Heat transfer to fluids with phase change

Processes of heat transfer accompanied by phase are more complex than simple heat exchange between fluids since it concerns about thermodynamic and hydrodynamic.

Heat transfer from condensing vapors

- Here, we only focus on pure vapor condensation. The condensation of vapors on the surfaces of tubes cooler than the condensing temperature of the vapors is important.

- friction losses in a condenser are normally small, so that condensation is essentially a constant-pressure process.

- **The condensing temperature of a single pure substance depends only on the pressure, and therefore the process of condensation of a pure substance is isothermal.**

- **Mixed vapors, condensing at constant pressure, condense over a temperature range and yield a condensate of variable composition until the entire vapor stream is condensed.**

The condensation of mixed vapors is complicated and beyond the scope this text.

Dropwise and film-type condensation

A vapor may condense on a cold surface in one of two ways, which are well described by the terms dropwise and film-type.

In film condensation

the liquid condensate forms a film, or continuous layer, of liquid that flows over the surface of the tube under the action of gravity.

It is the layer of liquid interposed between the vapor and the wall of the tube which provides the resistance to heat flow and therefore which fixes the value of the heat-transfer coefficient.

In *dropwise condensation*

the condensate begins to form at microscopic nucleation sites.

Typical sites are tiny pits, scratches, and dust specks.

The drops grow and coalesce with their neighbors to form visible fine drops.

The fine drops, in turn, coalesce into rivulets, which flow down the tube under the action of gravity, sweep away condensate, and clear the surface for more droplets.

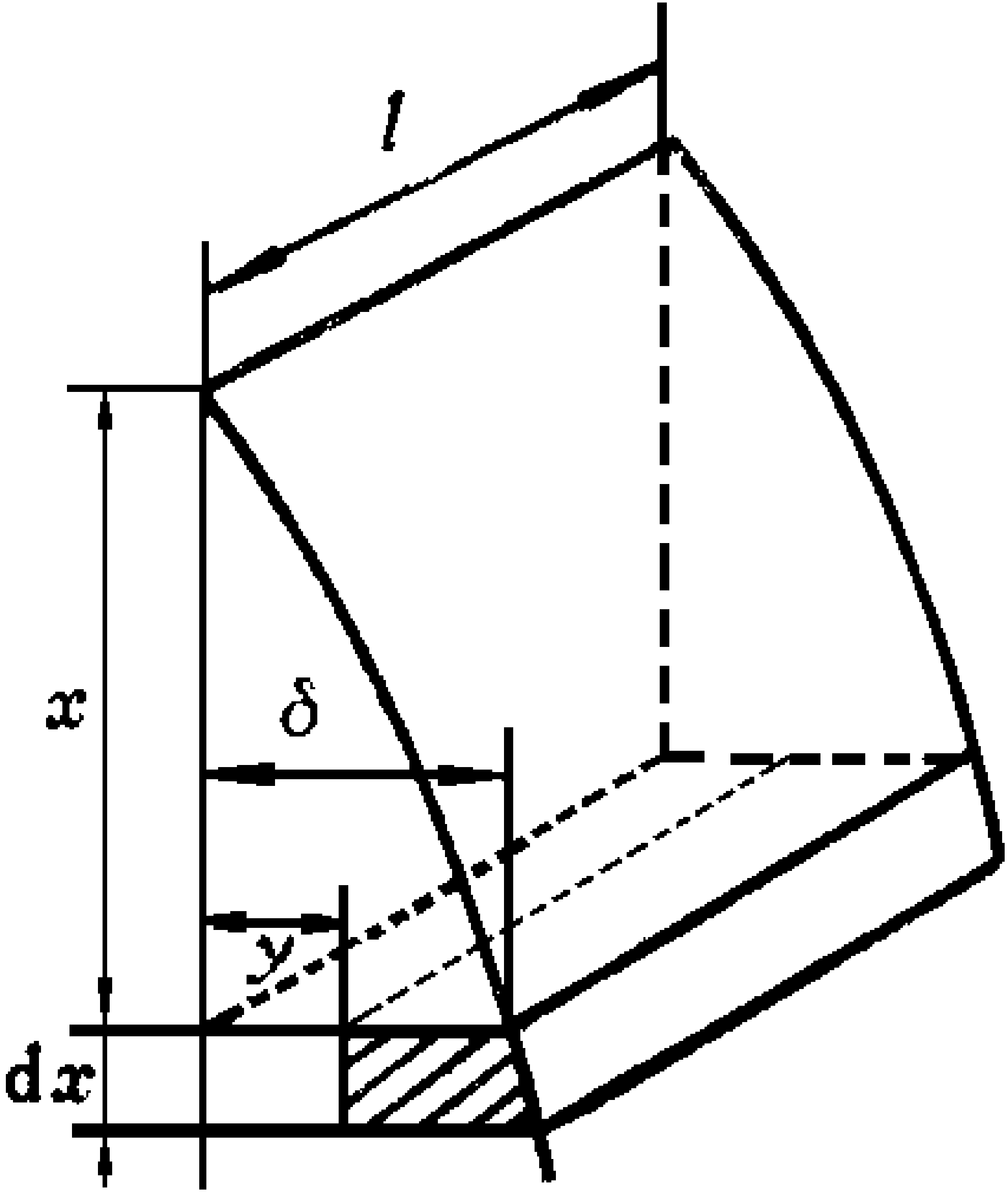
Because of this the heat-transfer coefficient at these areas is very high; the average coefficient for dropwise condensation may be 5 to 8 times that for film-type condensation. The average coefficient obtainable in pure dropwise condensation is as high as 114kW/m^2.°C.

- **Although attempts are sometimes made to realize practical benefits from these large coefficients by artificially inducing dropwise condensation, this type of condensation is so unstable and the difficulty of maintaining it is so great that the method is not common.**

Also the resistance of the layer of stream condensate even in film-type condensation is ordinarily small in comparison with the resistance inside the condenser tube, and increase in the overall coefficient is relatively small when dropwise condensation is achieved.

Coefficients for film-type condensation

The basic equation for the rate of heat transfer in film-type condensation were first derived by Nusselt



l
δ
x
y
dx

Vertical tubes

Two forces remaining acting on the control volume are shear force and gravity in the direction of flow.

$$dx \bullet (\delta - y) \bullet l \bullet \rho g = dx \bullet l \bullet \mu \frac{du_y}{dy}$$

或

$$du_y = \frac{\rho g}{\mu}(\delta - y)dy$$

Integration of the equation with the boundary condition $u_y=0$, $y=0$ gives the velocity distribution

$$u_y = \frac{\rho g}{\mu}\left(\delta y - \frac{1}{2}y^2\right)$$

Mean velocity within the film

$$u = \frac{1}{\delta}\int_0^\delta u_y dy + \frac{1}{\delta}\int_0^\delta \frac{\rho g}{\mu}\left(\delta y - \frac{1}{2}y^2\right)dy\text{k}$$

$$= \frac{\rho g \delta^2}{3\mu}$$

Rate of the condensate flow through the cross section at the x

$$m = 1 \bullet \delta \rho u = \frac{\rho^2 g \delta^3}{3\mu}$$

and

$$dm = \frac{\rho^2 g \delta^2}{\mu} d\delta$$

- **The rate of heat-transfer**

$$r \bullet dm = r\,\frac{\rho^2 g \delta^2}{\mu}\,d\delta$$

The rate of the heat transfers from a fluid to the wall by the conduction

$$r\frac{\rho^2 g\delta^2}{\mu}d\delta = 1\bullet dxk\frac{t_s - t_w}{\delta}$$

SO

$$\delta = \left(\frac{4\mu k x \Delta t}{r \rho^2 g} \right)^{\frac{1}{4}}$$

The local heat-transfer coefficient can be derived , based on the Newtonian law of cooling and the thermal conduction within the condensate film

$$\alpha = \frac{\lambda}{\delta} = \left(\frac{r \rho^2 g k^3}{4 \mu x \Delta t} \right)^{\frac{1}{4}}$$

The local heat-transfer coefficient varies with the distance from the entrance. The mean individual coefficient is attainable

$$\alpha = \frac{1}{L}\int_0^L \alpha_x dx = \frac{4}{3}\left(\frac{r\rho^2 g k^3}{4\mu L \Delta t}\right)^{\frac{1}{4}}$$

So for vertical plate

$$h = 0.943\left(\frac{k^3{}_f \rho_f{}^2 g\lambda}{\Delta T_o L \mu_f}\right)^{1/4}$$

(3-12)

Horizontal tubes

the following equation applies to single horizontal tubes

$$h = 0.729\left(\frac{k^3{}_f \rho_f{}^2 g \lambda}{\Delta T_o D_o \mu_f}\right)^{1/4} \quad \textbf{(3-14)}$$

Practical use of Nusselt equation Eq(13-14) can be used as they stand for calculating heat-transfer coefficients for film-type condensation on a single horizontal tubes.

For film-type condensation on a vertical stack of horizontal tubes, where the condensate falls cumulatively from tube to tube and the total condensate from the entire stack finally drops from the bottom tube. It is more accurate to use the equation below

$$h = 0.729\left(\frac{k_f^3 \rho_f^2 \lambda g}{\Delta T_o N D_o \mu_f}\right)^{1/4}$$

- For vertical tubes,

  the equations were derived on the assumption that the condensate flow was laminar.

- For long tubes,

  the condensate film becomes sufficiently thick and its velocity sufficiently large to cause turbulence in the low portions of the tube.

- **Also, even when the flow remains laminar throughout, coefficients measured experimentally are about 20 percent larger than those calculated from the equation. This attributed to the effect of ripples on the surface of the falling film.**

In general, the coefficient of a film condensing on a horizontal tube is considerably larger than that on a vertical tube under otherwise similar conditions unless the tubes are very short or there are very many horizontal tubes in the stack.

Vertical tubes are preferred when the condensate must be appreciably subcooled below its condensation temperature.

Mixtures of vapors and noncondensing gases are usually cooled and condensed inside vertical tubes, so that the inert gas is continually swept away from the heat-transfer surface by the incoming stream.

Effect of noncondensable gases on rate of condensation:

the presence of even small amounts of noncondensing gas in a condensing vapor seriously reduces the rate of condensation

Since the conductivity of gas is much smaller than liquid.

- **Effect of vapor flow direction on heat transfer rate of condensation.**

- **Effect of superheated vapor on heat transfer rate of condensation**

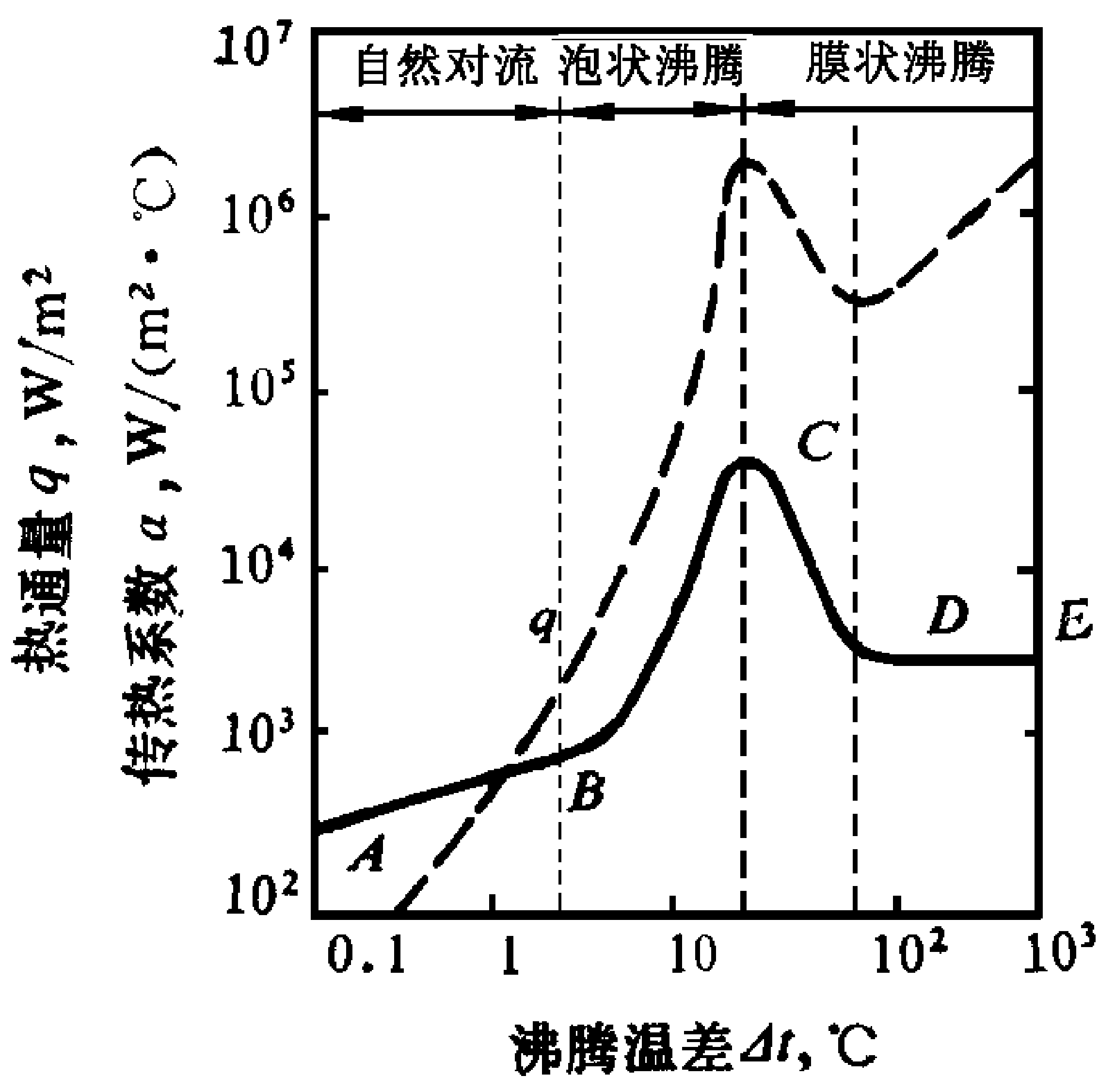
Heat transfer to boiling liquids

- *Pool boiling of saturated liquid*

consider a horizontal wire immersed in a vessel containing a boiling liquid. The difference between the temperature of the wire surface t_w and that of the boiling liquid t, are measured.

Start with a very low temperature drop Δt. Increase the temperature drop by steps, measuring q/A and Δt at each step, until very large values of Δt are reached

- A plot of *q/A vs Δt* on logarithmic coordinates will give a curve of the type shown in Fig



This curve can be divided into four segments. In the first segment, at low temperature drops, the line *AB* is straight and has a slope of 1.25. This is consistent with the equation

$$q/A = a\Delta T^{1.25} \tag{13-20}$$

In the first section, at low temperature drops, the mechanism is that of heat transfer to a liquid in *natural convection*. The heat-transfer coefficient is low in this segment.

The second segment, line *BC*, is also approximately straight, the slope of the line lies between 3 and 4.

The second segment terminates at a definite point of maximum flux, which is point C.

- **the temperature drop corresponding to point C is called the *critical temperature drop*. The action occurring at temperature drops below the critical temperature drop is called *nucleate boiling.***

In the third segment, line *CD*, the flux decreases as the temperature drop rises and reaches a minimum at point *D*.

point D is called the Leidenfrost point. Near the Leidenfrost point another distinct change in mechanism occurs.

The hot surface becomes covered with a quiescent film of vapor, through which heat is transferred by conduction and (at very high temperature drops) by radiation. The boiling action in this region is known as *film boiling*.

Film boiling is not usually desired in commercial equipment because the heat transfer rate is low for such a large temperature drop and temperature drop is not utilized effectively.

Heat-transfer apparatus should be so designed and operated that the temperature drop in the film of boiling liquid is smaller than the critical temperature drop.