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Review on Visualization Results of DNB and Relations with Hypertheses of DNB Models

In Cheol Bang, Soon Heung Chang and Won-Phil Baek*

Korea Advanced Institute of Science and Technology
373-1, Guseong-dong , Yuseong-gu, Daejeon, Korea, 305-701

*Korea Atomic Energy Research Institute
150, Dukjin-dong, Yuseong-gu, Daejeon, 305-353, Republic of Korea

Abstract

This paper provides the review of the previous results of visual experiments on DNB phenomena and the considerations of relations with hypertheses of DNB models. Hypotheses of DNB models with good prediction performance in forced convective boiling and Visualization results in various experiments of some major authors are summarized. And then, the relations with the hypertheses and the visual results are discussed. Two major models are competitive and one additional model is selected for good relation. Theses models have not be tightly linked to any visual results till now. However, recent some advanced visualizations capable to give a clue to the closely relation between the hypothesis and the results have reported.

1. Introduction

Forced convective nucleate boiling is very effective in achieving a high heat flux with a small temperature difference between the heated surface and the cooling fluid; however, there is a limit of this effective heat transfer regime, called the departure from nucleate boiling (DNB). Reliable understanding of this DNB phenomena and the good prediction are important for effective and safe operation of nuclear systems and other thermal-hydraulic equipment. DNB is a transition of the heat transfer regime from nucleate boiling to film boiling or partial film boiling. This usually involves the transition of the flow regime from bubbly flow to inverted annular flow. This has been actively studied during the last 50 years. There are many experimental correlations and theoretical models for prediction DNB. While the correlations have narrow prediction range, the theoretical models based on the various hypertheses have extensive prediction range in the design of the thermal-hydraulic device. However, the prediction performance of these theoretical models has not outstandingly advanced during last 20 years. It may be mainly due to the theoretical limit of hyportheses of such models that are not proven really or visually. Of course, there are extensive observations of DNB phenomena and neighboring flow boiling phenomena which are reported in many visualization experiments. Nevertheless, detailed physical mechanisms leading to DNB have not been clearly understood mainly due to the difficulty in observing the near-wall region. Several investigators have tried to get rid of this difficulty by means of various flow visualization tests with advanced techniques and/or simulation fluids. Digital photographic techniques have significantly advanced for recent decades.

In this paper, the first objective is to review the previous results of visual experiments on DNB phenomena. The second objective is to analyze the relations with hypertheses of DNB models that are selected. In addition, the recent closely-linked visualization results of a hypothesis and basic boiling phenomena are reviewed.

2. Visualization of DNB

2.1 Review of DNB mechanisms according to visual flow patterns

Generally, Critical heat flux(CHF) is divided into two categories; departure from nucleate boiling(DNB) for a subcooled flow and liquid film dryout(LFD) for an annular flow. The mechanisms for the CHF are closely associated flow patterns. Tong and Hewitt[22] have identified at least three separate mechanisms according to CHF condition: (a) Dryout under a vapor clot. This is related to high subcooling conditions. As a result of evaporation of the microlayer, a dry patch forms on the heating surface under a growing vapor bubble. When the bubble departs from the surface this dry patch or dry spot is rewetted. Fiori and Bergles[7]and Kirby et al.[8] reported that if the heat flux is high the temperature rise of the dry patch is such that it cannot easily be rewetted following bubble departure and there is a significant increase in the temperature occurring CHF. (b) Bubble crowding and vapor blanketing. At moderate subcoolings, a boundary layer of bubbles may grow to the point where it restricts the access of liquid to the heated suface. (c) Evaporating of liquid surrounding a slug flow bubble. At low mass velocities the slug flow pattern may occur with a liquid film initially remaining between the vapor bubble and the heated wall. If the heat flux is high, this film may be completely evaporated and a form of ‘dryout’ with consequent overheating of the tube wall may occur. A tentative map with mass velocity and subcooling as ordinates, showing where these various mechanisms might be expected to occur, has been published by Semeria and Hewitt[23] as shown in Fig 1..

2.2 Experimental observations of the flow near and at DNB

Previous visual observations have produced macroscopic flow structures relatively at low pressure of water due to complex near-wall phenomena, difficulty of visualization at high pressure conditions, visualization techniques with low spatial resolutions. To get rid of this limit of observation, visualization experiments have been performed variously according to working fluids of water and simulation fluid such as new Freon series, geometric types of visual test sections of annulus window with a heating rod and rectangular window with one-sided heater or both-sided heater, heating materials such as transparent sapphire, and visualization techniques of various optical devices and non-optical devices such as radiography and NMR.

Classification of visualization conditions macroscopically

Visualization studies of boiling phenomena in literatures are given in Table 1. They have extensive experimental conditions and sometimes have different flow patterns macroscopically each other in CHF occurrence. Therefore, for the first all, we macroscopically classified the studies according to mass fluxes an quality in a way of the tentative map of Semeria and Hewitt[23] in order to distinguish between macroscopic or apparent flow patterns such as bubble patterns and slug patterns. Fig.2 show the classification. In this, almost all studies seem to belong to regime of bubble crowding and vapor blanketing of the map. Naturally, this mean that the studies have the purpose of the clear observation of DNB phenomenon. More specifically and tentatively, Bricard and Souyri[25] classified the results in 3 categories : the mechanisms related to a single bubble, to a bubbly layer and to a vapor clot or blanket. These classes respectively are similar to the proposal of Tong and Hewitt[22]'s three separate mechanisms such as wall overheating under a growing bubble, bubble crowding and vapor blanketing near the wall, and dryout of the film under a vapor clot in slug flow. Anyway, we can conclude that the visualization results are macroscopically and closely related to the proposals of Tong and Hewitt[22] and Semeria and Hewitt[23].

Classification of visualization results microscopically and based on major phenomena.

We knew that present classification and analyses on the visualization results by individual opinions of an analyst did not provide outstanding information. We determined to collect real observational images of visualization in order to acquire new breakthrough. We have adventurously classified the observational images in some categories : General boiling phenomena of water or individual bubbles, Formation of large vapor clots before DNB occurrence of water, and Freon boiling. Specially, because the physical properties of Freon such as surface tension and viscosity are significantly different to water and so, physical phenomena will have different basics. Therefore we need to consider water and Freon separately and inherently.

(a) General boiling characteristics : individual bubbles and coalescences : In a range of low heat flux as shown in the figures such as Hosler[26], Tippets[24], Hino & Ueda[1993], Kureta & Akimoto[9], and Chang et al[11]. single phase heat transfer were first achieved and then in a range of heat flux over nucleation condition, discrete bubbles formed on heated surface are observed. While bubbles repeat to grow and decay, with the more increase of heat flux bubbles begin to move along the heated surface. The more increase of this moving bubbles and active nucleation sites with heat flux increase brings about bubble coalescences. As the result of the coalescence of bubbles, large bubbles get formed. The large bubbles get formed large vapor clots due to more active nucleation sites. These vapor clots are continually observed in relatively constant time interval. It is the reason that this vapor clots repeatedly formed on local heated surface according to nucleation site density and bubble frequency. Nucleation site density generally has the order of 10^6 nucleation/m^2 at high heat flux occurring bubble coalescences and increases with the increase of heat flux. Outstanding change by mass flux effect is that the dimension of bubbles decreases with the increase of mass flux. Specially, Kureta and Akimoto[9] observed that flow patterns at the burnout were classified into three types; large bubble type, small bubble type and tiny bubble type in considering general boiling characteristics. (Fig. 2,3,4,5,6)

(b) Formation of some large vapor clots before DNB : Authors reported various observations and made related assumptions on flow structures and CHF mechanisms through the visualization experiments. Commonly they reported that large vapor clots appears before DNB occurrence. Gunther[1] thought that when the local vapor film due to bubbles coalescence was formed, the CHF would occur. It was related to the observation of large vapor clusters. Kirby et al.[8] postulated that when the wall temperature reached at the moment of bubble departure was such that rewetting was prevented, it would occur. It was related to the microlayer dryout under a growing bubble. However, their observations really show the formation of some large vapor clots as Fig. 8. Fiori and Bergles proposed that when the wall temperature rise due to the dryout by a vapor clot was higher that the temperature drop due to rewetting, it would occur. However, we cannot judge really what the phenomena occurs through the photos because of poor resolution.(Fig. 10) But, they reported that near CHF the flow pattern in their glass annular test section was that of a slug or vapor clot flow. Del Valle [3] did not provide the real observation images but conceptual images as shown in Fig 11. They reported that transition from bubbly to slug flow before burnout occurred and nucleation continually occurred on the wall under the large, moving vapor patches. This really have strong linking with Chang et al[11]'s images before DNB. Nariai et al.[10] provided the images of wavy vapor clots maybe because of the visualization tool with low speed and resolution unable to capture bubble or clots. Theses erroneous images have been reported in various experiments. We need to distinguish between right images and erroneous images in various observations. Anyway, it is the fact that the images are closely linked to large vapor clots.

(c) Images of clear DNB occurrence : We have made an effort to find the images at the instant of DNB occurrence. the Visualization results before this part only provides images of the large vapor clots just before DNB. We could not understand what is happening at the instant. Next two papers supply the images at the instant to resolve doubts. Celata et al.[14] thought that when the liquid sublayer during the passage time of the vapor blanket was dried out, it would occur. Their images show that the near-wall flow pattern is characterized by the periodic presence of vapor blankets adjacent to the heated wall, and of few spherical bubbles carried by the coolant, always in the region close to the heated wall. Figure 13(a) and (b) of Chang et al[11] illustrates the flow structure before and after CHF occurrence. The top region is occupied sometimes by a large wavy vapor clot and sometimes by small or coalesced bubbles. This indicates that large vapor clots would periodically grow and escape from the top region of the heated surface. Figure 13(b) shows the flow structure just after the occurrence of CHF. The region of DNB occurrence dries out and the dried region expands with time. At the same time, the region occupied by large vapor clots move downward and upward as the heat flux becomes higher near the CHF location due to axial heat conduction from the CHF region with poor heat transfer to water. The heated surface was damaged severely due to the sudden temperature rise.

(d) Distinct boiling phenomena of Freon series : Tong et al.[4] performed a photographic study of subcooled boiling flow and DNB of Freon 113 in a vertical channel. They provided the general boiling images and the slug flow pattern images at DNB. The results did not have the outstanding difference with the boiling phenomena of water. Mattson et al.[6] proposed that the DNB was characterized by the existence of a thin vapor layer on the heated surface through the images of Freon 113. However, we cannot identify the thin vapor layer at the images but only some long bubble or vapor. Interestingly Galloway and Mudawar[5] reported that at low heat fluxes and high velocities, very thin liquid sub-film was observed to be trapped below discrete elongated bubbles that slid over the heater surface. Also, vapor bubbles coalesce into large vapor waves at heat fluxes about 60% of CHF while liquid was supplied through wetting fronts when the depressions in the liquid vapor interface touched surface. The heater surface between wetting fronts became increasingly dry as heat flux approached CHF. They proposed that one of the wetting fronts was dried out due to the radial inertial of vapor related to wave like succession of vapor clots. Sturgis and Mudawar[28]'s visualization is also related to a wavy vapor layer. Bang et al[21] performed a photographic study on Freon 134a. they provided the general boiling images and the slug flow pattern images at DNB similar to Tong et al's results

3. Hypotheses of DNB models

The major theoretical models have focused on bubbly layer and the liquid layer near wall or vapor clots. Particularly, Weisman & Pei[16] 's model and Lee & Mudawar[12]'s model are competitive in prediction of DNB. Many theorists in both sides have studied models based on bubble crowding in bubbly layer and based on liquid sublayer. Therefore, we have a focus of reviewing the DNB models. Bubble crowding model proposed by Weisman & Pei[16] focuses on the bubble concentration in the bubble boundary layer. The CHF is postulated to occur when the bubble packing at the control volume reaches a critical void fraction that can hinder the supply of cooling liquid from the core region. According to the flow condition, Weisman's group made the continuous efforts in order to extend the applicable range to the lower mass velocity to higher void fraction or to higher subcooling. However, the critical void fraction that plays a role of like a fitting constant is a point of dispute.

However, this bubble crowding phenomena near wall have become more supported by last early visualization results. The liquid layer superheat limit model proposed by Tong et al.[17] is graphically presented in Fig 19. The control volume of this model is a thin liquid layer beneath the bubble layer. The CHF is assumed to occur when the thin liquid layer beneath the bubble layer reaches a critical superheat due to the difficulty of heat transport through the bubbly layer. However, What the superheat condition is was not physically defined in this model. In addition, Tong et al. did not suggest a CHF model but evaluate the upstream or memory effect for the nonuniform axial heat flux condition. The liquid sublayer dryout model proposed by Lee & Mudawar[12] considers the liquid sublayer(similar to macrolayer in pool boiling) under a single vapor clot as a control volume. CHF occurrence is postulated as the complete evaporation of the liquid in the control volume during the passage time of the vapor blanket. All these models has still many ambiguous areas related to the micro-scale behaviors in the boiling process. Closer observation is inevitable to understand the bubble behavior near the wall and to provide the clear basis of the theoretical model.

4. Newly strong linking between the hypothesis and visual observation

We have reviewed various visualization results on DNB phenomena. However, any results did not have strong linking to theoretical DNB models or hyportheses due to poor resolutions of near-wall phenomena. For the purpose of understanding of physical CHF mechanisms that are important for reliable prediction and development of enhancement technology, we need to have strong evidences through visualization of micro behavior near wall in details. Traditionally, two regions are considered for subcooled flow boiling structure: the bubbly layer near the heated wall and the liquid core region. This has been supported by a variety of experimental works, though detailed information on the bubbly layer has not been obtained. Some investigators proposed the existence of the superheated liquid layer or liquid sublayer between the bubbly layer and the heated surface, which leads to three-layer flow structure: the superheated liquid layer, the flowing bubble layer, and the liquid core. Among them, Larson and Tong[17] developed an analytical model for void fraction distribution in subcooled flow boiling assuming the three layer structure and Lee and Mudawar[12] developed a mechanistic CHF model assuming a liquid sublayer below a large vapor clot. Recently, Chun et al.[20] also proposed a CHF model based on the concept of the depletion of the superheated liquid layer. However, there has been little experimental work directly showing the existence or characteristics of the liquid layer. Chang et al.[11] shows the existence of the liquid sublayer under large coalesced bubbles. The thin layers below coalesced bubbles in the lateral pictures of Fig. 20(a) are considered as the liquid sublayer that is assumed in many CHF modeling, e.g., Lee and Mudarwar[12], Katto[13] and Celata et al[14] of liquid sublayer dryout model. Fig 20(b) shows the front visualization with lateral lighting. The bright area behind a bubble would be due to the existence of a liquid sublayer that reflects light less than the coalesced bubble. More important photographs related to the flow structure were obtained by intentionally applying the long exposure time in Fig.

21. The thin, bright lines in the liquid core region correspond to the movement of small bubbles. The coaxial direction and almost the same length of those lines in the liquid core region indicate the coaxial flow of small bubbles at almost the same velocity. The wavy lines would be the cumulative images of the caps of attached small bubbles that are generated during the exposure time. Then the wavy lines would be an indication of the superheated liquid layer with small attached bubbles. They proposed a direct experiment evidence for the three-layer structure of subcooled flow boiling under low pressure: the superheated liquid layer with very small bubbles attached on the heated surface, the flowing bubble layer containing vapor clots and small bubbles(coalescence occurs in this layer), and the liquid core region over the flowing bubble layer. In addition, as another instance of really micro behavior of bubbles, Bang et al[21] observed near-wall tiny bubble growth behavior and vapor remnants below departing bubbles in Freon 134a. This remnant's photos is an evidence of Mitrovic[15]'s consideration as shown in Fig 22 and 23.

5. Conclusions

We have reviewed the hypotheses of major DNB models and summarized the observational results of the visualization experiments for DNB phenomena. We collected real observational images of visualization in order to acquire new breakthrough. We have adventurously classified the observational images in some categories : General boiling phenomena of water or individual bubbles, Formation of large vapor clots before DNB occurrence of water, and Freon boiling. We have made an effort to find the images at the instant of DNB occurrence. The Visualization results only provide images of the large vapor clots just before DNB. We could not understand what is happening at the instant. Some papers such as Celata et al [14] and Chang et al [11] supply the images at the instant to resolve doubts. We strongly require more clearer visualization results of both macroscopic and microscopic flow structures near wall approaching DNB.

5. References

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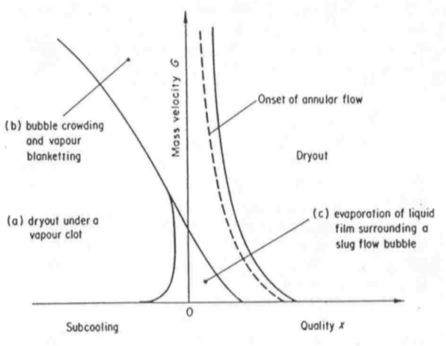
Table 1.Major visualization experiments

(l) : Length, (o) Outer Diameter, (i) Inlet Diameter, T: type, V: Vertical Rectangular, H: Horizontal Rectangular, A: Vertical Annulus, W: Water

Years	**Authors**	**type**	**fluids**	**De(mm)**	**L/D**	**Flow Area**	**Heater Size**	**P(MPa)**	**G (kg/m^2s)**	**ΔT**	**-X**	**method**	**Flow pattern**
‘51	Gunther[1]	V	W	6	10	4.76*12.7*152.4	3.175	0.1-1.1	1500-12000	12-160L	0.02-0.35	Visual	Bubbly
'60	Styrikovich&Nevsstrueva	H	W	7	4	4*20	30*3.7*0.2	0.12	500-1300	6-37	0.01-0.07	Beta ray	Bubbly
'62	Tippets[24]	V	W	20	45	53*12.7*1494	53*939.8	6.9	244-1950	-	-	Visual	
		V	W	17	55	27*12.7*1494							
'65	Hosler[27]	V	W			25.4*3.4*610	25.4*609.6	4.14	339	83-222I	-	Visual	-
'65	Kirby[8]	V	W	25.4	6	25.4*25.4	5*152.4*0.2	0.1-1.3	670-2025	2-21L	0.004-0.04	Visual	Slug
'66	Kirby[8]	A	W	19	8	25.4*25.4	142.2(l), 7.89(o)	0.17	1350	6L	0.01	Electrical	Slug
'67	Kirby[8]	A	W	19	8	25.4*25.4	152.4(l), 7.62(o)	0.17	1350	6-83L	0.01-0.17	Visual	Bubbly/slug
'66	Tong[4]	V	R113	11	58	60.33*6.35	60.325*635	0.13	540-2400	40-60L	0.04-0.1	Visual	Froth
'70	Fiori&Bergles [7]	A	R113	5	50	13(i)	254(l), 7.4(o)	0.2-0.6	700-10000	23-70L	0.05-0.14	Visual	Slug/froth
'70	Dean	A	W	13	22	-	-	0.7-1.4	1350-4050	2-42L	0.02-0.46	Visual	Bubbly
'73	Mattson[6]	H	W	11	14	19.05*7.62*750	3.175*152.4*0.127	0.7-2.4	1600-5500	22-67L	0.35-0.8	Visual	Bubbly
'78	Molen&Galjee	A	R113	6-35	5-32	-	-	0.1-0.2	1000-2500	10-60I	-	Visual	Bubbly/slug
'85	Valle & Kenning[3]	V	FC87	7	21	12*5	10*150	0.1	800-2000	24-84I	-	Visual	Bubbly/froth
'93	Hino&Ueda	A	W	10	40	800(l),18(i)	400*8	0.15	500-1240	10-30L	0.07-0.2	Visual	Froth
'95	Galloway& Mudawar[5]	V	W	2.5	5	1.6*6.4	1.6*12.7	0.14	600-3500	8I	-	Visual	Wave
'95	Celata[14]	A	W	0.239	-	7.2*7.2	100(l), 2(o)	0.28-1.16	3440-8000	110-164I	-	Visual	Slug
'97	Nariai[10]	V	W	6.88	0.7-11.6	11*5	5*(5,10,20,50,80)	0.1	2000,4000	60I	-	Visual	Slug
'98	Kureta & Akimoto[9]	V	W	0.39	0.008	7*0.2	5*50	0.1013	846-15100	10-70I	-	Visual	Bubbly
'99	Sturgis & Mudawar[28]	H	FC72	3.33	30.5	2.5*5	2.5*101.6	0.138	0.25-10m/s	3,16,29 outlet	-	Visual	Wave
2002	Chang et al.[11]	V	W	6.1	16.4	8*5	4*100*1.9	0.113	0-2000	15-60I	0.09-0.065	Visual	Bubbly



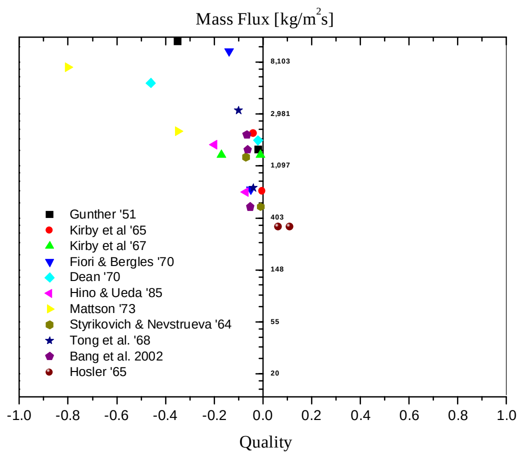


Fig. 1 Tentative Map for Mechanisms of CHF (Semeria and Hewitt [23])

Fig. 2 Condition Map for visualization experiments

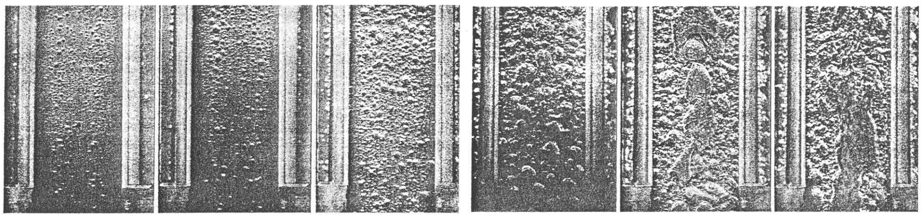


Fig. 3General boiling phenomena in low mass flux[Hosler [27]]

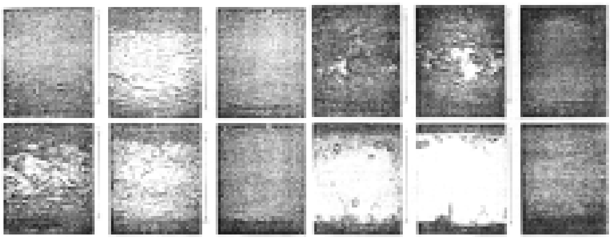


Fig. 4 General boiling [Tippets [24]]

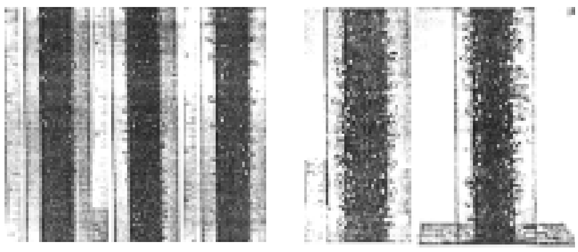


Fig. 5 General boiling [Hino & Ueda 1993]

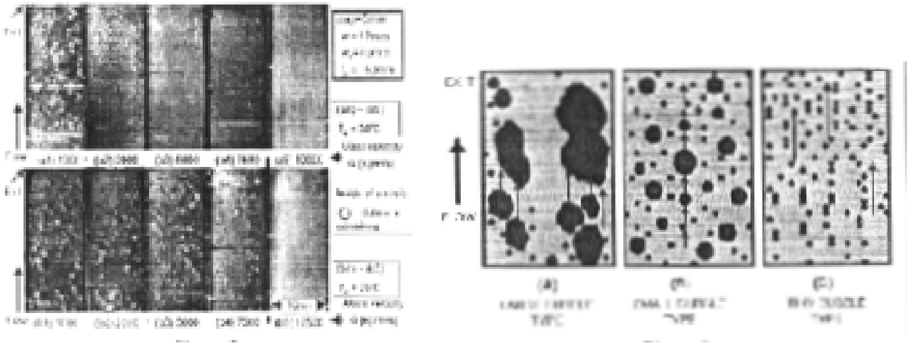


Fig. 6 Bubble pattern according flow condition [Kureta & Akimoto [9]]

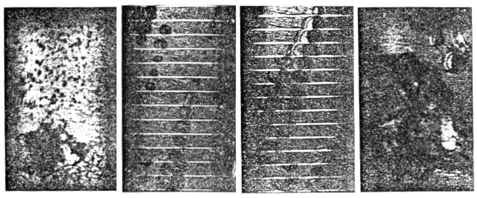
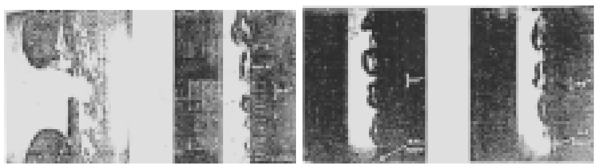


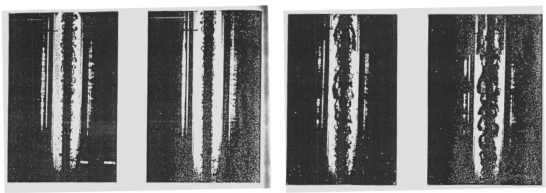
Fig. 7 Large vapor clot [Gunther [1]]

Nucleate bubbles/ Bubble coalescing/ Large Bubbles/ Larger bubbles

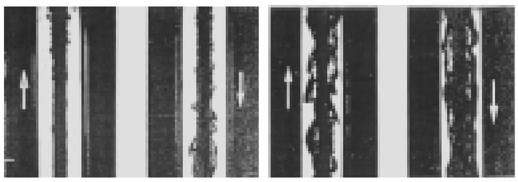


Close-up of steam / Bubble deflating/ Just before burnout/ Burnout

Fig. 8 Large vapor clot [Kirby [8]]



Bubble patterns



Flow patterns with upflow and downflow

Fig. 9 Flow pattern [Kirby [8]]

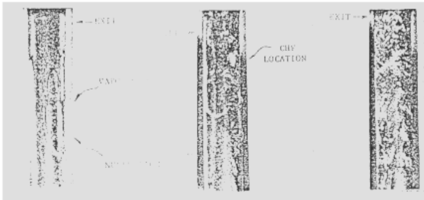
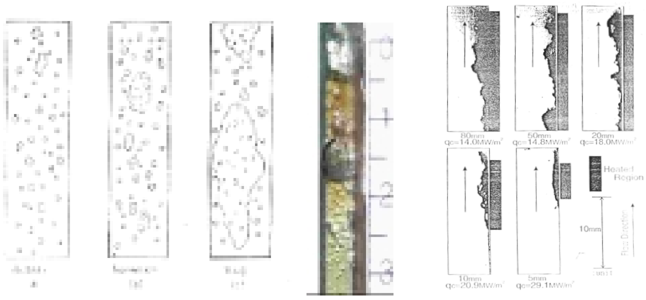
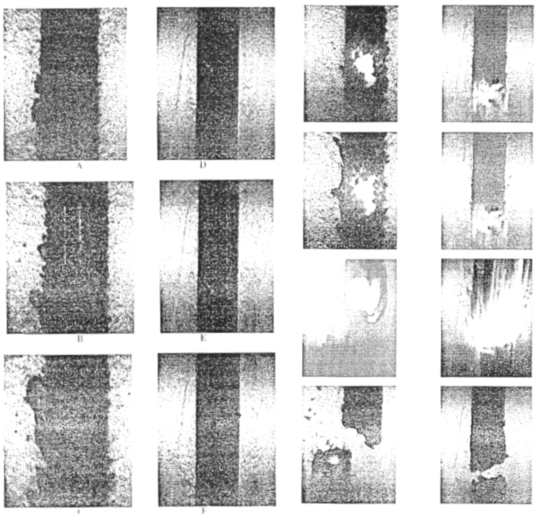


Fig. 10 Flow pattern [Fiori & Bergles [7]]



Bubbly / Transition / Slug [Flow regimes]

Fig. 11 Slug flow pattern [Del Valle [3]] [Nariai et al. [10]]



Low and higher subcoolings / Burnout sequences

Fig. 12 Burnout [Celata et al. [14]]

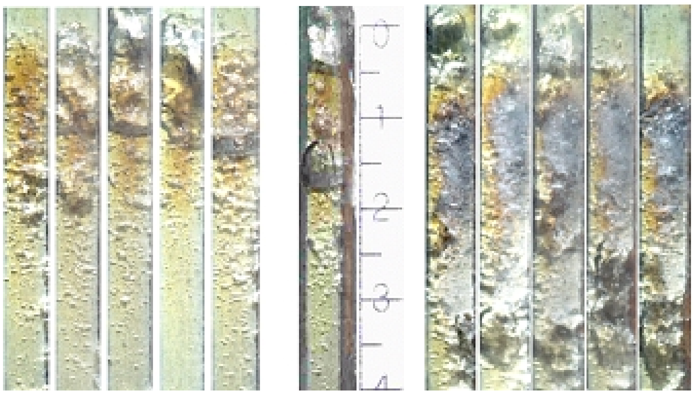
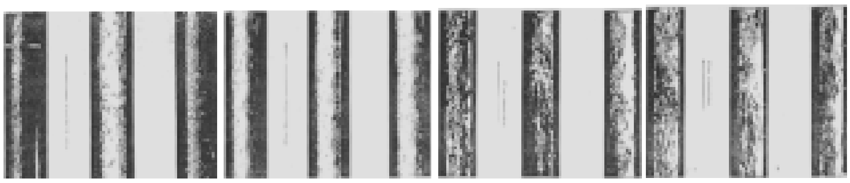


Fig. 13 Just before and at DNB [Chang et al. [11]]



Nuclate subcooled boiling flow with high subcooling/ Profile view of DNB

Fig. 14 Flow pattern of Freon 113 [Tong et al [4]]

Boiling at low subcooling / Boiling at higher subcooling/ DNB at higher subcooling

Fig. 15 Flow pattern of Freon 113 [Mattson et al. [6]]

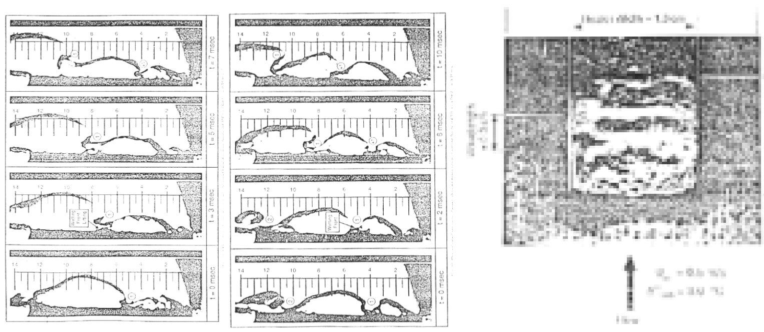
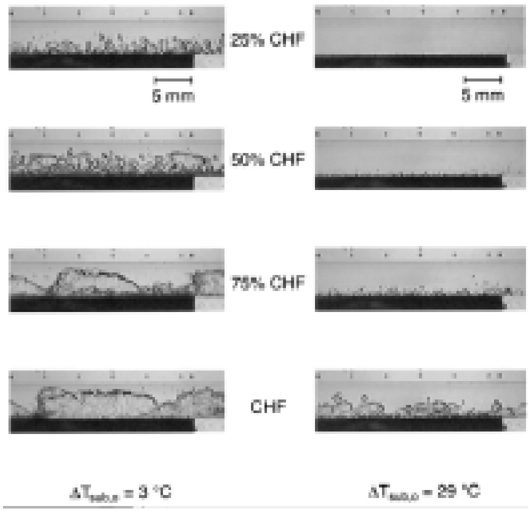


Fig. 16 Wavy flow pattern of FC87 [Galloway and Mudawar [5]]



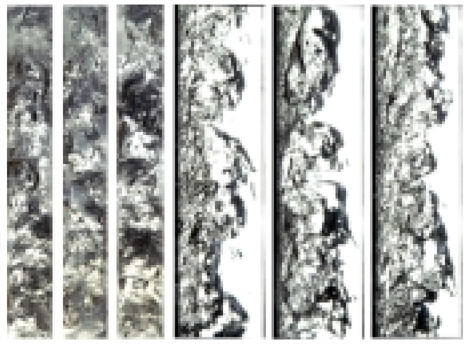
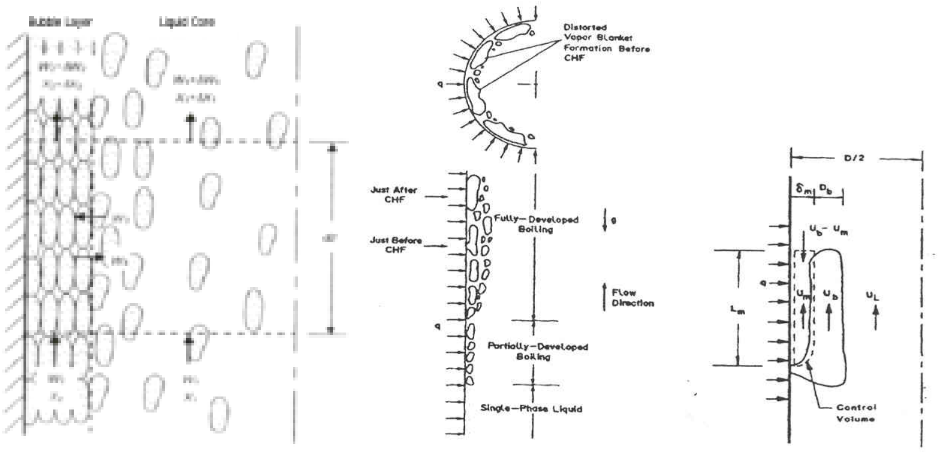
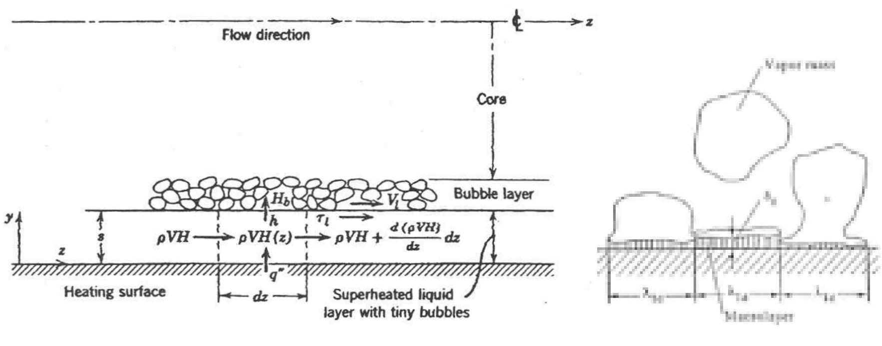


Fig. 17 FC 72 [Sturgis and Mudawar [28]] / Fig. 18 Freon 134a [Bang et al. [21]]



Bubble crowding of Weisman & Pei[16]/ Liquid sublayer dryout of Lee & Mudawar[18]



Liquid layer superheat of Tong [17]/ Macrolayer of Haramura & Katto[19]

Fig. 19 Hyportheses of major theoretical models

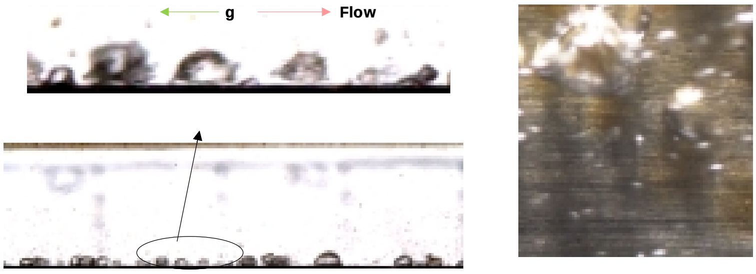


Fig. 20 Existence of Liquid sublayer [Chang et al.[11]]

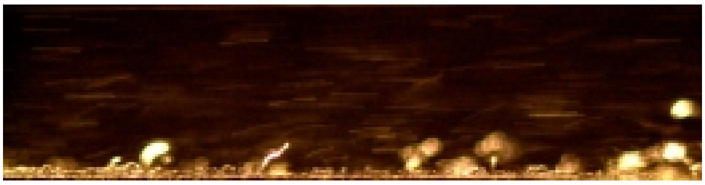


Fig. 21 Three-layer flow structure [Chang et al.[11]]

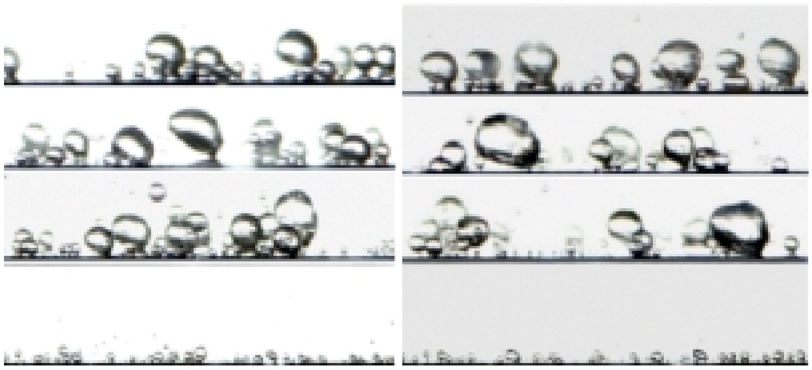


Fig.22 Growth, departure and coalescence of individual bubbles [Bang et al.[21]]

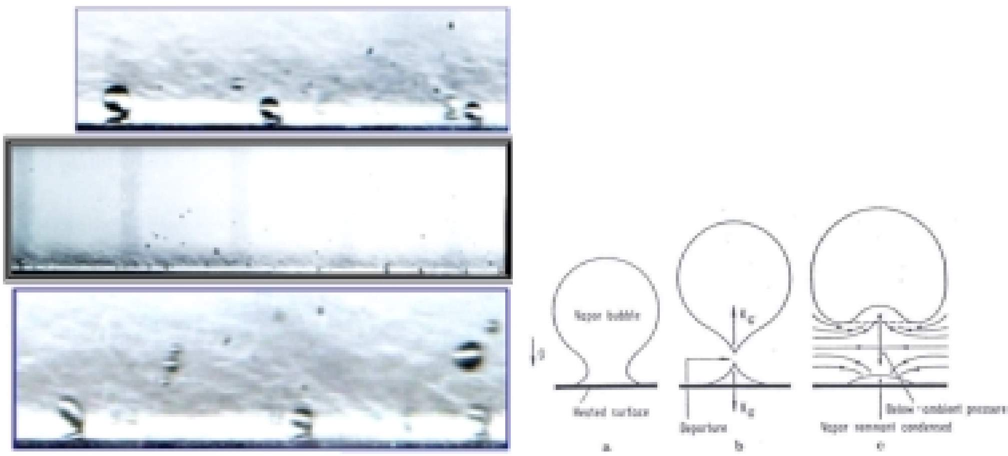


Fig. 23 Vapor Remnants or Dry spot [Bang et al. [21] & Mitrovic [15]]