R-134a/polyolester. Wang et al. [91] numerically investigated the bubble dynamics in nanofluid and reported that the bubble grew faster and departed from the heating surface earlier in nanofluid as compared to base fluid because of greater heat transfer capacity of nanofluid.

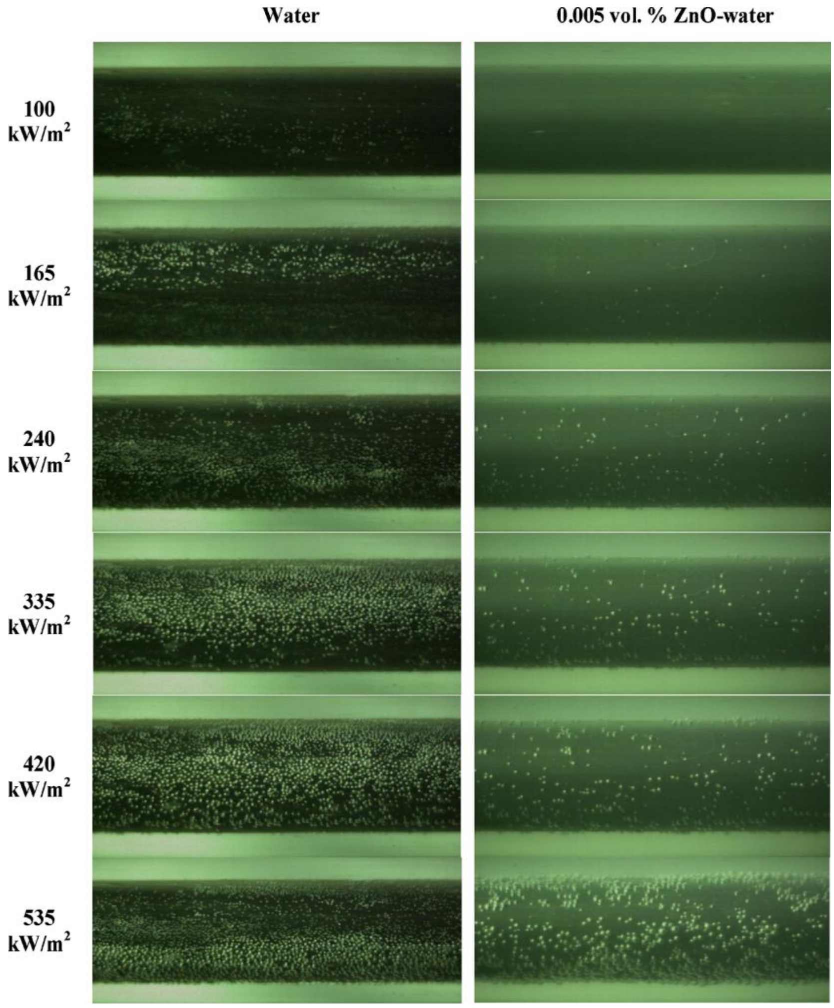


Fig. 2.10 Bubble images on heating surface with water and ZnO nanofluid (0.005 vol.%) at different heat fluxes and constant flow rate of 0.1 lps [73]

Xu and Xu [16] observed that the microchannel was less occupied by elongated bubbles for Al_2O_3/water nanofluids than for pure water. High speed visualization confirmed that miniature bubbles were the major flow pattern for the nanofluids, which delayed the flow instability as shown in Fig. 2.11. They concluded that the smaller bubble size before bubble departure was due to decreased surface tension force acting on the bubbles. Yu et al. [75] studied subcooled flow boiling of alumina nanofluids in a circular stainless steel mini channel. They found that the flow boiling of nanofluid was more stable and the presence of nanoparticles delayed the ONB and suppressed the onset of flow instability (OFI). They attributed the effects on the instability, ONB, and OFI to the changes in available nucleation sites and surface wettability as well as thinning of thermal boundary layers in nanofluid flow. Edel and Mukherjee [76] investigated the flow boiling dynamics of Al_2O_3/water nanofluids with a nanoparticle concentration of 0.001 vol% in a single rectangular micro channel. It was found that the frequency of the onset of nucleate boiling (ONB) decreased with nanoparticle deposition on the microchannel surface because the more efficient mass transfer into the thin film regions cooled the micro channel surface more effectively and caused local surface temperature to rise more slowly during two-phase flow. The progression of the location of the onset of bubble elongation (OBE) in the upstream direction was found to occur more slowly for nanofluids. The addition of nanoparticles was found to stabilize bubble nucleation and growth and increase heat transfer in thin film regions.

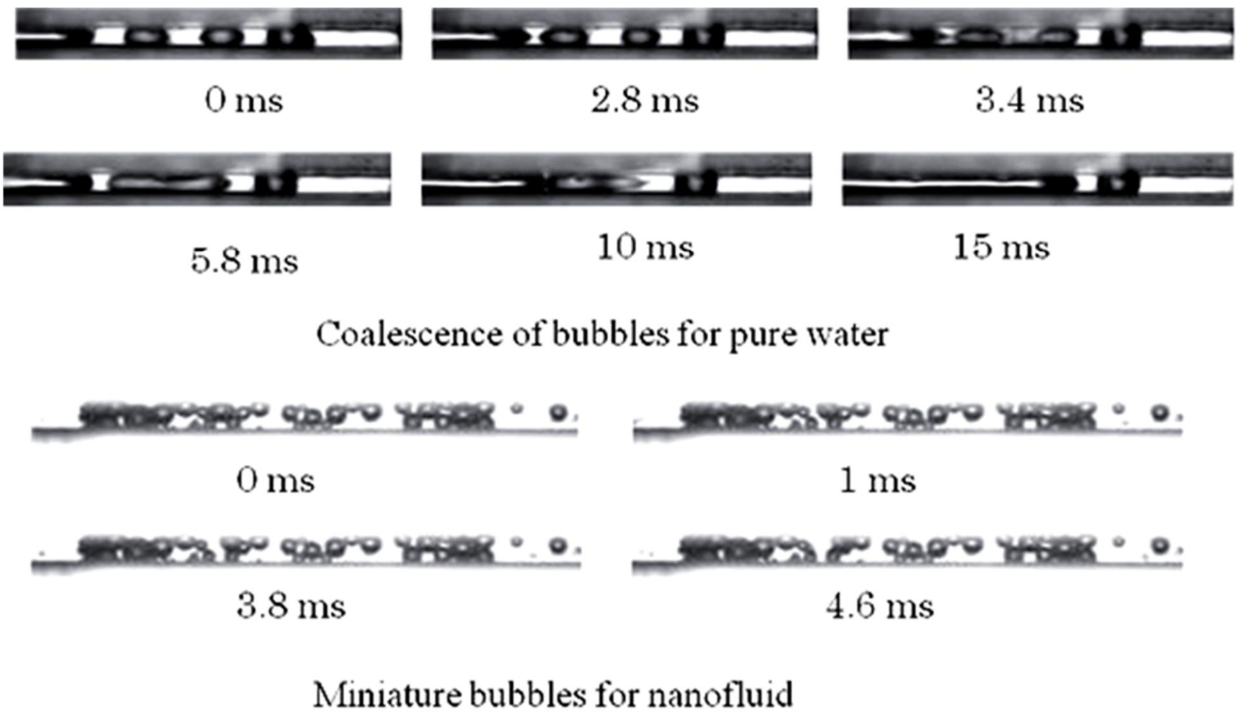


Fig. 2.11 Bubble behaviour of pure water and nanofluid in microchannel at OFI [16]

Wang and Bao [92] performed visualization studies in a vertical capillary tube in which they used nitrogen as the vapor phase and CuO/water nanofluid and pure water as the liquid phase, respectively. They observed higher void fraction with bubbly flow pattern in nanofluids than pure water enhancing two-phase heat and mass transfers. The authors found the variation in liquid surface tension to be responsible for change in flow pattern transition. Park and Chang [93] experimentally estimated the bubbly flow parameters in water and water based alumina nanofluid using a conductivity double-sensor probe. The results exhibited a more flattened distribution of void fraction, higher concentration of interfacial area and small bubble size in case of air-nanofluid flow than those in the air-water flow.

2.2.3 Thermo-physical properties

Nanofluids have been reported to have improved thermo-physical properties in a number of articles [94-100]. The thermal conductivity has been shown to improve with the use of nanofluids having nanoparticles such as aluminum oxide (Al_2O_3), titanium oxide (TiO_2), silicon oxide (SiO_2) as well as carbon nanotubes (CNT). Nanofluid thermal conductivity can be measured by transient hot wire method [101], optical beam deflection method [102], temperature oscillation technique [103] and thermal lensing method [104], out of which, transient hot wire is common. The enhancement of the thermal conductivity depends on the nanoparticle material, size and concentration in the base fluid. The improvement of the thermal conductivity usually ranges from about 10 to 300 percent, as discussed by Wang et al. [105]. Eastman et al. [106] and Keblinski et al. [107] suggested different mechanisms for nanofluid thermal conductivity enhancement which include effect of nanoparticle clustering, Brownian motion of nanoparticles and heat transport within the nanoparticles. The effect of particle concentration, material, size, shape etc. were considered by many researchers and the results were summarized in a review by Yu et al. [108].

Apart from thermal conductivity, viscosity of nanofluids plays important role in thermal hydraulic phenomenon during boiling. It has been reported that the viscosity is significantly influenced by parameters such as temperature, particle size and shape as well as volume fractions [109]. Viscosity and rheological properties are very essential for practical applications of nanofluids. Thus, to reveal the possible mechanism of the heat transfer performance in boiling systems, these parameters should not be neglected. The enhancement in viscosity of nanofluid can be calculated through solid-fluid homogeneous equations. The available theoretical models [110-115] have been derived from the Einstein [116] model. But these models do not include the effect of temperature, particle size and shape, dispersion of nanoparticles in the base fluid. Hence, investigators later developed empirical correlations in which they had tried to incorporate the above effects [117-123]. Masuda et al. [124] measured the viscosity of some water-based nanofluids for Al_2O_3, SiO_2 and TiO_2. Then Pak and Cho [125] presented some additional data for Al_2O_3/water nanofluid. Some parameters like, temperature, particle size and shape, volume concentrations have shown to have a great effect over viscosity of nanofluid. Murshed et al. [96] measured the volumetric effect on viscosity for Al_2O_3 and TiO_2 with deionized water (DIW) and concluded that viscosity increases about 82% and 86%, respectively, for 5 vol.% of Al_2O_3 and TiO_2. Prasher et al. [122] reported that, nanofluid viscosity is not a strong function of nanoparticle diameter.

2.2.4 Summary

From the literature survey, it is clear that studies regarding flow pattern evolution in a vertical channel with a concentric heater similar to a nuclear pin using nanofluids are rather scarce. Visualization of flow patterns could provide better insight to the heat transfer mechanism in vertical channels. The flow boiling heat transfer in nanofluids is more complex than that in the water. The nanoparticle in the boiling nanofluids will produce effects on bubble generation, growth and departure. No research about the nanofluids boiling heat transfer characteristics from the viewpoint of bubble behavior has been reported. Hence, an effort has been made to contribute to a better understanding of the underlying physical phenomena in single-phase and specially boiling two-phase flow heat transfer of dilute oxide based nanofluids in a vertical channel.