SEOUL NATIONAL UNIVERSITY

2상유동 열전달 공학

Two-phase flow and heat transfer Engineering

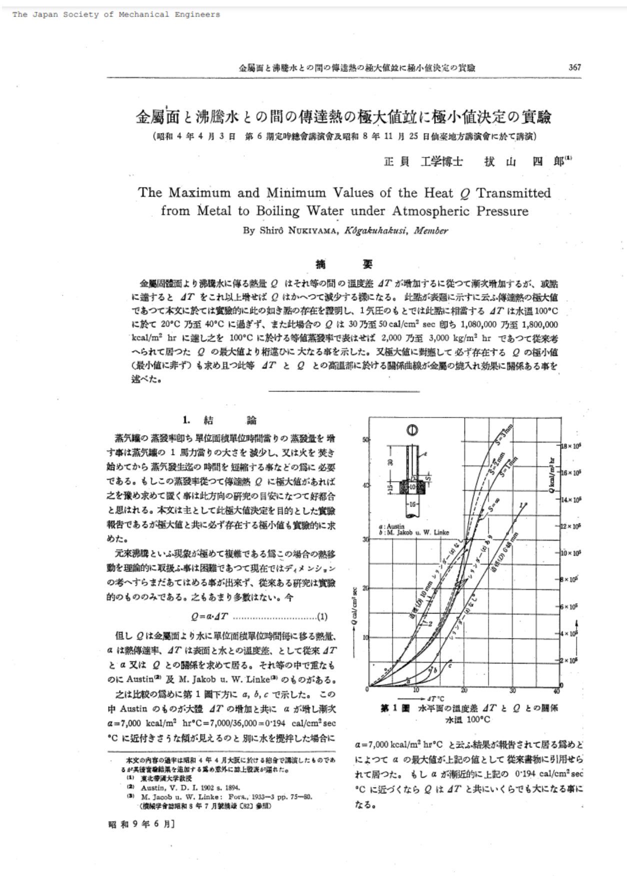
2022년 1학기

서울대학교 원자핵공학과
조형규

11.1 Pool boiling curve

- Pool boiling
  - ✓ Boiling processes without an imposed forced flow
- Nukiyama's experiment (1934)

Shiro Nukiyama



金屬面と沸騰水との間の傳達熱の極大値並に極小値決定の實驗

(昭和 4 年 4 月 3 日　第 6 冊定時總會講演會及昭和 8 年 11 月 25 日仙臺地方講演會に於て講演)

正 員　工學博士　拔 山 四 郎[1]

The Maximum and Minimum Values of the Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure

By Shirō Nukiyama, *Kōgakuhakusi, Member*

摘　要

金屬固體面より沸騰水に傳る熱量 Q は其等の間の溫度差 ΔT が增加するに從つて漸次增加するが、或點に達すると ΔT を之れ以上增せば Q はかへつて減少する樣になる。此點が表題に示すに云ふ傳達熱の極大値であつて本文に於ては實驗的に此の如き點の存在を證明し、1 気圧のもとでは此點に相當する ΔT は水溫 100°C に於て 20°C 乃至 40°C に過ぎず、また此場合の Q は 30 乃至 50 cal/cm² sec 即ち 1,080,000 乃至 1,800,000 kcal/m² hr に達し之を 100°C に於ける等値蒸發率で表はせば 2,000 乃至 3,000 kg/m² hr であつて從來考へられて居つた Q の最大値より桁違ひに大なる事を示した。又極大値に對應して必ず存在する Q の極小値（最小値に非ず）も求め且つ此等 ΔT と Q との高溫部に於ける關係曲線が金屬の燒入れ效果に關係ある事を述べた。

1.　結　　論

蒸気罐の蒸發率即ち單位面積單位時間當りの蒸發量を增す事は蒸気罐の 1 馬力當りの大さを減少し、又は火を焚き始めてから蒸気發生迄の時間を短縮する事などの爲に必要である。もしこの蒸發率從つて傳達熱 Q に極大値があれば之を豫め求めて置く事は此方向の研究の目安になつて好都合と思はれる。本文は主として此極大値決定を目的とした實驗報告であるが極大値と共に必ず存在する極小値も實驗的に求めた。

元來沸騰といふ現象が極めて複雜である爲この場合の熱移動を理論的に取扱ふ事は困難であつて現在ではディメンションの考へすらまだあてはめる事が出來ず、從來ある研究は實驗的のもののみである。之もあまり多數はない。今

$$Q = \alpha \cdot \Delta T \quad \text{......(1)}$$

但し Q は金屬面より水に單位面積單位時間毎に移る熱量、α は熱傳達率、ΔT は表面と水との溫度差、として從來 ΔT と α 又は Q との關係を求めて居る。それ等の中で重なものに Austin[2] 及 M. Jakob u. W. Linke[3] のものがある。

之は比較の爲めに第 1 圖下方に a, b, c で示した。この中 Austin のものが大體 ΔT の增加と共に α が增し漸次 α=7,000 kcal/m² hr°C=7,000/36,000=0·194 cal/cm² sec °C に近付きさうな傾が見えるのと別に水を攪拌した場合に α=7,000 kcal/m² hr°C と云ふ結果が報告されて居る爲めとによつて α の最大値が上記の値として從來書物に引用せられて居つた。もし α が漸近的に上記の 0·194 cal/cm² sec °C に近づくなら Q は ΔT と共にいくらでも大になる事になる。

第 1 圖　水平面の溫度差 ΔT と Q との關係　水溫 100°C

本文の內容の過半は昭和 4 年 4 月大阪に於ける總會で講演したものであるが其後實驗結果を追加する爲め意外に誌上發表が遲れた。

(1) 東北帝國大學教授

(2) Austin, V. D. I. 1902 s. 1894.

(3) M. Jacob u. W. Linke: Fors., 1933–3 pp. 75–80.（機械学會誌昭和 8 年 7 月號摘錄〔82〕參照）

Int. J. Heat Mass Transfer. Vol. 27, No. 7, pp. 959–970, 1984
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Pergamon Press Ltd.

THE MAXIMUM AND MINIMUM VALUES OF THE HEAT Q TRANSMITTED FROM METAL TO BOILING WATER UNDER ATMOSPHERIC PRESSURE*

Shiro Nukiyama†

J. Japan Soc. Mech. Engrs **37**, 367–374 (1934)

Abstract—The quantity of heat transmitted from a metal surface to boiling water increases as the temperature difference ΔT is increased, but after the ΔT has reached a certain limit, quantity Q decreases with further increase in ΔT. This turning point is the maximum value of heat transmitted. The existence of this point was actually observed in the experiment. Under atmospheric pressure, ΔT corresponding to the maximum value of heat transfer for water at 100°C falls between 20–40°C, and Q is between 1 080 000 and 1 800 000 kcal/m² h (i.e. between 2000 and 3000 kg/m² h, if expressed in constant evaporation rate at 100°C); this figure is larger than the maximum value of heat transfer as was previously considered. Also, the minimum value of heat transfer was obtained, and in the Q–ΔT curve for the high temperature region, the burn-out effect is discussed.

INTRODUCTION

The improving of evaporation rate (i.e. the quantity evaporated per unit time per unit area) for an evaporator is important, because it reduces the size of the evaporator of a fixed capacity as well as shortens the time required for the generation of steam. If the evaporation rate, hence the heat-transfer quantity Q, has a maximum value, the determination of this value is certainly necessary if one is to control the evaporation rate at all. This article is mainly a report of the experimental determination of the maximum value of heat transfer, although the related minimum value of heat transfer was also obtained experimentally.

As the boiling phenomenon is so involved and complicated, the analysis for boiling heat transfer is an almost impossible problem. Even with the powerful dimensional analysis, the research to date was not very satisfactory; besides, the reported work available in the literature was all experimental.

Now

$$Q = \alpha(\Delta T), \qquad (1)$$

where Q is the heat transmitted from the metal surface per unit area per unit time to the water; α is the heat-transfer coefficient, and ΔT is the temperature difference between the surface and the water. Equation (1) has been used for obtaining the relationship between ΔT, α and Q. Among the researchers on boiling heat transfer are Austin [1], and Jakob and Linke [2].

For the purpose of comparison, the work of previous workers is indicated by a, b, c, in Fig. 1. Austin [1] proposed that α asymptotically approaches 7000 kcal/m² h °C (0.194 cal/cm² s °C), and the quantity Q increases with ΔT without limit.

In the process of boiling, the water is fully agitated by the generated steam bubbles, and the degree of agitation first increases with increase in ΔT, but because of the lower heat-transfer rate of steam ($\frac{1}{30}$ of the heat-transfer rate of water), α is not a monotonically increasing function of ΔT. When the boiling is mild, the agitation by the steam bubbling has more effect on the heat transfer, so α and Q both increase as the ΔT is increased. Whereas, if the generation of steam becomes too fast, most of the metal surface is covered by the steam bubbles. As a result, there is no more water which is in direct contact with the metal surface to be agitated. Therefore, the negative effect (lowering of α) takes place and it becomes a matter of heat transfer between metal surface and steam. Thus, contrary to the conclusion of the previous workers, the value of α at 100 or 200°C ΔT is conceivably limited (in the order of 1 kcal/m² h °C). Therefore, in the ΔT–α curve, the ordinate first increases with increase in ΔT (Fig. 2) to a critical point, then it must decrease for further increase in ΔT. Since Q is the product of α and ΔT, it should not decrease when α first starts to decrease. Differentiating equation (1) and letting $dQ = 0$, one gets $\alpha/\Delta T = -d\alpha/d(\Delta T)$; thus at the point b, Q also starts to decrease (Fig. 2), and that is the maximum value of heat transfer, Q_{max}. If ΔT continues to increase, the radiation from the metal surface becomes pronounced and the values of α and Q can go very high, so that the α- and Q-curve should be concave upward again. The relational function of α or Q on ΔT is as presented in Fig. 2, where c is the point for the minimum value of Q. Nevertheless, the bc part of the curve (as will be discussed later) is so unstable that it is hard to obtain in practice.

FURTHER DISCUSSION ON THE Q–ΔT AND α–ΔT CURVES (FIG. 2)

Some special equipment might be used to maintain the metal surface at a constant temperature although, in general, equilibrium temperature is attained when the heat transmitted to the water is equal to the heat supplied by the heat source. Let Q be the heat supplied

* Translated from the Japanese by Dr C. J. Lee, while he was a graduate student in the School of Chemical Engineering, Oklahoma State University, Stillwater, Oklahoma. Dr Lee's present address is Heat Transfer and Process Equipment Research Section, Phillips Research Center, Phillips Petroleum Company, Bartlesville, Oklahoma, U.S.A.

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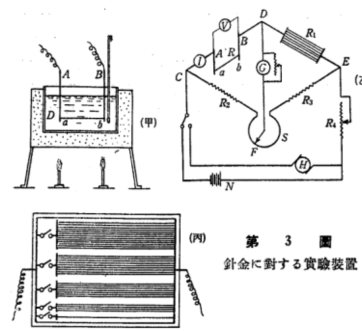
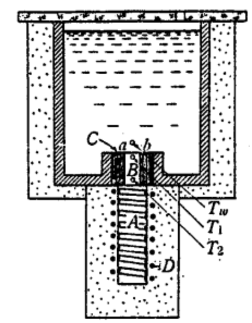


第 3 圖　針金に對する實驗裝置



第 15 圖　平面に對する實驗裝置

11.1 Pool boiling curve

❖ Nukiyama's experiment

Biography: Shiro Nukiyama

Shiro Nukiyama was born in 1896 in Tokyo, Japan. He graduated from Tokyo Imperial University, and immediately started his professional career as a Lecturer of Tohoku Im perial University (currently Tohoku University). He was appointed Associate Professor in 1921. He visited England, Germany, Switzerland and the United States in 1922~24. He was appointed Professor in 1926. In subsequent years he actively conducted boiling heat transfer research.

In 1934, Nukiyama published a pioneering paper*) which was entitled "The Maximum and Minimum Values of the Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure". This paper clarified and provided an overview of the boiling phenomena in the form of the Nukiyama Curve (boiling curve).

In this work, Nukiyama made an excellent experiment using a metallic wire or a metal wire, in which temperature and heat flux are evaluated accurately, and found that the relation between degree of superheating and heat flux is not monotonous, and that a maximum heat flux points appears in the nucleate boiling region and a minimum heat flux point appears in the film boiling region. He also found the hysteresis behavior that occurs in the transition region between the nucleate boiling and film boiling. Furthermore, he suggested that the boiling curve can be drawn even in the transition region if the state of the boiling water can be changed quasi-statically.

11.1 Pool boiling curve

- Nukiyama's experiment

Biography: Shiro Nukiyama

This was an epoch-making work which clarified the physics of boiling phenomena first. It has been highly appreciated in the international academic world of heat transfer. Also, it has become a guideline to heat transfer engineering for the design and control of combustion boilers and/or steam generators, and as such it has laid the foundation of modern energy technology. The Nukiyama Curve appears in every textbook of heat transfer today. Nukiyama is a great person in the international academic world of heat transfer.
In 1956 Nukiyama retired from Tohoku University, and was granted the title of Professor Emeritus. He served as the President of Heat Transfer Society of Japan in 1963~64. He received the Max Jacob Memorial Award in 1968. In 1983, he passed away in Sendai, Japan.
*) :

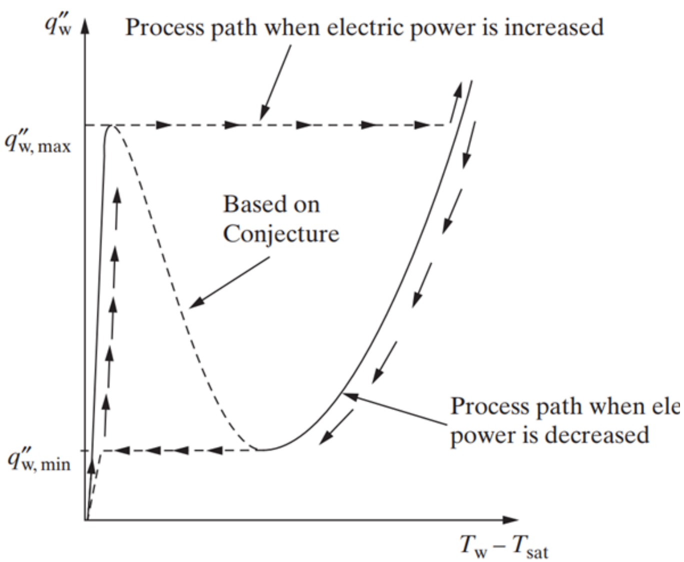
Journal of the Japan Society of Mechanical Engineers, vol. 37, no. 206, pp. 367-374, June 1934.
The English translation was published twice in International Journal of Heat and Mass Transfer, in vol. 9, pp. 1419-1433, 1966 and in vol. 27, pp. 959-970, 1984.

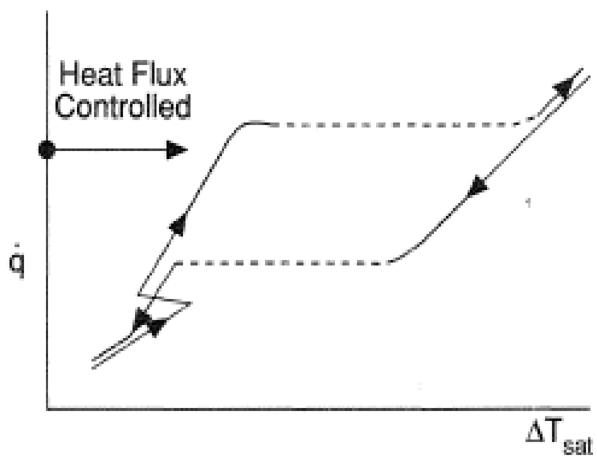
11.1 Pool boiling curve

- Nukiyama's experiment
  - ✓ Important observations
    - The three major regimes: nucleate boiling, transition boiling, and film boiling
    - The process paths for increasing and decreasing electric power (heat flux) are different.
      - – The dashed part of the boiling curve is completely bypassed.

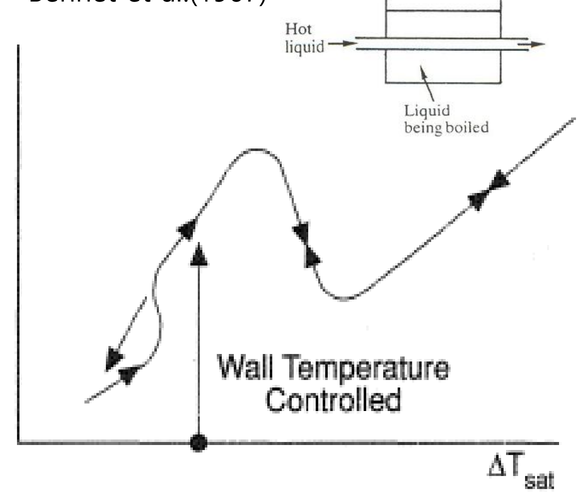
To form an opinion or idea without proof or sufficient evidence

      - – Based on his experimental data, Nukiyama correctly conjectured that the dashed part of the curve (transition boiling) must be producible when $T_w - T_{sat}$, rather than q_w, is controlled.





Bennet et al.(1967)



11.1 Pool boiling curve

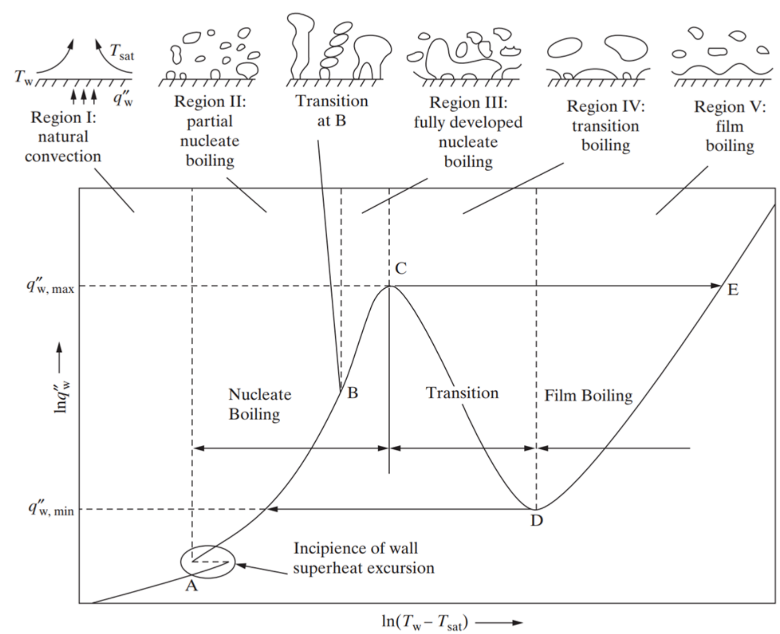
- Boiling curve
  - ✓ ONB, onset of nucleate boiling (A)
    - Wall superheat excursion

      a deviation from a regular activity or course

      having the property of transmitting electric force without conduction, insulating

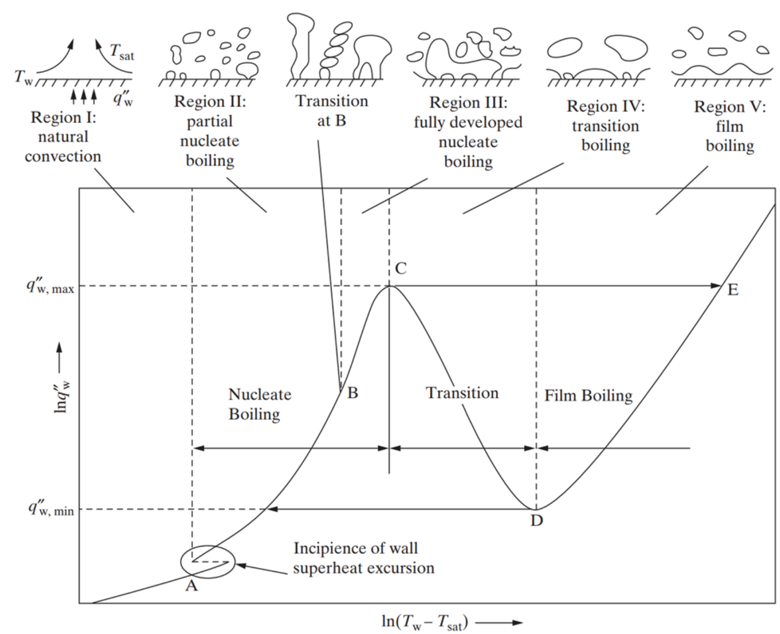
      – Depends on the surface wettability by the liquid and is significant for wetting dielectric fluids.

      – For the refrigerant R-113 on a platinum thin-film heater, for example, You et al. (1990) could measure wall superheat excursions as large as 73 °C.
  - ✓ Partial boiling region (AB)
    - Natural convection + boiling
    - Increasing slope is increased due to the contribution of boiling



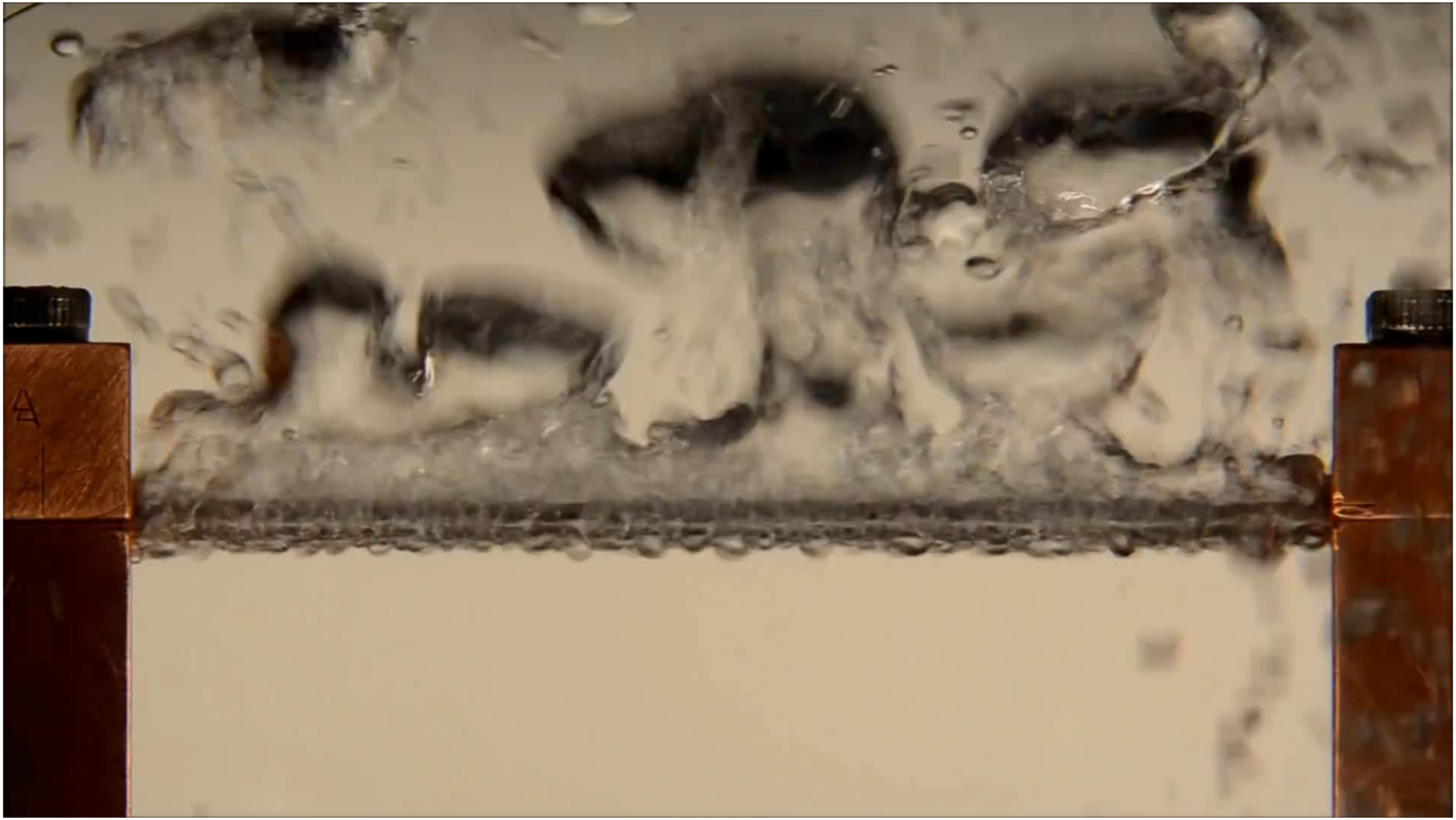
11.1 Pool boiling curve

- Boiling curve
  - ✓ Fully developed boiling region (BC)
    - Contribution of natural convection heat transfer is negligible.
  - ✓ Critical heat flux (C)
    - the end of uninhibited macroscopic contact between liquid and the heated surface
    - $q''_w > q''_{CHF}$ → hydrodynamic processes no longer allow for uninhibited contact
      - Partial and complete drying of the surface will occur.
  - ✓ Transient boiling regime (CD)
    - Intermittently dry surface or macroscopic contact with liquid
    - Dry fraction increases with T_{sup}
  - ✓ Minimum film boiling temp. (MFB, D)
    - No direct macroscopic contact
    - Surface is covered by a vapor film



11.1 Pool boiling curve

❖ Boiling curve

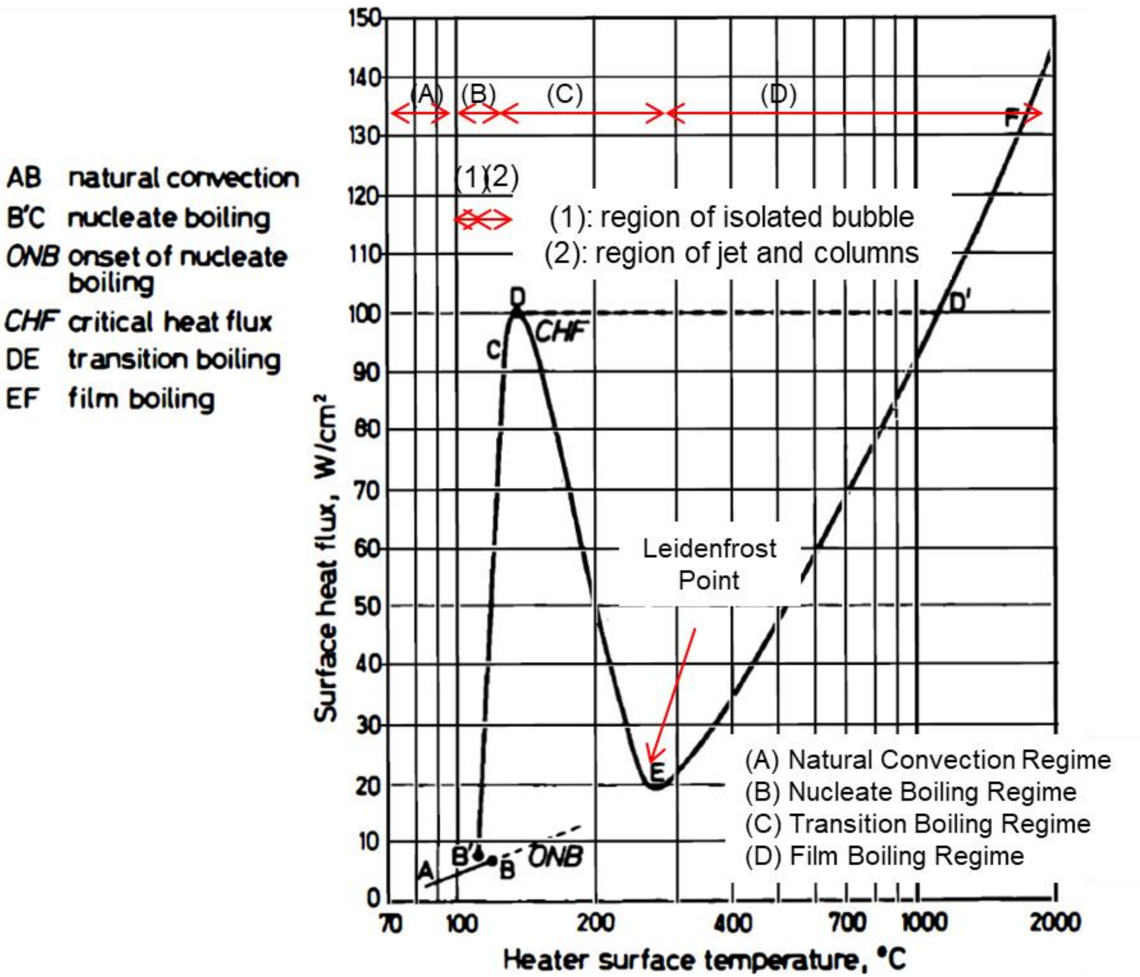


11.1 Pool boiling curve

❖ Boiling curve

11.1 Pool boiling curve

- Boiling curve



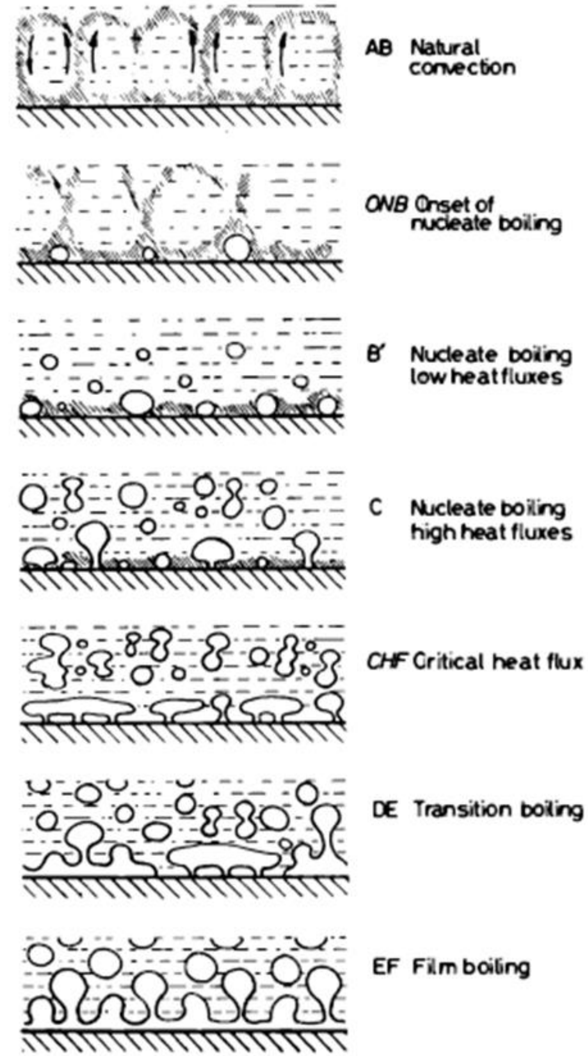
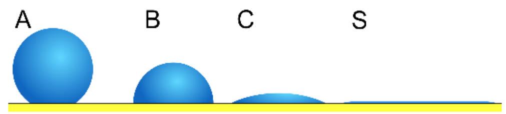


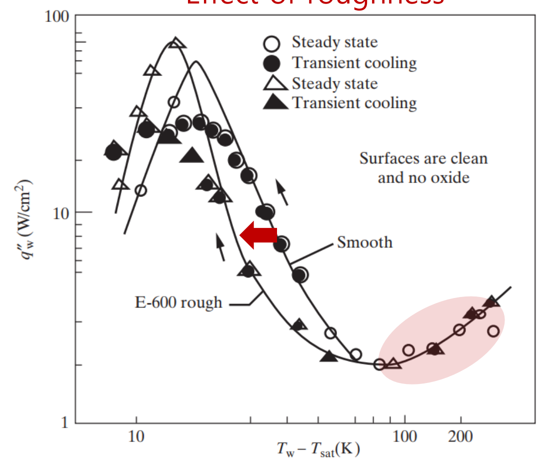
Fig. 4.11. The various stages in the pool boiling curve.

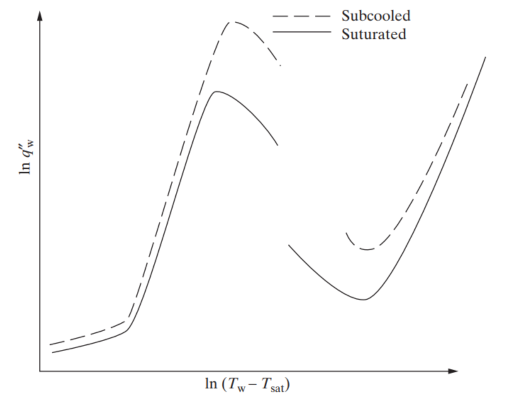
11.1 Pool boiling curve

- Parametric effects on pool boiling curve
  - Surface wettability (reduction in contact angle)
    - Shift of the boiling line to the right
    - Decreased boiling heat transfer coefficient
    - Increased maximum heat flux
  - Surface roughness
    - Shift the nucleate and transition lines to the left
    - Improvement in the nucleate boiling heat transfer
  - Surface contamination (deposition and oxidation)
    - Similar to surface roughness
  - Liquid pool subcooling
    - Improvement of heat transfer in all boiling regime



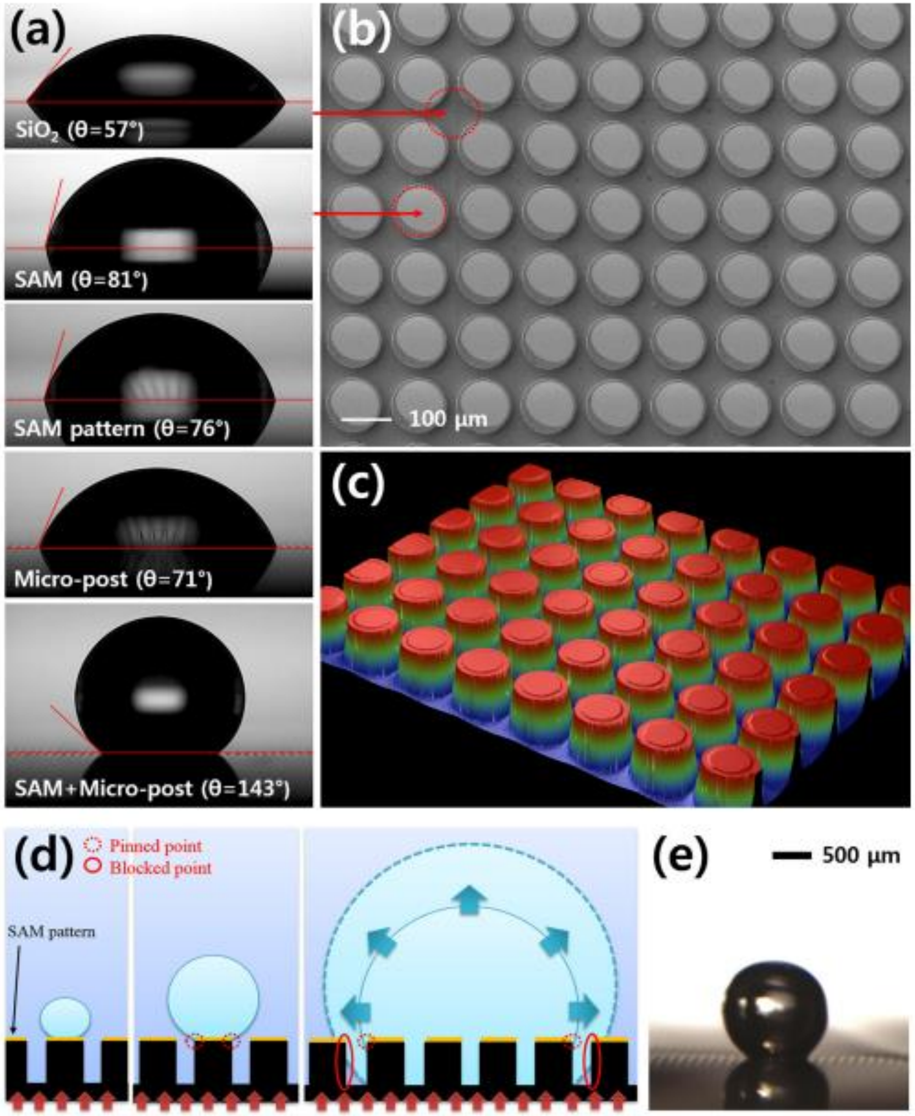
Effect of roughness

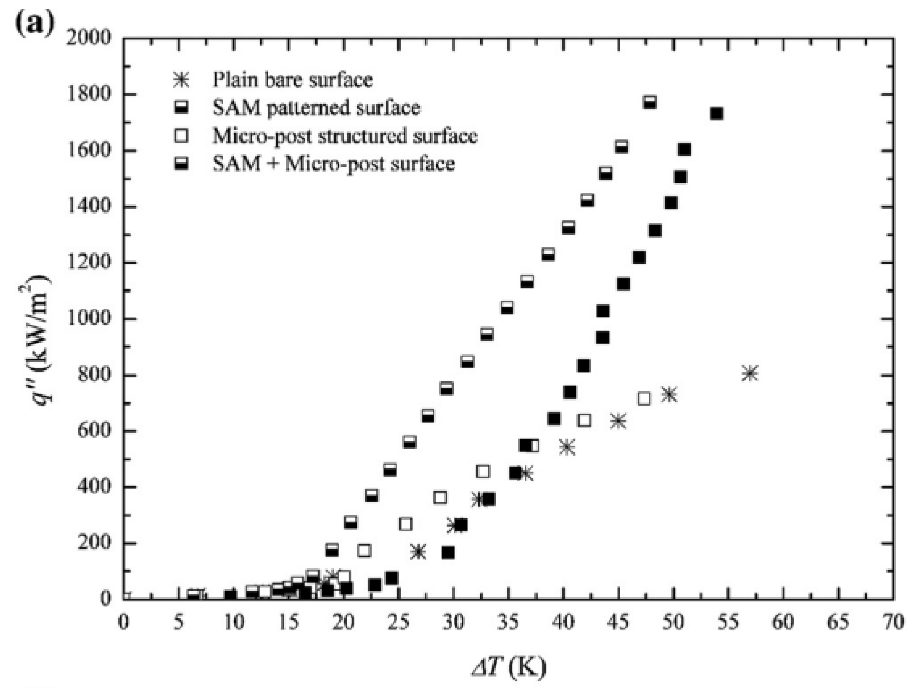




11.1 Pool boiling curve

POSTECH, APPLIED PHYSICS LETTERS 106, 181602 (2015)





11.1 Pool boiling curve

- Parametric effects on pool boiling curve

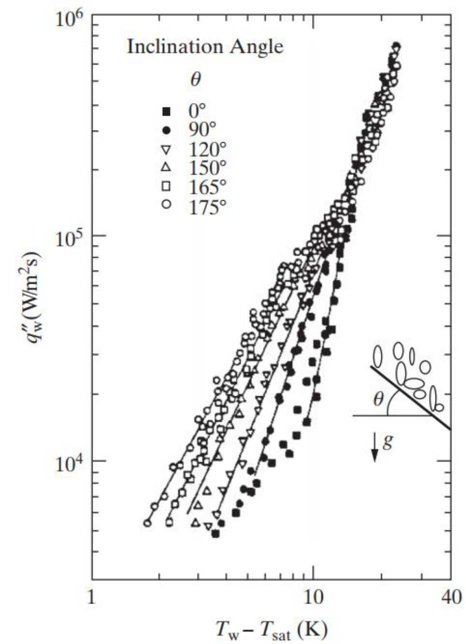
Harrison Fagan O'Hanley (MIT, 2012)

performance. The effect of wettability on the surface was dependent on the presence of porosity. For non-porous surfaces, wettability appeared to have no appreciable effect on either CHF or HTC. Porous hydrophilic surfaces tended to enhance CHF, while porous hydrophobic surfaces were extremely poor performing. Porosity had powerful effects on the boiling surface and was beneficial for hydrophilic surfaces and quite detrimental for hydrophobic surfaces. Surface roughness did not play an appreciable role in dictating the performance of the boiling surface, even when combined with other surface parameters. In summary, contrary to common beliefs, intrinsic wettability and surface roughness per se have very little effect on CHF and HTC, while the combination of porosity and wettability can determine CHF changes by an order of magnitude.

11.1 Pool boiling curve

✓ Surface orientation

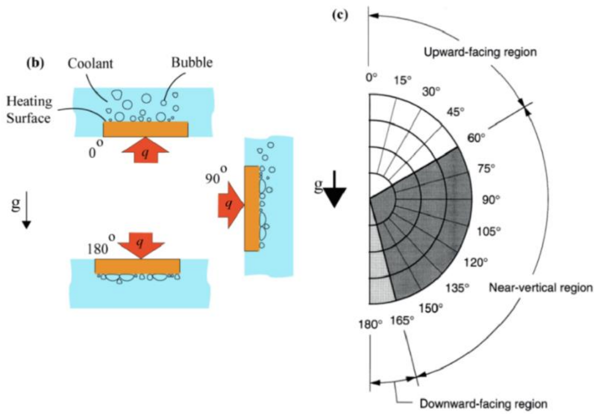
- Strong effect on partial boiling and film boiling
- Little effect on fully developed nucleate boiling.
- Two effects
  - Bubble rolling on inclined surfaces. Release of the bubbles from the surfaces.
    - Upward facing surfaces: disruption of the thermal boundary layer is rather limited
    - Downward facing surfaces: sliding → significant disruption of the boundary layer
  - Effect of thermal boundary layer on bubble nucleation
    - Natural convection boundary layer is thicker in downward-facing surfaces, promoting nucleation

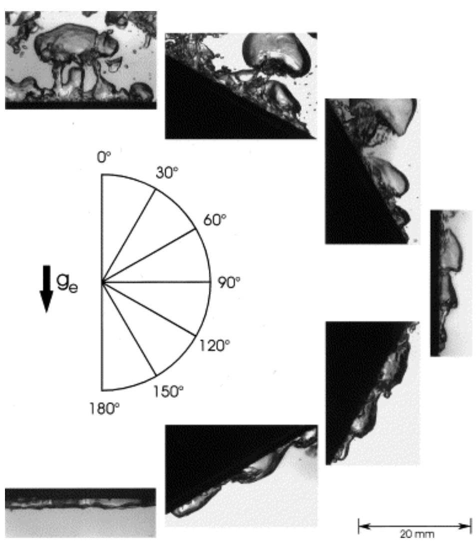


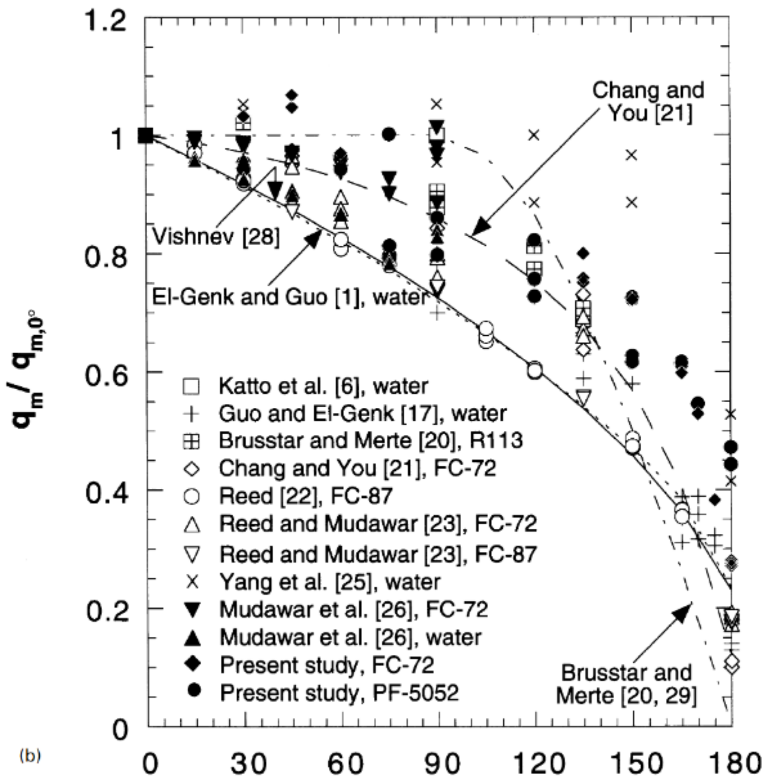
11.1 Pool boiling curve

✓ Surface orientation

Review: Surface orientation effects on Pool-boiling with plain andenhanced surfaces
Munonyedi Egbo, Mohammad Borumand, Yahya Nasersharifi, Gisuk Hwang
*Department of Mechanical Engineering, Wichita State Univ., Applied Thermal Engineering 204 (2022) 117927



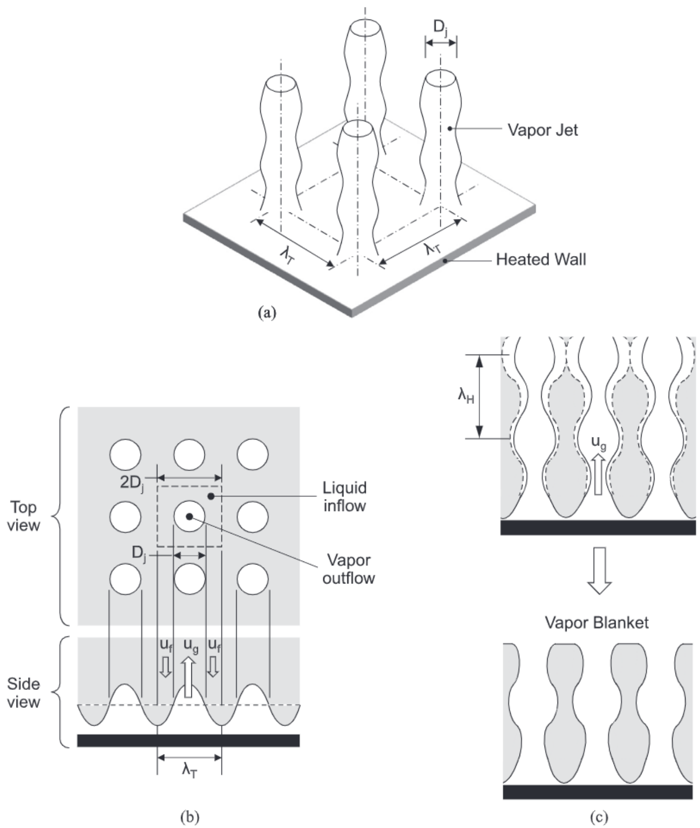


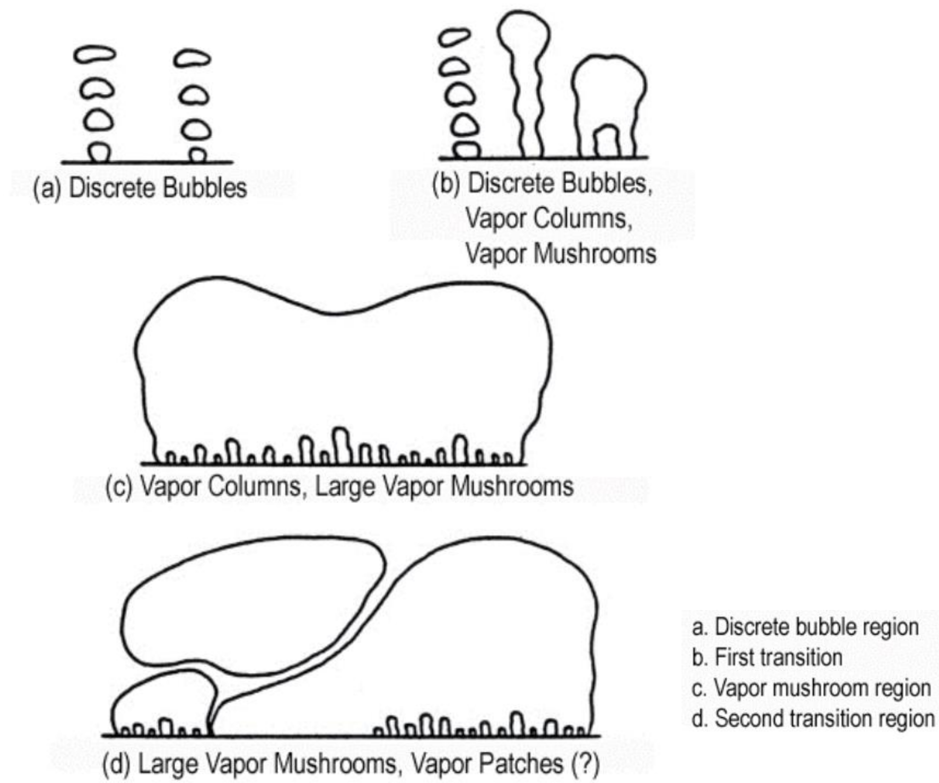


0 degree: horizontal upward heating

11.2 Heterogeneous Bubble Nucleation and Ebullition

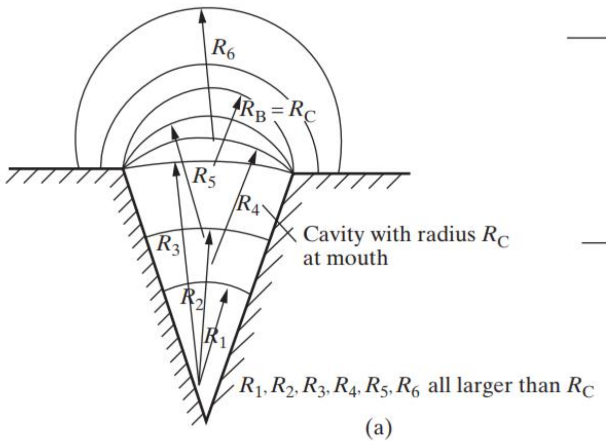
- Nucleate boiling under low-heat-flux conditions (partial boiling)
  - ✓ Heterogeneous bubble nucleation on the defects of the heated surfaces
- At higher-heat-flux conditions (fully developed nucleate boiling)
  - ✓ Vapor jets and mushrooms





11.2 Heterogeneous Bubble Nucleation and Ebullition

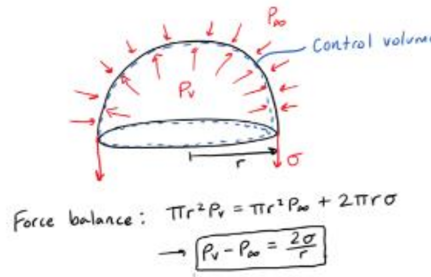
- Heterogeneous Bubble Nucleation and Active Nucleation Sites
  - ✓ Solid surfaces: microscopic cavities and crevices
    - Material, finishing, oxidation, contamination
  - ✓ Minute air pockets of air trapped in the crevices
    - Pre-existing gas-liquid interfacial area → embryo for bubble growth
    - No longer homogeneous nucleation → heterogeneous boiling
  - ✓ Relatively small superheat
  - ✓ Within a thin, moderately superheated liquid layer
  - ✓ Nucleation
    - Microbubble growth on a crevice
    - Most of surface crevice in metals: conical



11.2 Heterogeneous Bubble Nucleation and Ebullition

- Heterogeneous Bubble Nucleation and Active Nucleation Sites
  - ✓ Bubble growth
    - From a radius R1 until it extends outside the cavity
    - Largest curvature: $R_B = R_C$ (hemisphere)
    - Largest excess pressure needed for the bubble to remain at equilibrium
  - ✓ Bubble internal pressure and wall superheat

$$\pi R^2 (P_B - P_L) = 2\pi R \sigma$$



$$P_B - P_L = \frac{2\sigma}{R_C} \qquad T_L - T_{sat} \approx \frac{T_{sat}}{\rho_v h_{fg}}(P_B - P_L) = \frac{2 T_{sat} \sigma}{\rho_v h_{fg} R_C}$$

Clausius–Clapeyron relation

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{12}}{T v_{12}} \qquad \left(\frac{dT}{dP}\right)_{sat} = \frac{T_{sat} v_{fg}}{h_{fg}} \qquad T_v - T_{sat} = (P_v - P_l)\frac{T_{sat} v_{fg}}{h_{fg}}$$

- Valid for a uniformly heated liquid
- In practice, the liquid temperature can be non-uniform → larger wall superheat

❖ Heterogeneous Bubble Nucleation and Active Nucleation Sites

✓ Bubble internal pressure and wall superheat

Fog in the atmosphere can be small as 2μm in diameter, Pressure inside a droplet of this size at 20 ℃?

$$\sigma = 0.0728 N/m$$

$$P_{inside} = P_{outside} + \frac{2\sigma}{r}$$

$$= 101325 Pa + \frac{2 \times 0.0728 N/m}{1.0 \mu m}$$

$$= 243 kPa$$

Example 6.2 For water at atmospheric pressure, estimate the critical bubble radius r^* for liquid superheat levels of 2, 10 and 40°C.

For water at atmospheric pressure, $T_{sat} = 100$°C, $\sigma = 0.05878$ N/m, $v_{lv} = 1.672$ m³/kg, $h_{lv} = 2257$ kJ/kg. The critical radius r^* is determined by substituting these values into Eq. (6.31):

$$r^* = \frac{2\sigma\, T_{sat}(P_l)\, v_{lv}}{h_{lv}[T_l - T_{sat}(P_l)]}$$

$$= \frac{2(0.05878)(100 + 273)\, 1.672}{(2257 \times 1000)[T_l - T_{sat}(P_l)]}$$

Substituting 2, 10 and 40 for $[T_l - T_{sat}(P_l)]$ yields

$[T_l - T_{sat}(P_l)]$ (°C)	r^* (μm)
2	16.20
10	3.25
40	0.81

11.2 Heterogeneous Bubble Nucleation and Ebullition

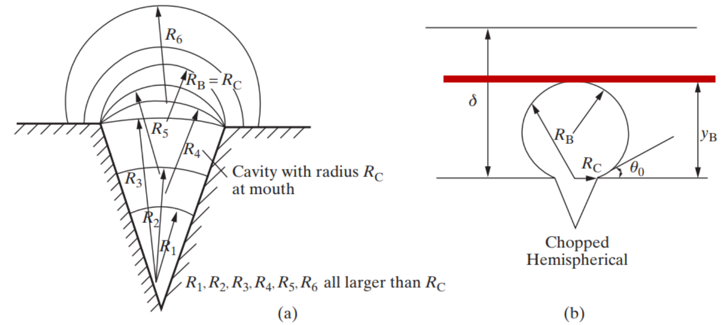
❖ Heterogeneous Bubble Nucleation and Active Nucleation Sites

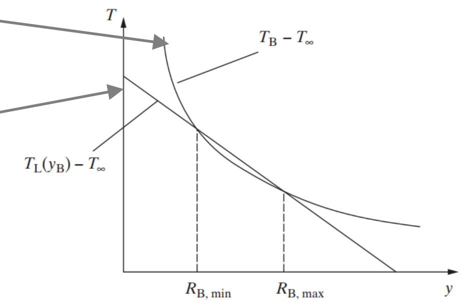
✓ Bubble nucleation criterion (Hsu, 1962)

$$y_B = C_1 R_C \qquad C_1 = (1+\cos\theta)/\sin\theta$$

$$R_B = C_2 R_C \qquad C_2 = 1/\sin\theta$$

$$T_B = T_{sat} + \frac{2\sigma T_{sat}}{C_2 R_C \rho_v h_{fg}}$$





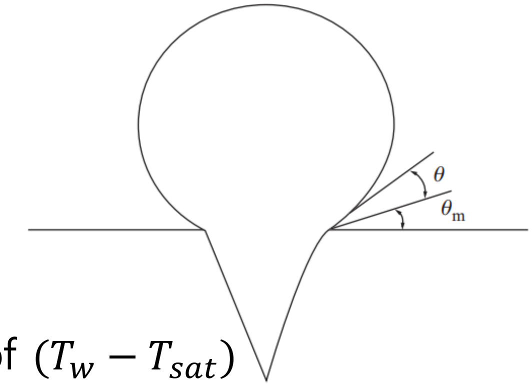
- Criterion: $T_{L,y=y_B} \geq T_B$
- Linear temperature profile in a thermal boundary layer
  - $\frac{T_L(y)-T_\infty}{T_W-T_\infty} = 1 - y/\delta$
  - $\frac{T_B-T_\infty}{T_W-T_\infty} = 1 - \frac{C_1 R_C}{\delta}$
- Two points of intersection

$$R_{C,min}, R_{C,max} = \frac{\delta(T_w - T_{sat})}{2C_1(T_w - T_\infty)}\left[1 \mp \sqrt{1 - \frac{8C_1}{C_2}\frac{(T_w - T_\infty)T_{sat}\sigma}{(T_w - T_{sat})^2\delta\rho_v h_{fg}}}\right]$$

  - Activated crevices: $R_{C,min} \leq R_C \leq R_{C,max}$
  - $\delta = k_L/H$, H: convective heat transfer coefficient

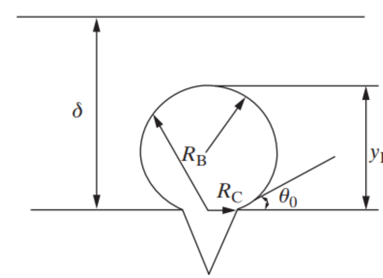
11.2 Heterogeneous Bubble Nucleation and Ebullition

- Heterogeneous Bubble Nucleation and Active Nucleation Sites
  - ✓ Cavity shape effect
    - C_1 & C_2: based on a sharp cavity mouth
    - Cavity mouth slope θ_m : $\theta \rightarrow \theta + \theta_m$



  - ✓ Improvement of Hsu's criterion
    - Hsu's criterion was conservative → over-prediction of $(T_w - T_{sat})$
    - Assumption of bubble surrounded everywhere by liquid warmer than the bubble (X)
    - Modification

$$T_w - T_{sat} \geq \begin{cases} \dfrac{4\sigma T_{sat}}{h_{fg}\rho_v \delta} & \text{for } R_c > \delta \\ \left(\dfrac{2\sigma T_{sat}}{h_{fg}\rho_v R_C}\right) \dfrac{1}{1 - \frac{R_C}{2\delta}} & \text{for } R_c < \delta \end{cases}$$



EXAMPLE 11.1. A horizontal circular disk that is 10 cm in diameter is submerged in a shallow pool of quiescent water that is at 95 °C. Calculate the size range of active nucleation sites for $T_w = 109$ °C, assuming that the contact angle is 50°.

SOLUTION. The thermophysical properties of water at the film temperature $T_{film} = \frac{1}{2}(T_w + \overline{T}_L) = \frac{1}{2}(382 + 368) = 375$ K are $\rho_L = 957$ kg/m^3, $k_L = 0.666$ W/m·k, $\alpha_L = 1.648 \times 10^{-7}$ m^2/s, $\nu_L = 2.89 \times 10^{-7}$ m^2/s, $\sigma = 0.059$ N/m, and $\mathrm{Pr}_L = 1.75$. Other properties are $T_{sat} = 373.1$ K, $\rho_g = 0.597$ kg/m^3, and $h_{fg} = 2.257 \times 10^6$ J/kg.

We need to estimate δ, the thickness of the thermal boundary layer, and for that we need to calculate the convection heat transfer coefficient. We can use a natural convection correlation. For an upward-facing, heated horizontal surface (Ghiaasiaan, 2011),

$$l_c = A/p,$$

where A and p are the surface area and perimeter, respectively, and l_c is the characteristic length of the surface. We thus get

$$l_c = D/4 = 0.025 \text{ m}.$$

The calculations then continue as follows. The thermal expansion coefficient is $\beta = 7.49 \times 10^{-4}\mathrm{K}^{-1}$. The Rayleigh number is therefore

$$\mathrm{Ra} = \frac{g\beta(T_w - T_\infty)l_c^3}{\nu_L \alpha_L} = 3.377 \times 10^7.$$

The average Nusselt number is

$$\mathrm{Nu}_{lc} = 0.15\,\mathrm{Ra}^{1/3} = 48.2.$$

The average heat transfer coefficient is

$$H = \mathrm{Nu}_{lc} k_L / l_c = 1{,}283 \text{ W/m}^2\cdot\text{K},$$

with

$$\delta = \frac{k_L}{H} = 5.19 \times 10^{-4} \text{ m}.$$

The minimum and maximum crevice radii can now be found from Eq. (11.9), and that leads to

$$R_{C,min} = 2.87 \times 10^{-6} \text{ m} \approx 2.9\ \mu\text{m},$$
$$R_{C,max} = 1.50 \times 10^{-4} \text{ m} \approx 150\ \mu\text{m}.$$

11.2 Heterogeneous Bubble Nucleation and Ebullition

❖ Active Nucleation Sites

- ✓ Most difficult problem with respect to the mechanistic modeling of boiling
- ✓ Depends on
  - Surface material, finishing, oxidation, contamination
  - Wall heat flux or wall superheat $N \sim (T_{\mathrm{w}} - T_{\mathrm{sat}})^m$, m=4-6
    - – m: depend on the shape and size of the cavities
- ✓ Interaction among neighboring nucleation sites
  - A nucleation site can activate or deactivate neighboring sites.
  - Interaction between neighboring sites depend on the distance between them.
    - – Larger than three times of departing bubbles, two sites operate independently.
    - – One~three times, a bubble at one site inhibits the formation of a bubble at the other.
    - – For smaller distance, one promotes the formation at the other
- ✓ Kocamustafaogullari and Ishii (1983)

$$N^* = \left\{ \left[\frac{2R_{\mathrm{C}}}{d_{\mathrm{Bd}}} \right]^{-4.4} \left[2.157 \times 10^{-7} \rho^{*-3.2} (1 + 0.0049\rho^*)^{4.13} \right] \right\}^{1/4.4}$$

$$R_{\mathrm{C}} = \frac{2\sigma[1 + \rho_{\mathrm{L}}/\rho_{\mathrm{v}}]}{P_{\mathrm{L}}} \left\{ \exp\left[\frac{h_{\mathrm{fg}}(T_{\mathrm{v}} - T_{\mathrm{sat}})}{\frac{R_{\mathrm{u}}}{M} T_{\mathrm{v}} T_{\mathrm{sat}}} \right] - 1 \right\}$$

$$N^* = N d_{\mathrm{Bd}}^2$$

$$\rho^* = \Delta\rho/\rho_{\mathrm{v}}$$

$$d_{\mathrm{Bd}} = 0.0012 \rho^{*0.9} \left[0.0208\, \theta \sqrt{\frac{\sigma}{g\Delta\rho}} \right]$$

11.2 Heterogeneous Bubble Nucleation and Ebullition

- Periodic processes
  - ✓ Inception → growth during t_{gr} → departure
    - Departing bubble leaves a small pocket of gas-vapor mixture behind
  - ✓ Disruption of the thermal boundary layer → rush-in of cooling liquid
  - ✓ A new thermal boundary layer is formed and grows in thickness during t_{wt}
  - ✓ Then, the embryonic gas pocket starts to grow.
  - ✓ Bubble release frequency: $f_B = 1/(t_{gr} + t_{wt})$.
  - ✓ Nucleate boiling heat transfer (q''_{NB})

$$q''_{NB} = N f_B \rho_g h_{fg} \frac{\pi}{6} d_{Bd}^3$$

11.2 Heterogeneous Bubble Nucleation and Ebullition

- Growth period
  - Bubble growth mechanism-1
    - Growth by evaporation around the bubble while it is surrounded by superheated liquid
    - Plesset and Zwick (1954), Forster and Zuber (1954), Mikic et al. (1970), etc.
    - May not be realistic for a bubble attached to a surface
  - Bubble growth mechanism-2
    - Growth from thin liquid layer, the microlayer
    - Much of the evaporation occurs in the microlayer
    - Average thickness of the microlayer

(Cooper & Lloyd, 1969) (Lee & Nydahl, 1989)

$$\delta_m = C(\nu_f t_{gr})^{1/2} \qquad C \approx 0.3\text{–}1.3 \qquad C \approx 1$$

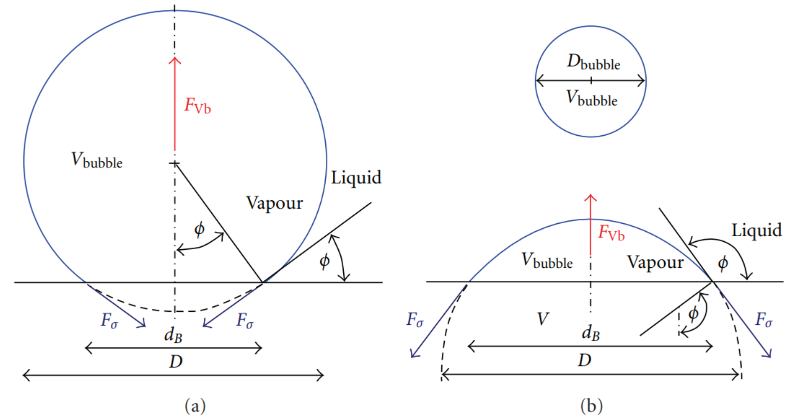
– Order of the molecular length near the center of the bubble base

11.2 Heterogeneous Bubble Nucleation and Ebullition

- Bubble departure
  - ✓ Fritz correlation

$$d_{\mathrm{Bd}} = 0.0208\,\theta\sqrt{\frac{\sigma}{g\Delta\rho}},$$

θ: contact angle in degree



  - Buoyancy and surface tension

  - ✓ Forces
    - Forces to dislocate the bubble: buoyancy, wake caused by the preceding bubble
    - Forces to resist bubble detachment: surface tension, drag, and inertia
  - ✓ Cole and Shulman (1966), modified model

$$d_{\mathrm{Bd}} = 0.0208\,\theta\sqrt{\frac{\sigma}{g\Delta\rho}}\left[1 + 0.0025(dd_{\mathrm{B}}/dt)^{3/2}\right]$$

  - ddB/dt: in millimeters per second
  - ✓ Bubble departure is a stochastic process even in well-controlled experiments.