HT: Convection

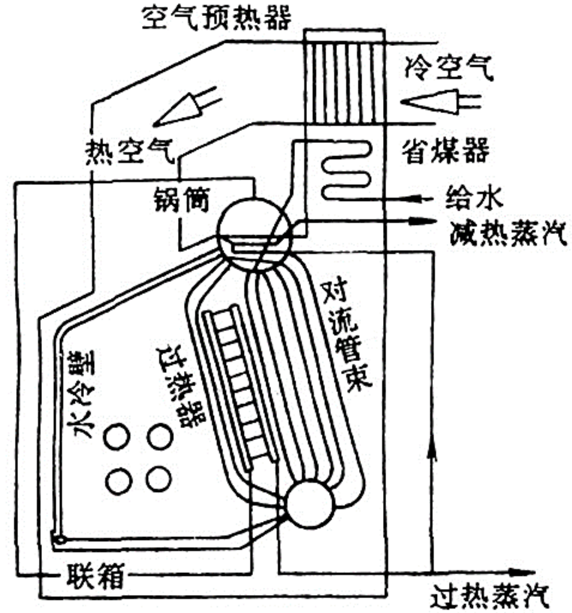
L12: Phase change convection heat transfer

Learning Objectives:

- **film condensation and dropwise condensation**
- **pool boiling**
- **in-tube boiling**

§ 7-1 condensation

★ practical cases

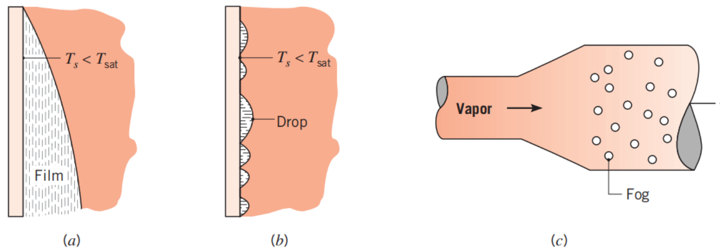


cooling wall

condensor

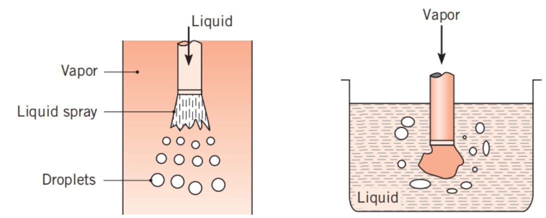
§ 7-1 condensation

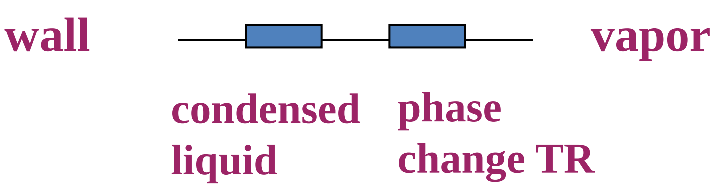
(1) condition to condense： Condensation occurs when the temperature of a vapor is reduced below its saturation temperature. The latent energy of the vapor is released, heat is transferred to the surface, and the condensate is formed



(2)The thermal resistance

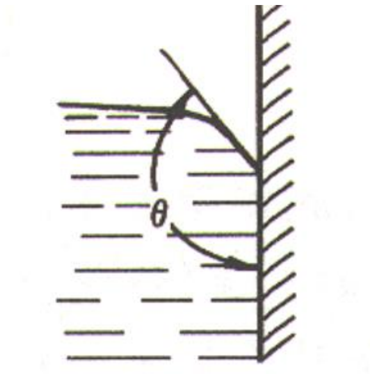
Condensed liquid is a thermal resistance carrier for heat exchange between vapor and wall surface. The larger and thicker the liquid layer separating vapor and cold wall surface is, the greater the thermal resistance will be

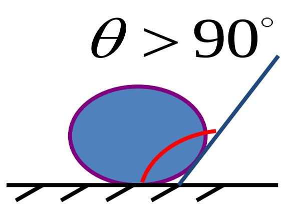


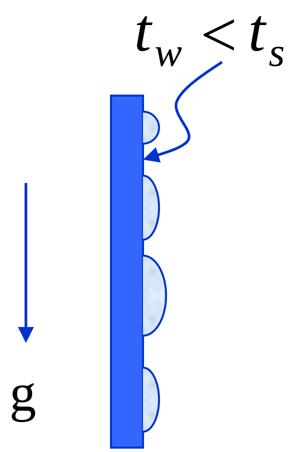


(3)Dropwise condensation

$h \rightarrow 10^5$







The condensation can not wet the wall surface, but the formation of small droplet on the wall surface

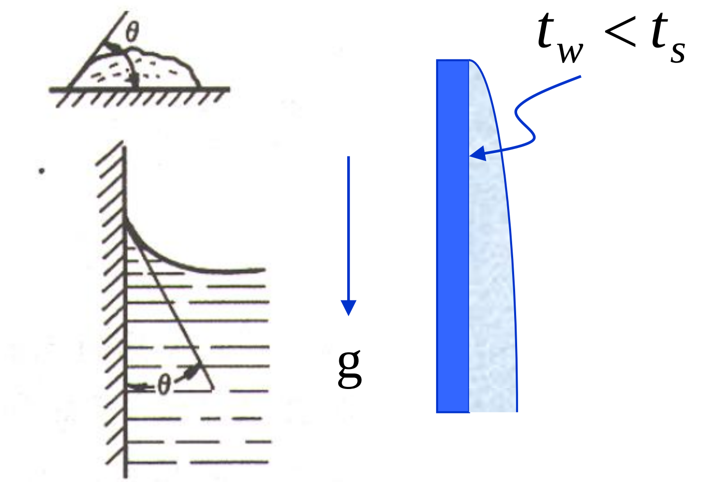
The droplet will sweep the wall and partial wall will directly contact vapor.

high condensation and heat transfer rates； high cost and difficult to maintain

§ 7-1 condensation

(4)film condensation

h →10⁴



Film condensation is generally characteristic of clean, uncontaminated surfaces， and under the action of gravity the film flows continuously from the surface.。

In industry, 98%~99% condensor occurs film condensation

§ 7-1 condensation

(5)summary

★ The surface heat transfer coefficient of dropwise condensation is 10~15 times larger than that of film condensation

dropwise：4×10^4~10^5；film： 6×10^3~10^4 W/(m^2K)

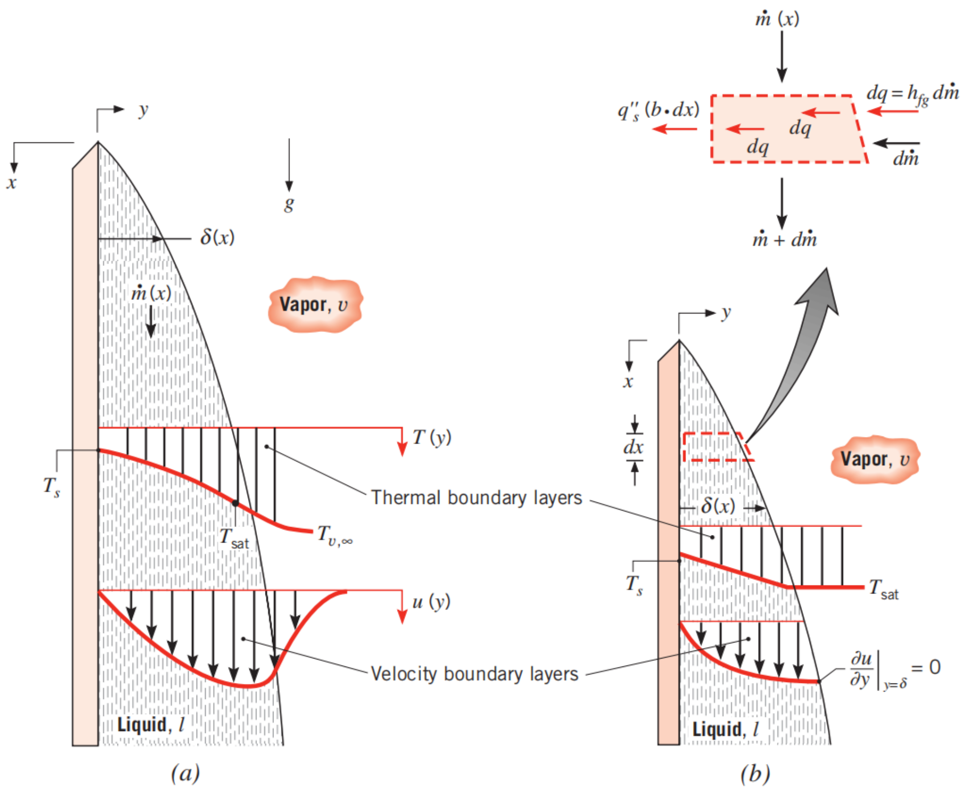
★ The reason for the two different forms of condensation is that the condensation liquid is different from the wall lubrication. On clean, uncontaminated surfaces, the condensation is usually film-like; dropwise condensation is often produced on lubricated walls.

Although the heat transfer of bead condensation is much greater than that of film condensation, it is a pity that bead condensation is difficult to maintain. Therefore, most of the condensation heat transfer encountered in engineering belongs to film condensation, so the textbook only introduces film condensation briefly.

The main way to enhance heat transfer by film condensation is to reduce the thickness of liquid film.

§ 7-2 Analytic solution of film condensation

Assumptions that originated with an analysis by Nusselt



1. film resistance is the main thermal resistance

2. flow in film is slow thereby neglect the convection

Key point

§ 7-2 Analytic solution of film condensation

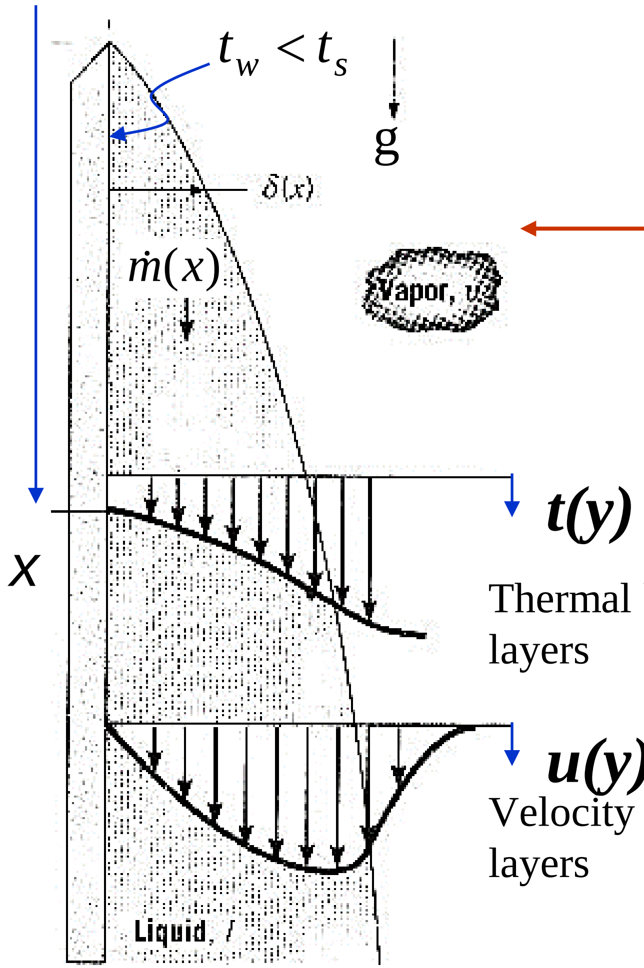
1. Laminar flow and constant properties are assumed for the liquid film.

2. The gas is assumed to be a pure vapor and at a uniform temperature equal to T_{sat}. With no temperature gradient in the vapor, heat transfer to the liquid–vapor interface can occur only by condensation at the interface and not by conduction from the vapor.

3. The shear stress at the liquid–vapor interface is assumed to be negligible. With this assumption and the foregoing assumption of a uniform vapor temperature, there is no need to consider the vapor velocity or thermal boundary layers

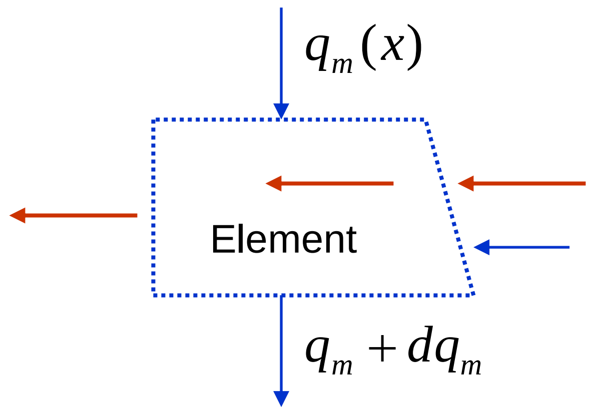
4.Momentum and energy transfer by advection in the condensate film are assumed to be negligible. This assumption is reasonable by virtue of the low velocities associated with the film. It follows that heat transfer across the film occurs only by conduction, in which case the liquid temperature distribution is linear

§ 7-2 Analytic solution of film condensation



Thermal boundary layers

Velocity boundary layers



边界层微分方程组：

$$
\begin{cases}
\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} = 0 \\[2ex]
\rho_l \left(u \dfrac{\partial u}{\partial x} + v \dfrac{\partial u}{\partial y}\right) = -\dfrac{dp}{dx} + \rho_l g + \eta_l \dfrac{\partial^2 u}{\partial y^2} \\[2ex]
u \dfrac{\partial t}{\partial x} + v \dfrac{\partial t}{\partial y} = a_l \dfrac{\partial^2 t}{\partial y^2}
\end{cases}
$$

§ 7-2 Analytic solution of film condensation

neglect the inerial force $\Rightarrow$

$$\rho_l \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}\right) = 0$$

neglect the density of vapor/or the vapor is non-flow $\Rightarrow$

$$\frac{dp}{dx} = 0$$

no convection only conduction in y direction $\Rightarrow$

$$u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} = 0$$

therefore we get:

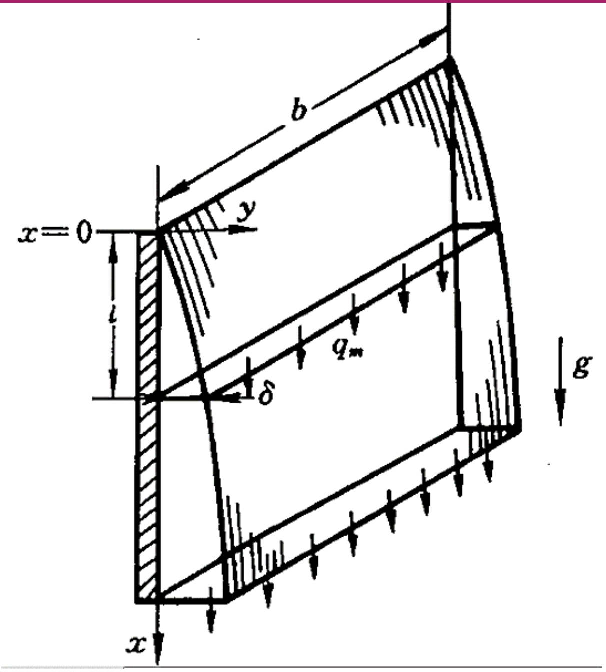
$$\boxed{\begin{cases} \rho_l g + \eta_l \dfrac{\partial^2 u}{\partial y^2} = 0 \\ a_l \dfrac{\partial^2 t}{\partial y^2} = 0 \end{cases}}$$

§ 7-2 Analytic solution of film condensation

boundary condition：

$$y=0\text{时}，\quad u=0,\quad t=t_w$$

$$y=\delta\text{时}，\quad \left.\frac{\mathrm{d}u}{\mathrm{d}y}\right|_\delta=0,\quad t=t_s$$



竖壁上层流液膜的质量流量

the velocity and temperature

distribution：

$$u(y)=\frac{g\rho_l\delta^2}{\eta_l}\left[\frac{y}{\delta}-\frac{1}{2}\left(\frac{y}{\delta}\right)^2\right]\qquad t=t_w+(t_s-t_w)\frac{y}{\delta}$$

求解的关键在于获得液膜厚度δ关于x的变化规律。

§ 7-2 Analytic solution of film condensation

mass flow:

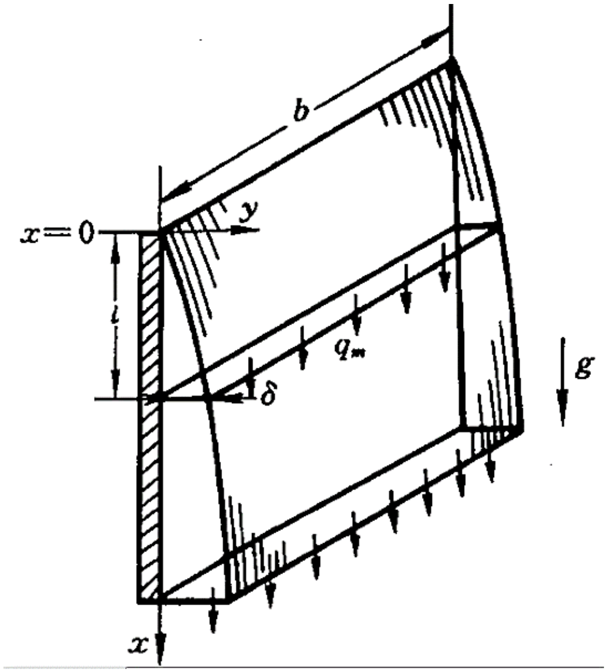
$$q_{m,x} = \int_0^{\delta(x)} \rho_l u dy = \frac{g\rho_l^2\delta^3}{3\eta_l}$$

the increase of mass flow rate with dx element:

$$dq_{m,x} = \frac{g\rho_l^2\delta^2 d\delta}{\eta_l}$$

the heat release:

$$r dq_{m,x} = r\frac{g\rho_l^2\delta^2 d\delta}{\eta_l} = \lambda\frac{t_s - t_w}{\delta}dx$$



竖壁上层流液膜的质量流量

§ 7-2 Analytic solution of film condensation

(1) thickness of the film

$$\delta = \left[\frac{4\eta_l \lambda_l (t_s - t_w) x}{g \rho_l^2 r} \right]^{1/4}$$

Reference temperature： $$t_m = \frac{t_s + t_w}{2}$$

§ 7-2 Analytic solution of film condensation

(2) convective heat transfer coefficient

$$h_x = \frac{\lambda_l}{\delta(x)} \quad ?$$

$$h_x = \left[\frac{g r \rho_l^2 \lambda_l^3}{4\eta_l (t_s - t_w) x} \right]^{1/4}$$

因为 $(\boldsymbol{\Delta t = t_s - t_w = const})$

average h:

$$h_V = \frac{1}{l}\int_0^l h_x dx = 0.943 \left[\frac{g r \rho_l^2 \lambda_l^3}{\eta_l l (t_s - t_w)} \right]^{1/4}$$

$$t_m = \frac{t_s + t_w}{2}$$

§ 7-2 Analytic solution of film condensation

(3) modify: The experiment shows that when the *Re* number is greater than 20, the condensation heat transfer is enhanced due to the fluctuation of the liquid film surface. Therefore, the experimental value is about 20% higher.

$$h_V = 1.13\left[\frac{gr\rho_l^2\lambda_l^3}{\eta_l l(t_s - t_w)}\right]^{1/4}$$

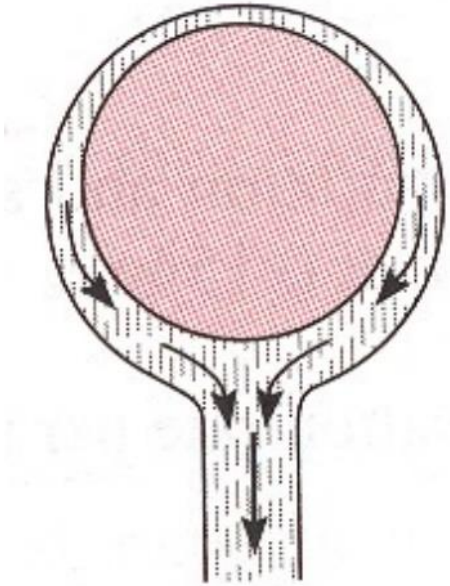
For plate with angle, replace g with gsinθ

§ 7-2 Analytic solution of film condensation

(4) horizontal tube and sphere

$$h_H = 0.729\left[\frac{gr\rho_l^2\lambda_l^3}{\eta_l d(t_s - t_w)}\right]^{1/4}$$

$$h_S = 0.826\left[\frac{gr\rho_l^2\lambda_l^3}{\eta_l d(t_s - t_w)}\right]^{1/4}$$



Reference temperature: $t_m = \frac{t_s + t_w}{2}$ r determined by t_s:

(5) For verticle tube:

$$\frac{h_{Hg}}{h_{Vg}} = 0.77\left(\frac{l}{d}\right)^{1/4}$$

• § 7-3 Flow state

The flow state within condensation film

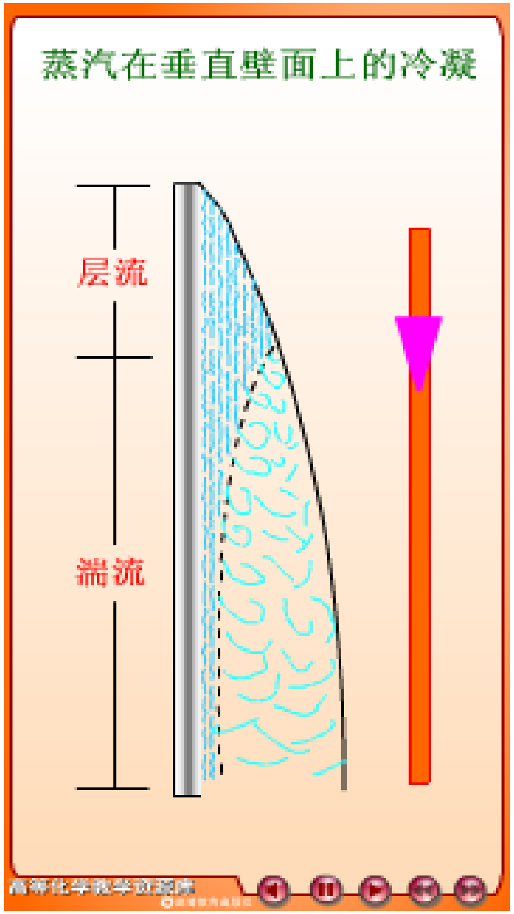
Also can be divided into laminar and turbulence, with characteristic number *Re*:

$$Re = \frac{d_e \rho u_l}{\eta}$$

where:

u_l is the average velocity at $x = l$

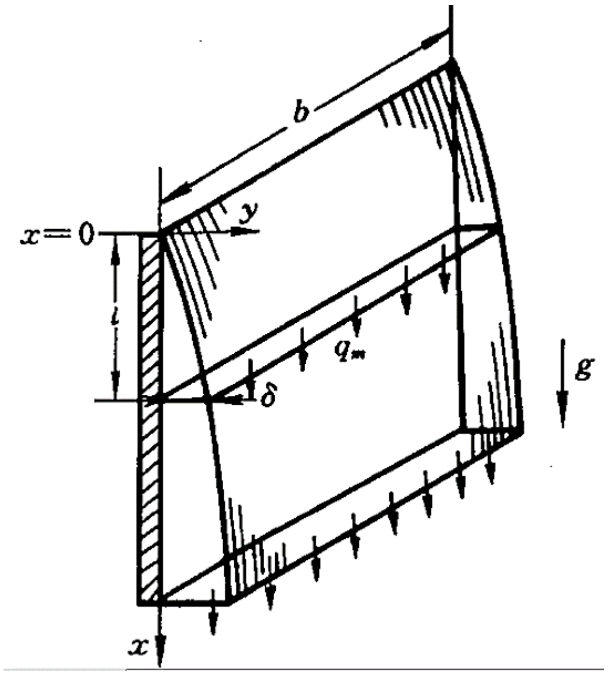
d_e is the hydraulic diameter at $x = l$



• § 7-3 Flow state

$$d_e = 4A_c / P = 4b\delta / b = 4\delta$$

$$Re = \frac{4\delta\rho u_l}{\eta} = \frac{4q_{ml}}{\eta}$$



Energy conservation:

$$h(t_s - t_w)l = rq_{ml}$$

Therefore: $$Re = \frac{4hl(t_s - t_w)}{\eta r}$$

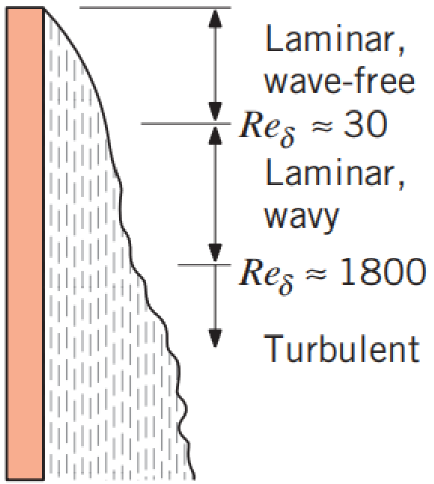
For horizonal tube, replace l with πr

Normally, the flow inside keeps laminar

• § 7-3 Flow state

Transition from laminar to turbulence:

- Re < 30： laminar wave-free
- 30<Re<1800:laminar wavy
- Re>1800: turbulence



For turbulent liquid film, except the laminar sublayer near the wall still relies on heat conduction to transfer heat, the other is mainly turbulent transfer, heat transfer is greatly enhanced.

For turbulence we have the average h：

$$h = h_l \frac{x_c}{l} + h_t \left(1 - \frac{x_c}{l} \right)$$

h_l is h in laminar；

h_t is h in turbulence；

x_c the Height where laminar transits to turbulence

l the total Height

• § 7-3 Flow state

The experimental correlation：

$$Nu = Ga^{1/3}\frac{Re}{58\,Pr_s^{-1/2}\left(\dfrac{Pr_w}{Pr_s}\right)^{1/4}(Re^{3/4}-253)+9200}$$

where：

$$Nu = hl/\lambda;$$

$$Ga = gl^3/\nu^2$$

Except Pr_w is calculated by t_w, others are determined by t_s

例 1

压力为$1.013 \times 10^5 Pa$的水蒸气在方形竖壁上凝结，壁的尺寸为$30cm \times 30cm$，壁温保持98℃，试计算每小时的传热量及凝结蒸气量。

解：假设液膜为层流。

根据$t_s = 100°C$，从附录查得$r = 2257kJ/kg$。其他物性按液膜平均温度

$$t_m = (100°C + 98°C)/2 = 99°C$$

从附录查取，得：

$$\rho = 958.4kg/m^3, \eta = 2.825 \times 10^{-4} Pa \cdot s, \lambda = 0.68\,W/(m \cdot K)$$

选用层流液膜平均表面传热系数计算式：

$$h = 1.13\left[\frac{g\rho^2\lambda^3 r}{\eta l(t_s - t_w)}\right]^{1/4} = 1.57 \times 10^4\,W/(m^2 \cdot K)$$

核算Re准则，

$$\mathrm{Re} = \frac{4hl(t_s - t_w)}{\eta r} = 59.1$$

§ 7-3 膜状凝结分析解及计算关联式

说明假设液膜为层流成立。

传热量按牛顿冷却公式计算：

$$\phi = hA(t_s - t_w) = 2.83 \times 10^3 W$$

凝结蒸气量为

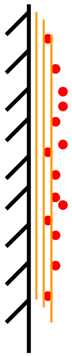
$$q_m = \frac{\phi}{r} = 1.25 \times 10^{-3} kg/s = 4.50 kg/h$$

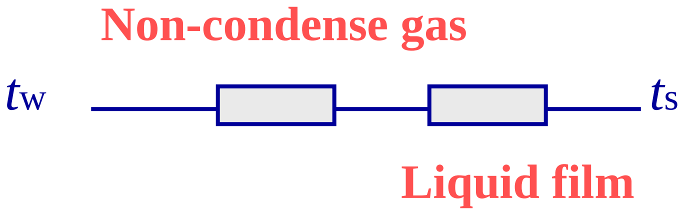
§ 7-4 sensitive factors affect condensation

The film condensation process in engineering is complicated and subject to various conditions

1. non-condense gas

The non-condense gas prevent the heat transfer process and reduce the saturated temperature, weaking the heat transfer performance





By experiments， 1% of non-condensing gas can reduce $\boldsymbol{h}$ by 60%

§ 7-4 sensitive factors affect condensation

2.Vapor velocity

At higher velocity, the vapor flow produces model viscous stress on the liquid film surface. When the vapor flow same direction with liquid, then the film would be stretched and become thin; if with inverse direction the film would be stressed and become thick

3.Superheated steam

4.Degree of supercooling of liquid & non-linear distribution of temperature

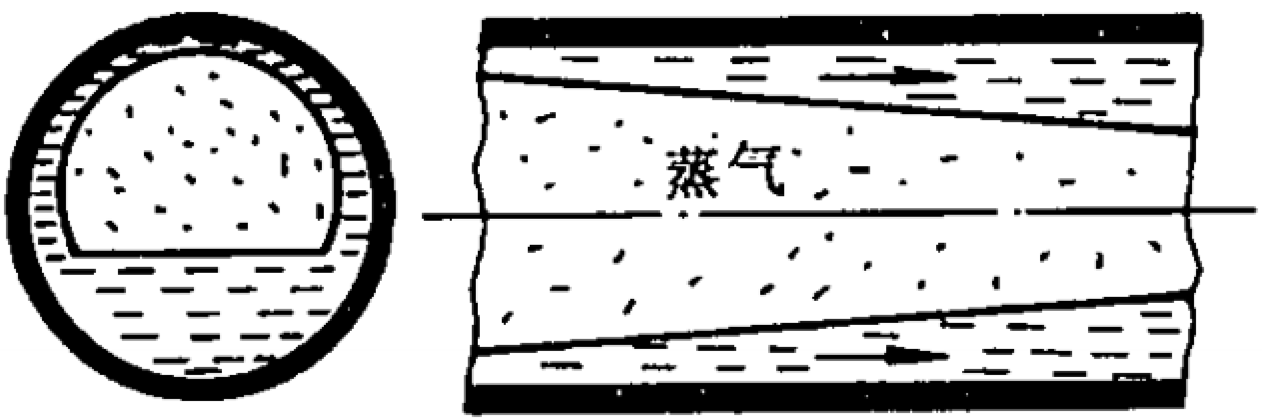
$$r' = r + 0.68c_p(t_s - t_w) \quad 或 \quad r' = r(1 + 0.68Ja)$$

§ 7-4 sensitive factors affect condensation

5.condensation in a tube

When the vapor flow rate is low, the condensate is mainly at the bottom of the pipe, and the vapor is located in the upper part of the pipe.

At higher velocity, circular flow is formed, and the condensate is evenly distributed around the pipe, with the vapor core at the c**enter.**



§ 7-4 sensitive factors affect condensation

6.The augment of condensation heat transfer

- The principle of strengthening condensation heat transfer is to minimize the thickness of the liquid film sticking on the heat transfer surface.

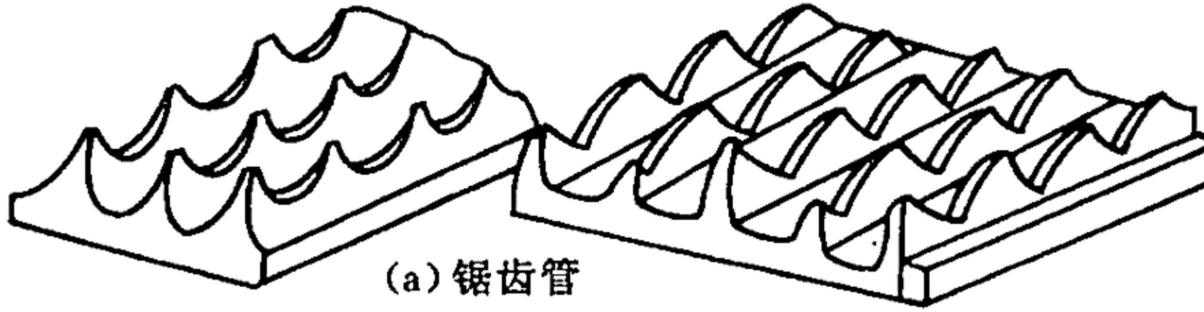
Detailed methods:

For the vertical wall or standpipe, reduce the height of the heat transfer surface as far as possible, or change the standpipe to the transverse pipe

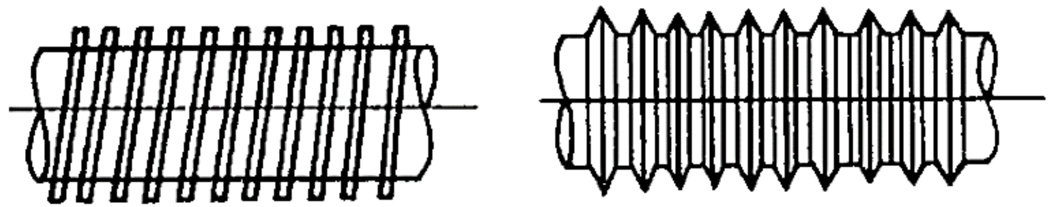
A variety of surfaces with spikes can be used to thin the liquid film; The vertical condenser adopts stage discharge; to remove the condensed liquid from the heat exchange surface as soon as possible.

§ 7-4 sensitive factors affect condensation

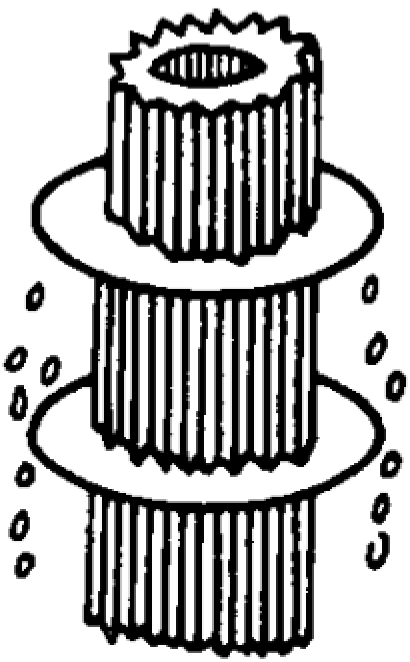
Some surfaces：



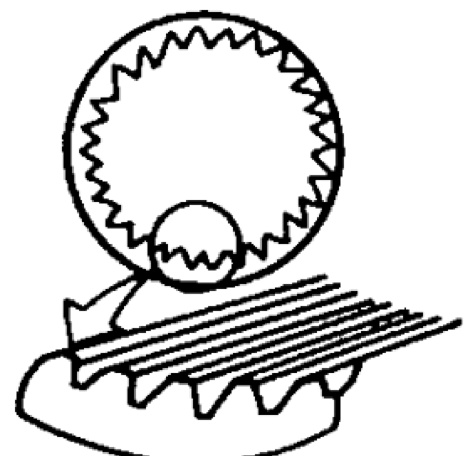
(a) 锯齿管



(b) 低肋管



(c)沟槽管



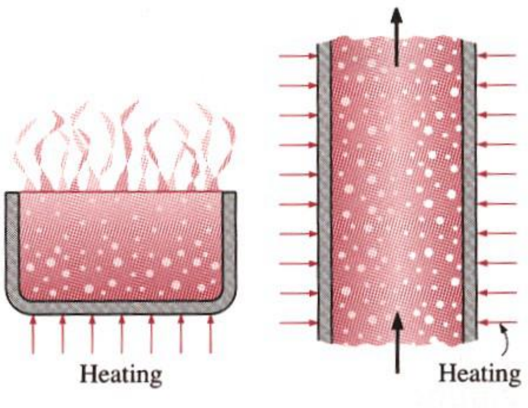
(d)微肋管

§ 7-5 Boiling heat transfer

1.definition：

a Boiling： The vaporization occurs with generating gas bubbles inside the liquid；

b Boiling heat transfer： the heat removed by gas bubbles motion and vaporization



(a) Pool boiling (b) Flow boiling

2.classification：

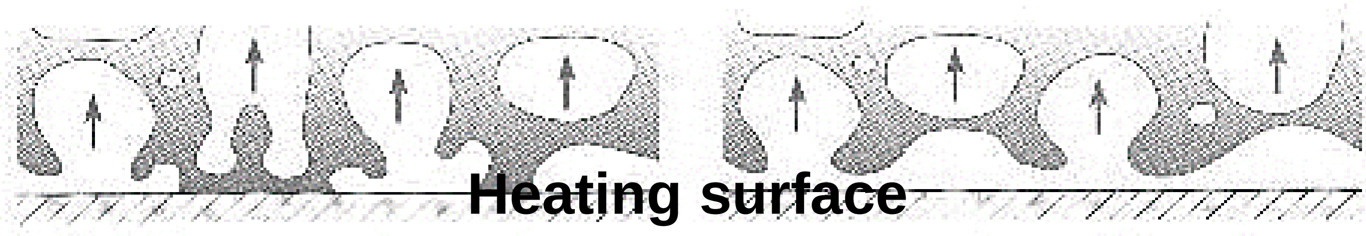
- Pool boiling
- In-tube boiling

Saturated boiling and subcooled boiling

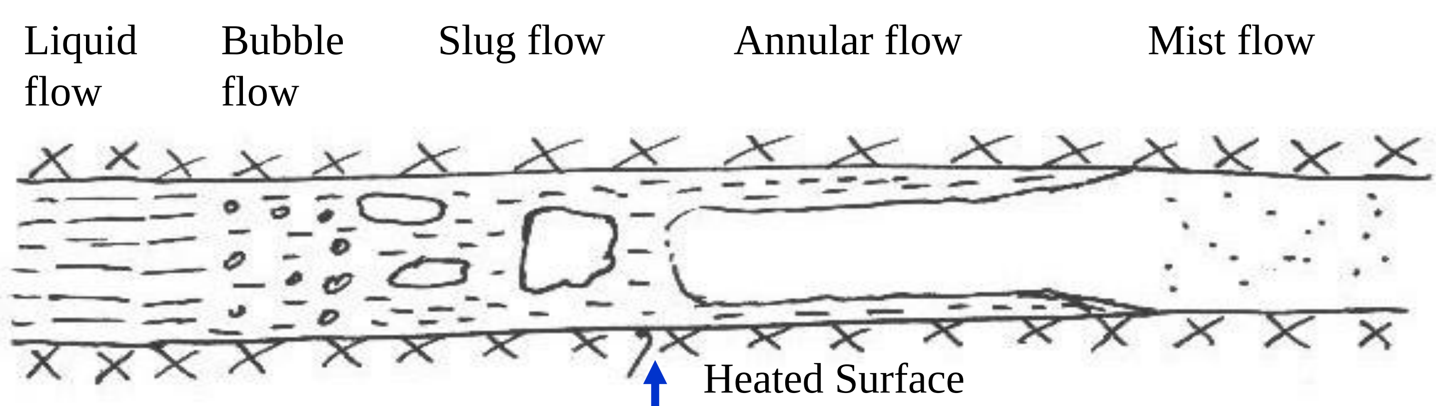
Pool boiling is caused by temperature difference and bubble disturbance, and inner boiling needs external pressure difference to maintain.

§ 7-5 Boiling heat transfer

(1)Pool boiling: Boiling occurs when the heating wall is immersed in a liquid with a free surface, which is caused by the temperature difference between the liquid and the heating surface and the disturbance **of bubbles.**



(2)in-tube boiling: Forced convection + boiling, liquid forced to flow through the heating surface to produce boiling, at this time both liquid forced flow and liquid bubble flow on the high temperature wall surface, belongs to the two-phase flow. The liquid absorbs heat along the way, increasing the flow rate and gas content.



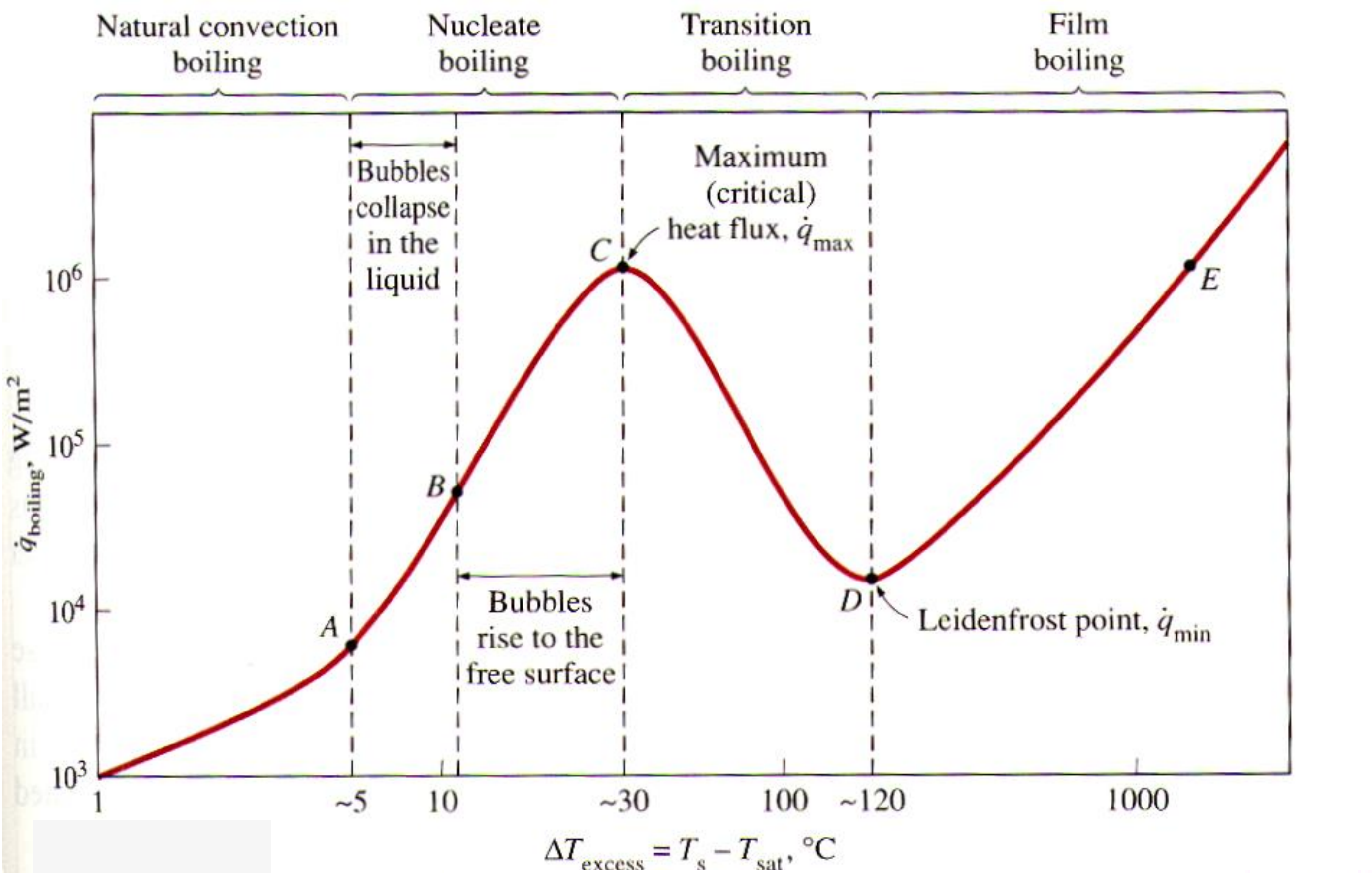
§ 7-5 Boiling heat transfer

(3) Supercooled boiling: refers to the liquid mainstream has not reached saturation temperature, that is, in a supercooled state, and the wall surface began to produce bubbles, known as supercooled boiling.

(4) Saturated boiling: When the temperature of the liquid body reaches the saturation temperature and the wall temperature is higher than the saturation temperature, it is called saturated boiling.

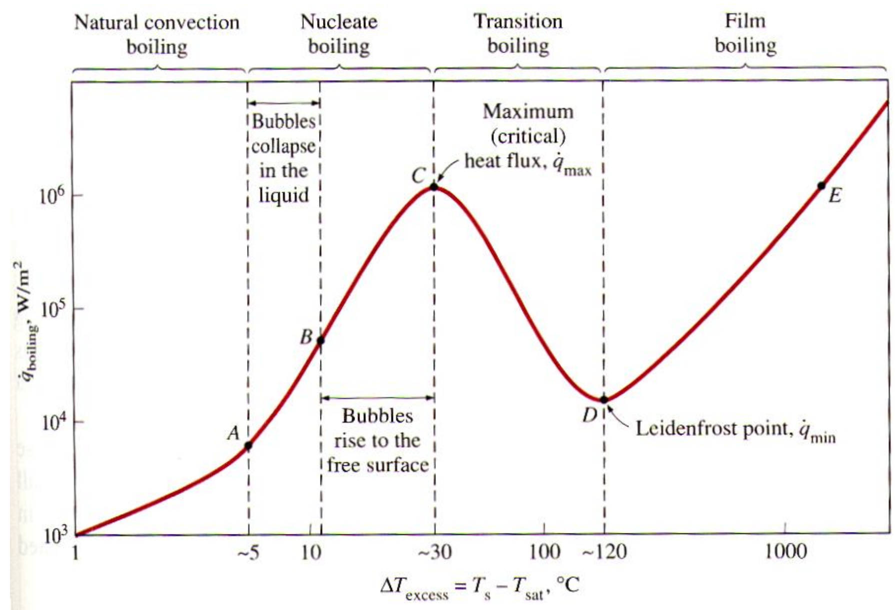
§ 7-6 Pool Boiling heat transfer

The whole process of saturated pool evolves four stages with different heat transfer phenomena: natural convection, nuclear boiling, transition boiling and film boiling, as shown in the figure



Typical boiling curve for water at 1 atm: surface heat flux q_s'' as a function of excess temperature, $\Delta T_e \equiv T_s - T_{sat}$.

§ 7-5 沸腾传热的模式



Naturanl convenction: $\Delta t \approx 3 \sim 5^\circ \mathrm{C}; \quad h < 1000\ \mathrm{W/(m^2\,{}^\circ C)}$

Nucleate boiling: $\Delta t \geq 4°\mathrm{C}$

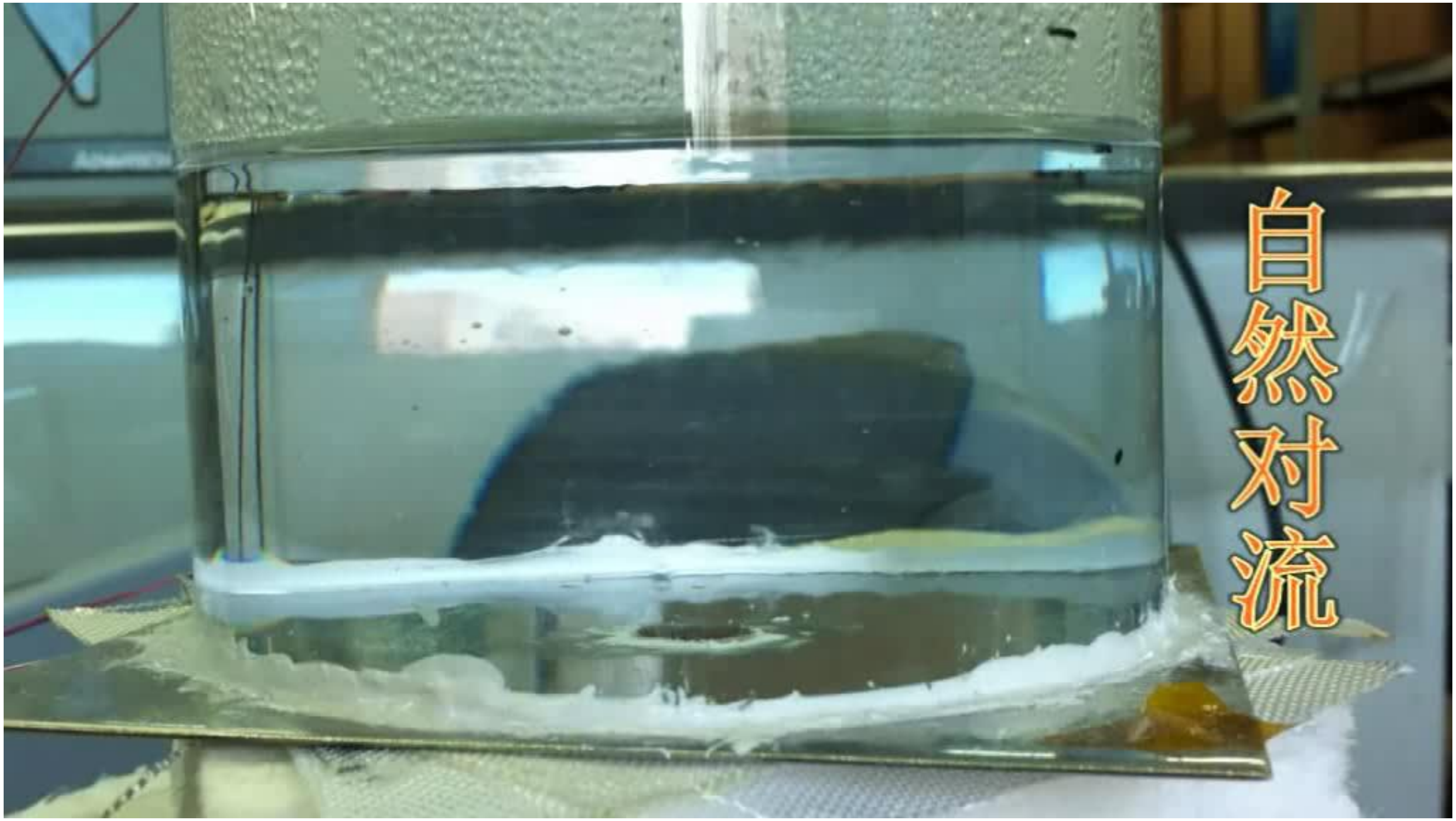
CTD: Δt_c **CHF: q (burned point)**

Transition boiling: The vapor is difficult to pool out.

film boiling: a stable film cover the boiling surface

§ 7-6 Pool Boiling heat transfer

Pool boiling heat transfer experiments



§ 7-5 Boiling heat transfer

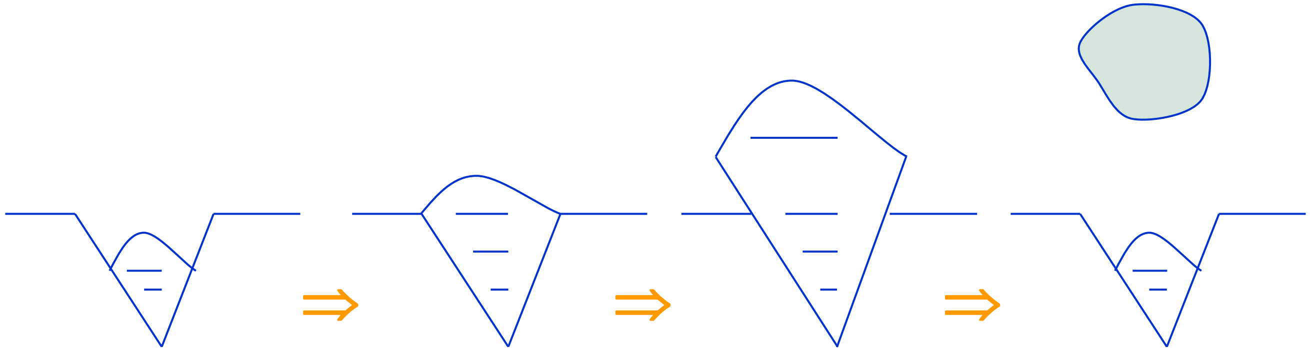
Some comments:

- The critical heat flux is called burnout point, above which the surface would be damaged.
- Normally we use DNB as the safe point.
- If one use heat flux boundary to heat, once over the critical value, the wall temperature (1000 celsuis) will increase rapid and burn the equipment.
- For film boiling, due to the existence of the vapor film, the heat transfer is much lower than nucleate boiling.
- The high heat transfer coefficient is due to the bubble generation, nucleation and departure.

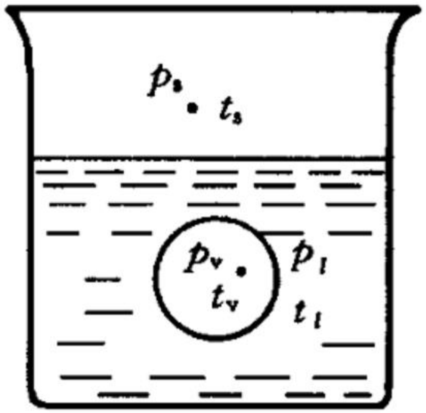
§ 7-6 bubble dynamics

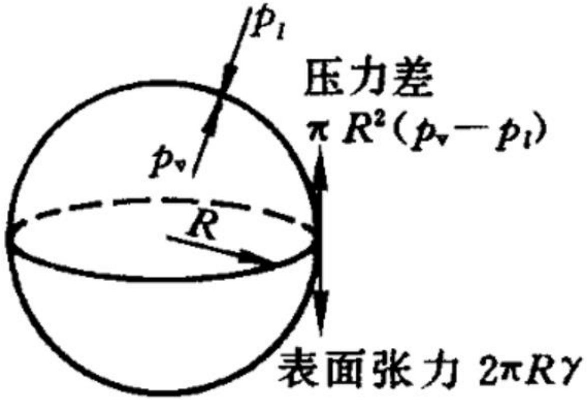
The generation process:

Usually, bubbles occur only at certain points on the heating surface, rather than the whole hot surface. These points producing bubbles are called the core of vaporization. It is generally believed that the pits and cracks on the wall are easy to retain gas and are the best core of vaporization, as shown in the figure.



§ 7-6 bubble dynamics





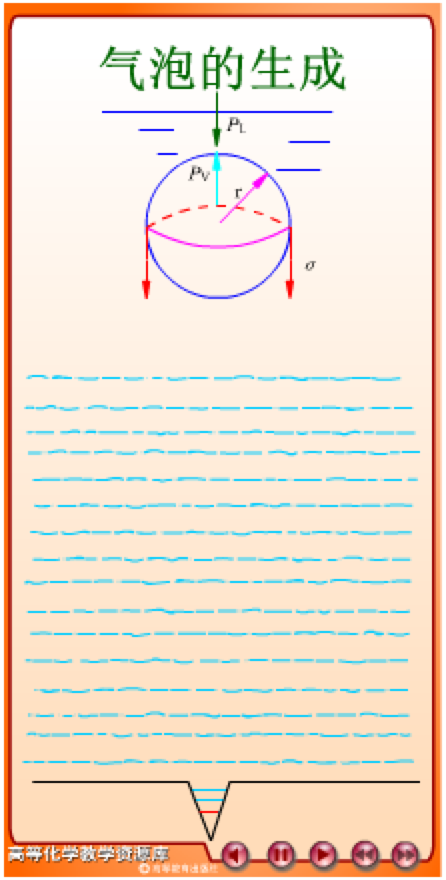
$$2\pi R\gamma = \left(p_v - p_l\right)\cdot \pi R^2$$

The surface tension = the pressure difference within and without the bubble

$$R \geq R_{\min} = \frac{2\sigma T_s}{r\rho_v(t_w - t_s)}$$ Clausius-Clapeyron equation

§ 7-6 bubble dynamics

$$R \geq R_{\min} = \frac{2\sigma T_s}{r\rho_v(t_w - t_s)}$$



where： σ — surface tension， N/m；

r — latent heat of vaporization， J/kg

ρv — vapor density， kg/m3；

tw — wall temperature， °C

ts — saturated temperature， °C

可见， (tw – ts) ↑ , Rmin↓ ⇒ On the same heating surface, the number of cavitation in the vaporization core increases

⇒ vaporization core ⇒ heat transfer

The high heat transfer intensity of boiling heat transfer is mainly due to the formation and growth of bubbles and the disturbance caused by leaving the heating wall surface。

例　2

两滴完全相同的水滴在大气压下分别滴在表面温度为120℃和400℃的铁板上，试问滴在那块板上的水滴先被烧干，为什么？

解：壁面过热度$\varDelta t = t_w - t_s$，对应饱和水在水平加热面沸腾的$q \sim \varDelta t$曲线，$q_{t_w=120°C} > q_{t_w=400°C}$，所以120℃铁板上的水滴先被烧干。

§ 7-7 The experimental correlation of pool boiling

Boiling heat transfer is also a kind of convection heat transfer, so Newton cooling formula is still applicable, namely

$$q = h(t_w - t_s) = h\Delta t$$

For *h* calculation of nucleate boling:

The main factors affecting nuclear boiling are superheat and the number of vaporized core, and the number of vaporized core is dominated by surface materials, surface conditions, pressure and other factors, so the situation liquid of boiling heat transfer is complicated, resulting in a large difference in the calculation formula

§ 7-7 The experimental correlation of pool boiling

(1)Pool boiling of water

推荐适用米海耶夫公式，压力范围：10^5～4×10^6 Pa

$$h = C_1 \Delta t^{2.33} p^{0.5} \qquad C_1 = 0.122\, W/(m \cdot N^{0.5} \cdot K^{3.33})$$

按 $q = h\Delta t \quad \Rightarrow \quad h = C_2 q^{0.7} p^{0.15}$

$$C_2 = 0.533\, W^{0.3}/(m^{0.3} \cdot N^{0.15} \cdot K)$$

§ 7-7 The experimental correlation of pool boiling

(2)Rohsenow——widely used

$$\boxed{St^{-1} = C_{wl} \cdot \mathrm{Re}^{0.33} \cdot \mathrm{Pr}_l^s}$$

式中，$St = \dfrac{Nu}{\mathrm{Re} \cdot \mathrm{Pr}} = \dfrac{r}{C_{pl} \cdot \Delta t}$

r — latent heat of vaporization；

C_{pl} — heat capacity of saturated liquid

$$\mathrm{Re} = \frac{q}{\eta_l r}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

η_l —viscosity of saturated liquid

C_{wl} —constant

$$\mathrm{Pr}_l = \frac{C_{pl}\eta_l}{\lambda_l}$$

q — heat flux

s — water:1 otherwise:1.7

§ 7-7 The experimental correlation of pool boiling

★ Form the equation we can get：

$$q = \eta_l r \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{C_{pl} \Delta t}{C_{wl} r \, \mathrm{Pr}_l^s} \right]^3$$

therefore， $q \sim \Delta t^3$ ， though sometimes the formula to calculate the q with the experimental value deviation in the form of up to±100%， but when calculate Δt ， the error reduces to ±33%.

§ 7-7 The experimental correlation of pool boiling

For calculate the CHF:

By applying Taylor's instability principle to the motion of gas film:

$$q_{\max} = \frac{\pi}{24} r \rho_v \left[\frac{g\sigma(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4} \left(\frac{\rho_l + \rho_v}{\rho_v^2} \right)^{1/2}$$

When the pressure far from the critical pressure, the right it is close to 1:

$$q_{\max} = \frac{\pi}{24} r \rho_v^{1/2} \left[g\sigma(\rho_l - \rho_v) \right]^{1/4}$$

Reference temperature is saturated temperature,

Only applicable to the situation where the heating surface is an infinite horizontal wall. In fact, it can be used when the characteristic length of the heating surface is more than 3 times the average diameter of the bubble.

§ 7-7 The experimental correlation of pool boiling

Correlation formula for film boiling :

(1) Film boiling in a horizontal tube

$$h = 0.62\left[\frac{gr\rho_v(\rho_l - \rho_v)\lambda_v^3}{\eta_v d(t_w - t_s)}\right]^{1/4}$$

In the formula, except that the values of r and ρ_l are determined by the saturation temperature t_s , the rest of the physical properties take the average temperature $t_m =(t_w + t_s)/2$ as the qualitative temperature. The characteristic length is the outer diameter of the tube d. If the heating surface is spherical, the coefficient 0.62 in the above formula is changed to 0.67.

(2) Consider heat radiation

Since the wall temperature is generally higher during film state heat transfer, it is necessary to consider the influence of radiation heat transfer. Its influence has two parts, one is to directly increase the heat transfer, and the other is to increase the thickness of the vapor film, thereby reducing the heat transfer. Therefore, the thermal radiation effect must be considered comprehensively.

It is recommended to use the following transcendental equations for calculation:

$$h^{4/3} = h_c^{4/3} + h_r^{4/3}$$

where:

$$h_r = \frac{\varepsilon\sigma(T_w^4 - T_s^4)}{T_w - T_s}$$

§ 7-7 The experimental correlation of pool boiling

Approximate range of average surface heat transfer coefficients of commonly used working fluids air and water in various heat transfer processes

convective heat transfer process	Average surface heat transfer coefficient
Air natural convection heat transfer	5 ~ 50
air forced convection heat transfer	25 ~ 500
Water forced convection heat transfer	250 ~ 15000
water boiling heat transfer	2500 ~ 25000
Vapor condensation heat transfer	5000 ~ 10^5

例 3

试分析：液体在一定压力下作大容器饱和沸腾时，表面传热系数h增加1倍，壁面过热度增加多少倍？如果同一液体在圆管内作单相湍流强制对流传热（湍流充分发展），为使便面传热系数h增加1倍，流速应增加多少倍？这时流体的驱动功率将增加多少倍？

解：

（1）大容器饱和沸腾

$$h \sim \Delta t^{2.33} \qquad \frac{\Delta t\prime}{\Delta t} = \left(\frac{h\prime}{h}\right)^{\frac{1}{2.33}} = 2^{\frac{1}{2.33}} = 1.35$$

（2）管内湍流

$$h \sim V^{0.8} \qquad \frac{V\prime}{V} = \left(\frac{h\prime}{h}\right)^{\frac{1}{0.8}} = 2^{1.25} = 2.39$$

$$\Delta p \sim V^2 \qquad N \sim \Delta p.A.V \sim V^3$$

$$\frac{N'}{N} = \left(\frac{V'}{V}\right)^3 = 2.39^3 = 13.5$$

§ 7-7 sensitive factors and intensification

1. Sensitive factors of boiling heat transfer

Boiling heat transfer is the most complicated heat transfer phenomenon we have learned, and it also has the most influencing factors. Here, the influencing factors of boiling heat transfer in large vessels are described.

(1) non-condensable gas

Effect on film condensation heat transfer?对膜状凝结传热的影响？

Unlike film condensation heat transfer, the non-condensable gas in the liquid will enhance the boiling heat transfer to some extent. Because as the working temperature rises, the non-condensable gas will escape from the liquid, activating the tiny pits near the wall.

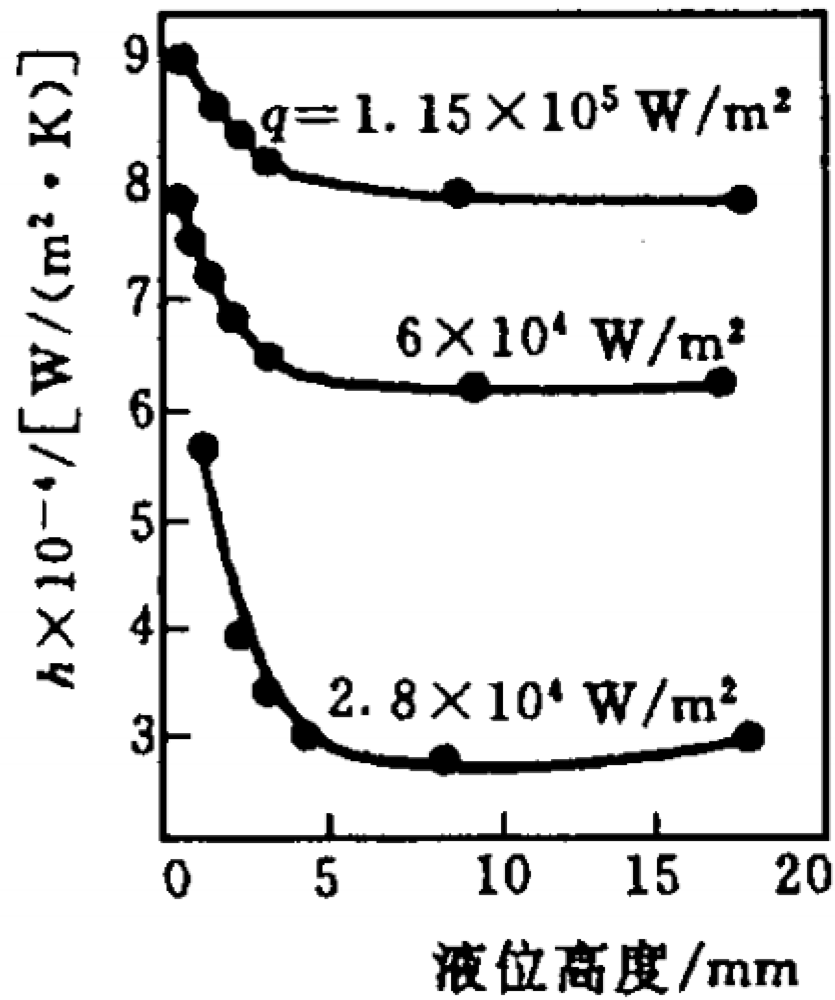
(2) Supercooling 过冷度

It only affects subcooled boiling, not saturated boiling; when heat is transferred due to natural convection, So supercooling will enhance heat transfer.

§ 7-7 sensitive factors and intensification

(3) Height of Liquid 液位高度

When the liquid level on the heat transfer surface is high enough, the boiling heat transfer surface heat transfer coefficient has nothing to do with the liquid level height. But when the liquid level decreases to a certain value, the surface heat transfer coefficient will obviously increase with the decrease of liquid level (critical liquid level).



图中介质为一个大气压下的水

(4) Acceleration of gravity重力加速度

With the development of aerospace technology in hypergravity and microgravity, The laws of heat transfer are flourishing, But it is far from mature.

§ 7-7 sensitive factors and intensification

From 0.1 ~ 100×9.8 m/s^2 , *g* has no effect on the law of nucleate boiling heat transfer, but has an effect on natural convection heat transfer, due to:

$$Gr = \frac{g\alpha \Delta t l^3}{\nu^2} \qquad Nu = C(\mathrm{Re}\,\mathrm{Pr})^n$$

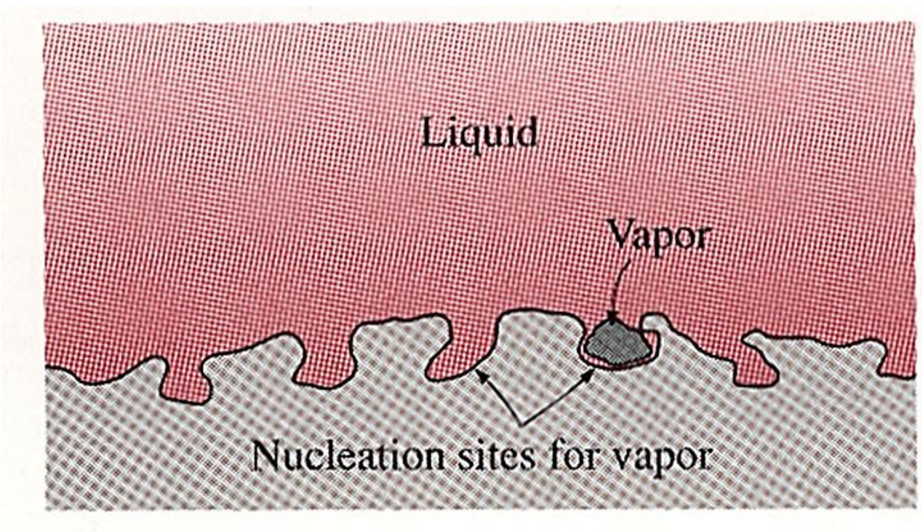
Therefore， g ↑ ⇒ Nu ↑ ⇒ Enhanced heat transfer.

§ 7-7 sensitive factors and intensification

2. Enhancement of boiling heat transfer

Small pits on the boiling surface are most likely to produce vaporization cores. Therefore, the more pits and more vaporization cores, the heat transfer will be enhanced. In recent decades, the enhancement of boiling heat transfer research is mainly to increase the surface dimples.

a) Bubble formation in the vaporization core (grooves, pores)



The cavities on a rough surface act as nucleation sites and enhance boiling heat transfer.

b) $\Delta t = t_w - t_s \uparrow \Rightarrow R_{\min} \downarrow \Rightarrow$ 气泡量增多 $\Rightarrow h \uparrow$

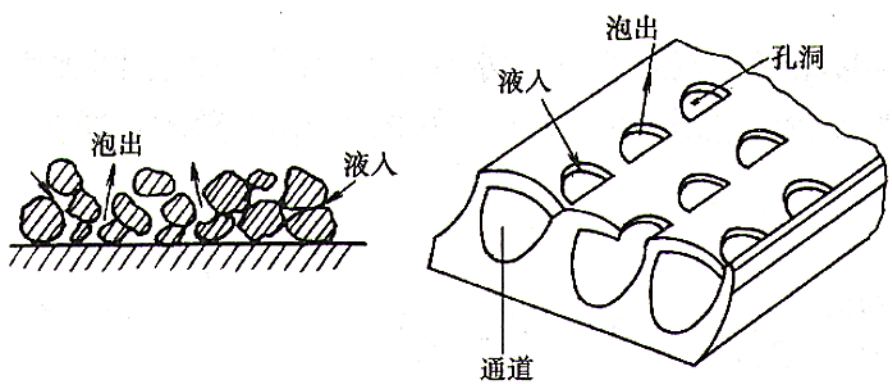
Increased bubble volume

§ 7-7 sensitive factors and intensification

(1) Enhancing the Surface Structure of Large Vessel Boiling

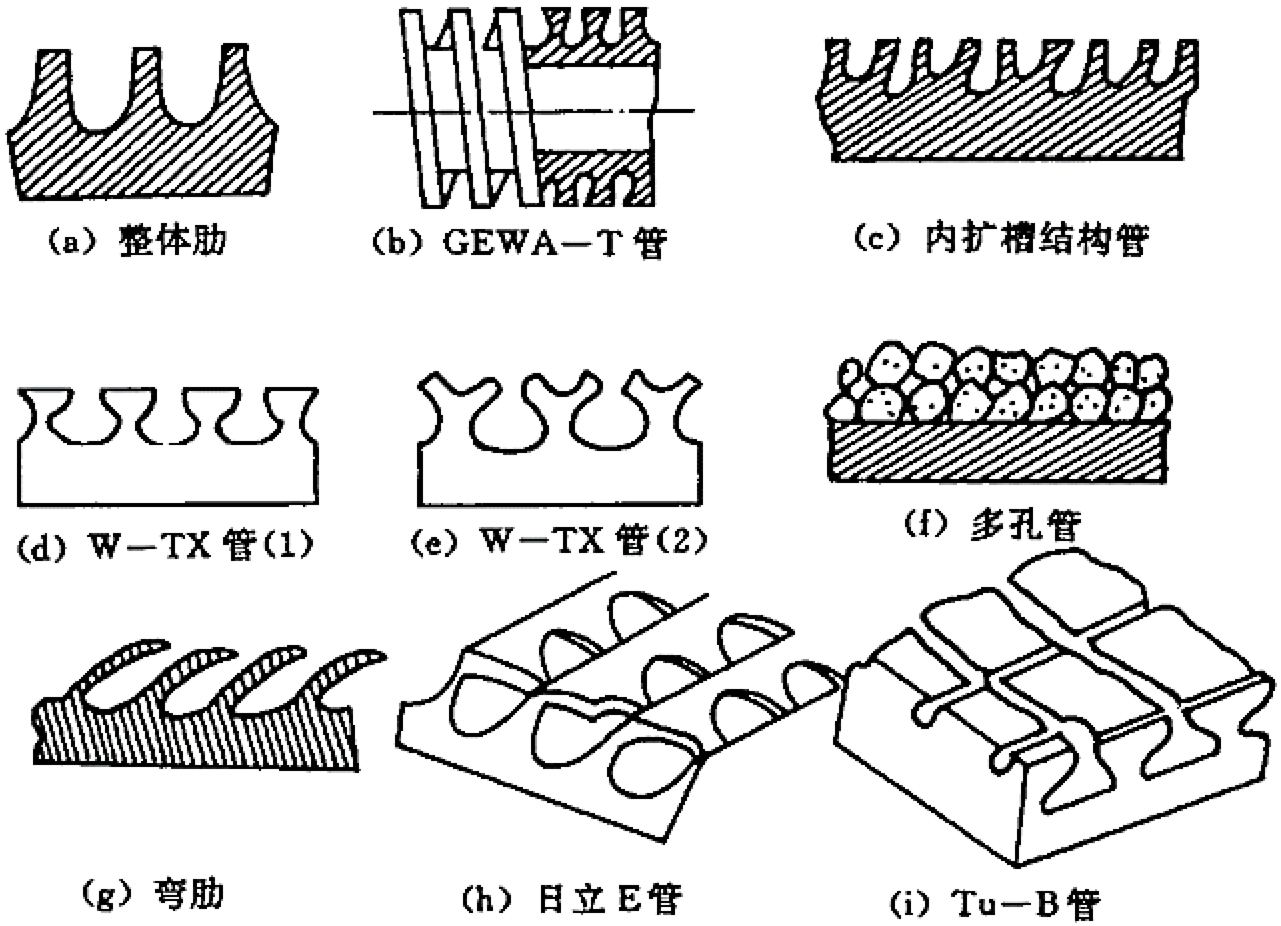
(a) Porous structures are formed on the heat transfer surface by physical and chemical means such as sintering, brazing, flame spraying, and ionization deposition.

(b) Machining method.



Porous media

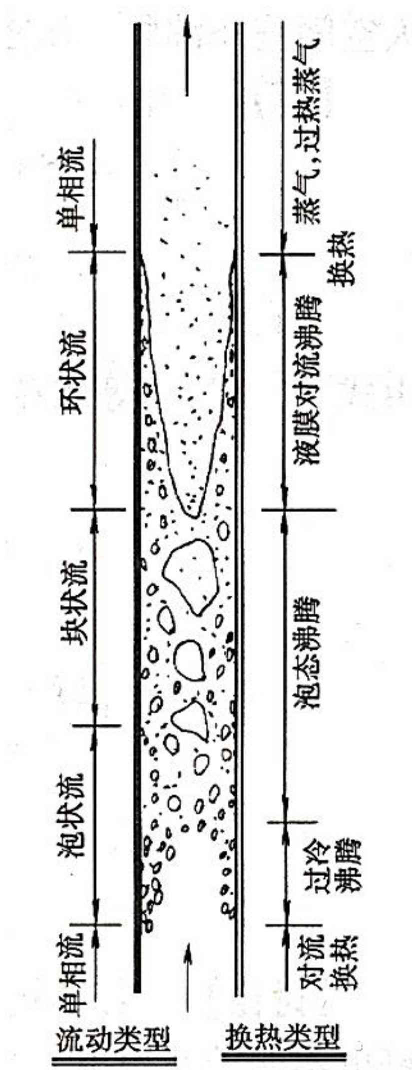
§ 7-7 sensitive factors and intensification



沸腾传热强化管表面结构示意图

§ 7-8 in-tube boiling

Boiling in tube evaporators in water tube boilers and refrigeration systems is tube boiling



竖直管内沸腾

When boiling in the tube, due to the limitation of the boiling space, the vapor produced by the boiling mixes with the liquid, vapor-liquid two-phase mixture——两相流

Flow pattern when boiling in a vertical tube：

单相流、泡状流、块状流、环状流

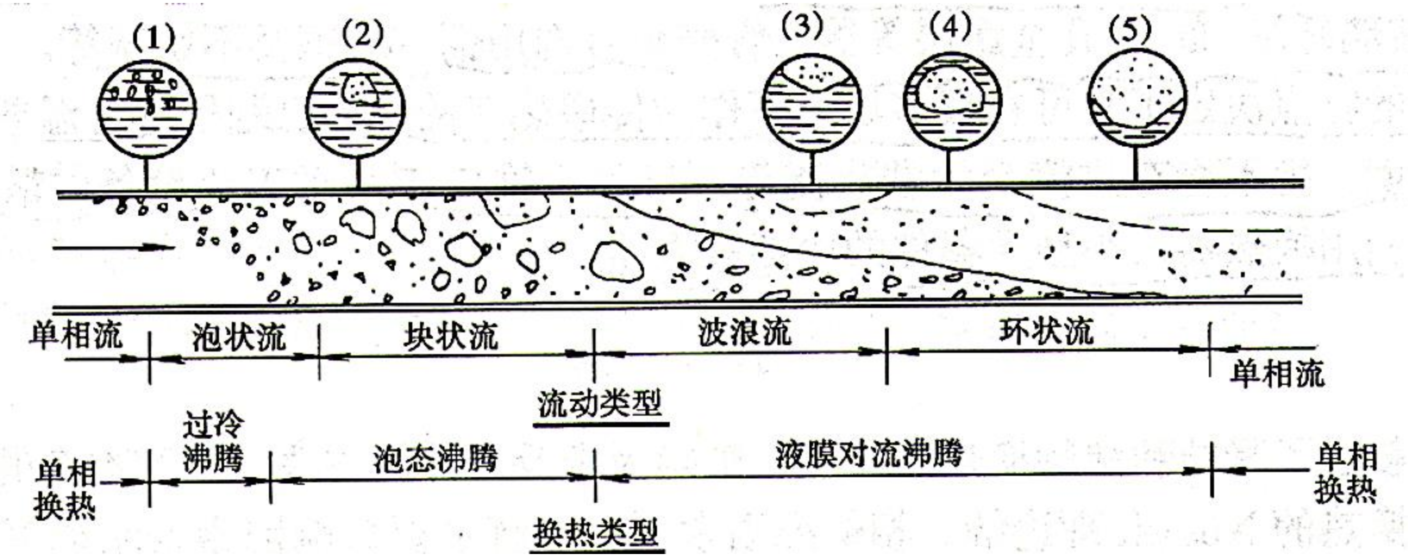
Single-phase flow, bubbly flow, block flow, annular flow

Heat transfer in a vertical tube when boiling：

单相对流传热、过冷沸腾、泡态沸腾、液膜对流沸腾、蒸气与过热蒸气传热

Single phase heat transfer, subcooled boiling, bubble boiling, Liquid film convective boiling, steam and superheated steam heat transfer

§ 7–8 in-tube boiling



水平管内沸腾

Boiling in a horizontal tube： When the flow rate is high, the situation is similar to that of a vertical pipe; when the flow rate is low, due to the influence of gravity, the gas and liquid will tend to concentrate in the upper and lower parts of the pipe respectively

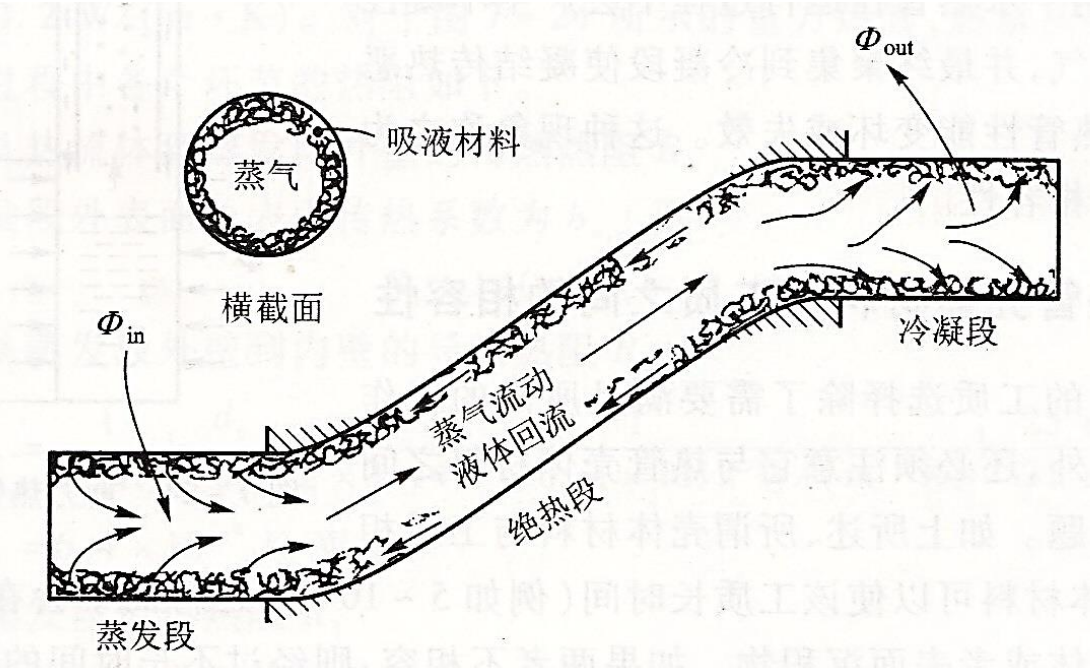
The boiling heat transfer in the tube also depends on the position of the tube, the length and diameter of the tube, wall condition, initial parameters of liquid, flow rate, ratio of vapor to liquid, etc. It is more complicated than large space boiling.

§ 7–9 Introduction to Heat pipe

1. How Heat Pipes Work?

Heat Pipe： A heat transfer element that transfers heat from a hot fluid at one end of a heat pipe through the heat pipe to a cold fluid at the other end of the heat pipe.

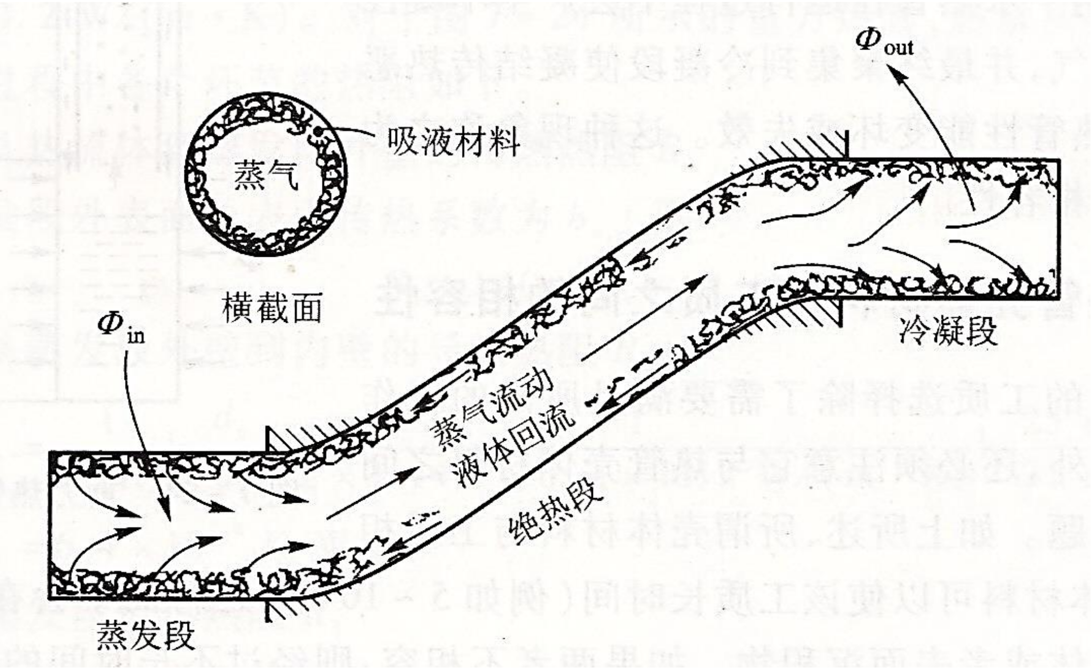
Composition: metal shell, wire mesh liquid-absorbing core (金属管壳、丝网状吸液芯)



Heat pipe

§ 7–9 Introduction to Heat pipe

Working principle: Vacuum the inside of the tube, then fill it with a suitable working liquid and seal the two ends. The working liquid is heated by the hot fluid outside the tube in the evaporating section, absorbing latent heat and evaporating. Its vapor flows through the adiabatic section to the condensing section, and the vapor releases latent heat and condenses into liquid. The released latent heat heats the cold fluid outside the tube, and the condensate passes through the liquid-absorbing core back to the evaporation section.

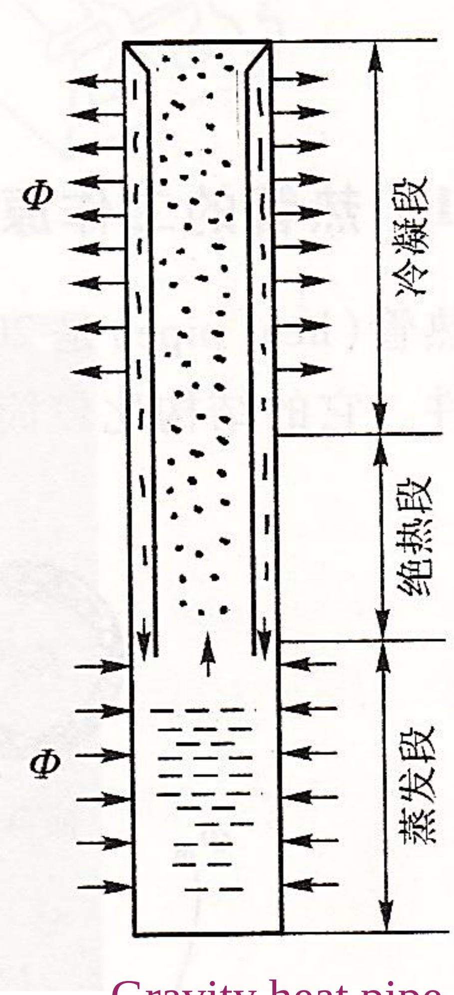


§ 7–9 Introduction to Heat pipe

In order to enhance heat transfer, adding fins to the evaporating section and condensing section can be used.

Gravity heat pipe (thermosiphon 热虹吸管) commonly used in engineering: the condensation section must be located at the upper end of the evaporation section. During the operation of the steel-water heat pipe, non-condensable gas (hydrogen) will be generated, which will deteriorate the heat transfer performance, which is called steel-water incompatibility 钢一水不相容性.

In order to overcome the steel-water incompatibility, the surface is often passivated, or a turbidity inhibitor is added to prevent or slow down the generation of hydrogen.



Gravity heat pipe

§ 7–9 Introduction to Heat pipe

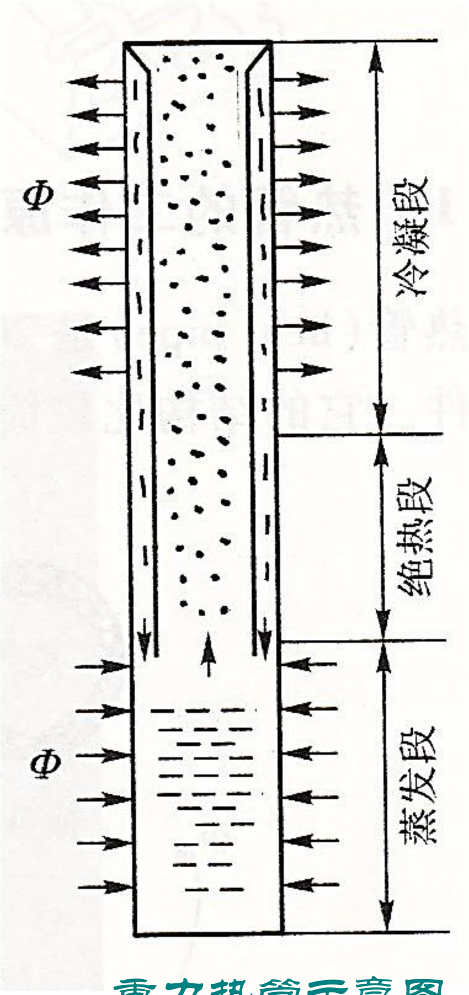
2. Thermal resistance analysis of the heat pipe:

(1) Heat transfer resistance between thermal fluid and outer wall of evaporation section

$$R_1 = \frac{1}{\pi d_0 l_e h_{oe}}$$

(2) Thermal resistance from outer wall to inner wall of evaporating section

$$R_2 = \frac{1}{2\pi\lambda l_e} \ln\frac{d_0}{d_i}$$



重力热管示意图

§ 7–9 Introduction to Heat pipe

(3) Thermal resistance of heat transfer on the inner wall of the evaporating section

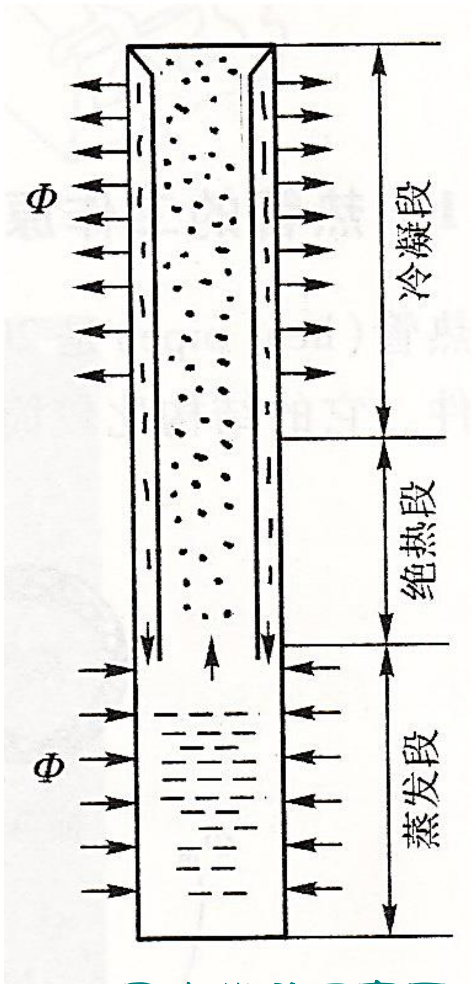
$$R_3 = \frac{1}{\pi d_i l_e h_{ie}}$$

(4) Thermal resistance due to pressure drop of vapor flow from evaporating section to condensing section

$$R_4 \approx 0$$

(5) Heat transfer resistance of inner wall of condensing section

$$R_5 = \frac{1}{\pi d_i l_c h_{ic}'}$$



重力热管示意图

§ 7–9 Introduction to Heat pipe

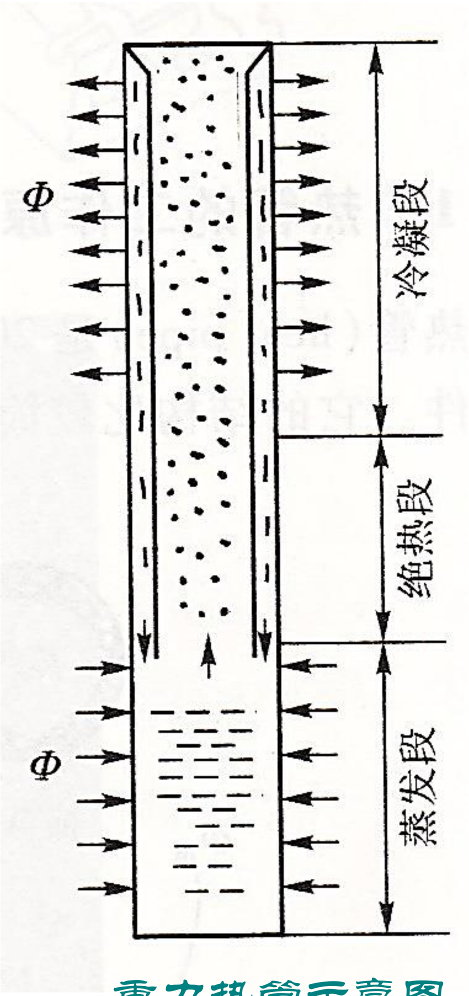
(6) Conductive thermal resistance from inter wall to outer wall for condensation section

$$R_6 = \frac{1}{2\pi\lambda l_c}\ln\frac{d_0}{d_i} = R_2$$

(7) External wall heat transfer resistance for condensation section

$$R_7 = \frac{1}{\pi d_o l_c h_{oc}'}$$

Analysis shows that, R_2 to R_6 are all thermal resistance inside the heat pipe. It can be seen from the specific calculation example that the sum is small , indicating that the heat pipe has particularly good thermal conductivity , also called ‘superconductivity’, achieving heat conduction with almost no temperature difference.



重力热管示意图

对流传热部分小结

- 对流换热
  - 无相变换热
    - 受迫对流换热
      - 内部流动
        - 圆管内受迫流动
        - 非圆形管内受迫流动
      - 外部流动
        - 外掠平板
        - 外掠单管
        - 外掠管束（光管；翅片管）
    - 自然对流换热
      - 无限空间
        - 竖壁；竖管
        - 横管
        - 水平壁（上表面和下表面）
      - 有限空间——夹层空间
    - 混合对流换热（受迫对流与自然对流并存）
  - 相变换热
    - 凝结换热
      - 垂直壁凝结换热
      - 水平单圆管及管束外凝结换热
      - 管内凝结换热
    - 沸腾换热
      - 大空间沸腾换热
      - 管内沸腾换热（横管，竖管）