ALAT PENUKAR PANAS DENGAN PERUBAHAN FASA

JENIS PERUBAHAN FASA

- PENGEMBUNAN →
- PENGUAPAN →

- CONDENSER
- REBOILER
- VAPORIZER
- EVAPORATOR

MENARA DISTILASI

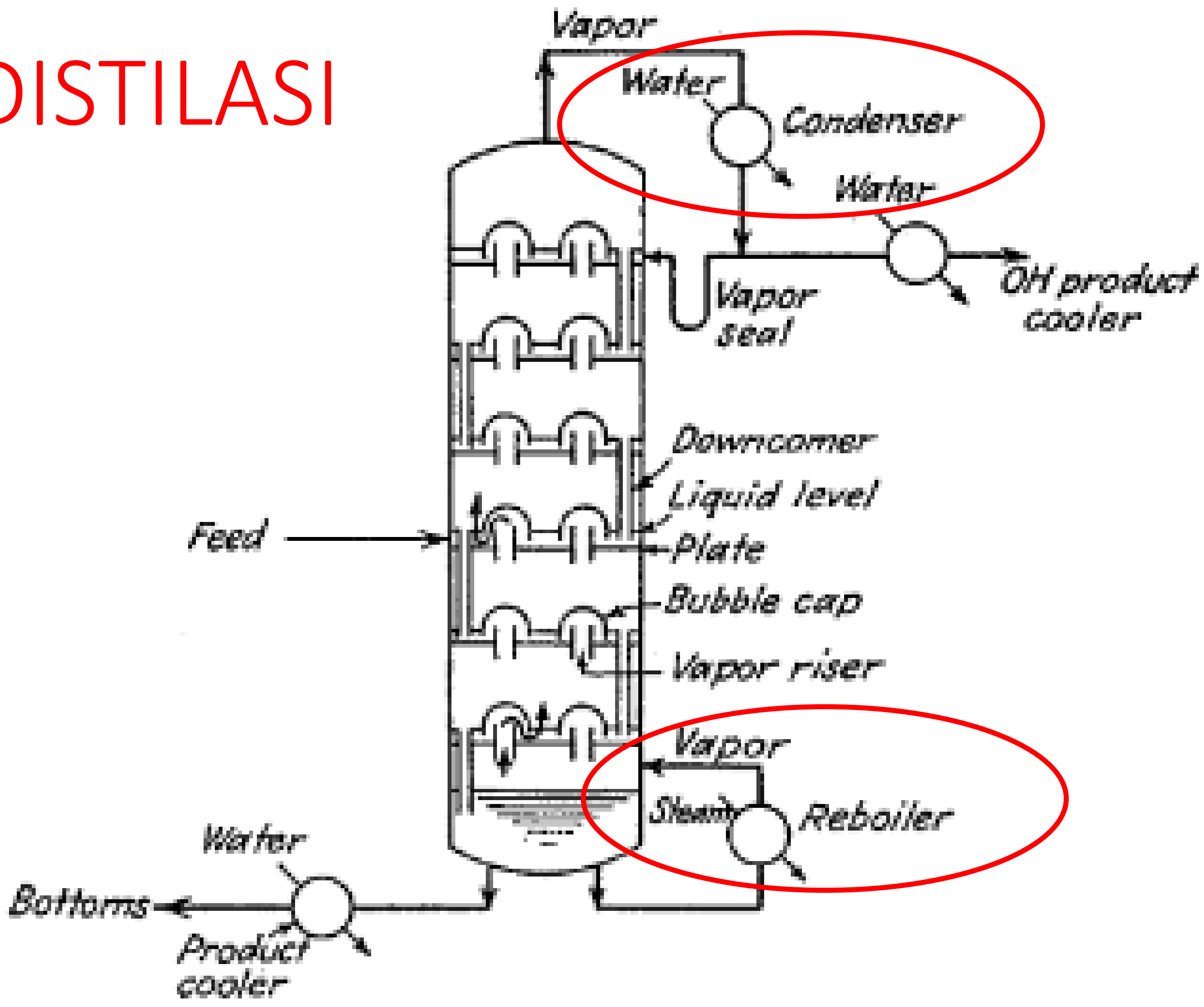


FIG. 12.1. Distilling column with auxiliaries.

CONDENSER

KLASIFIKASI

- KONDENSER TOTAL
- KONDENSER PARSIAL

- HORIZONTAL CONDENSER
- VERTICAL CONDENSER

HORIZONTAL CONDENSER

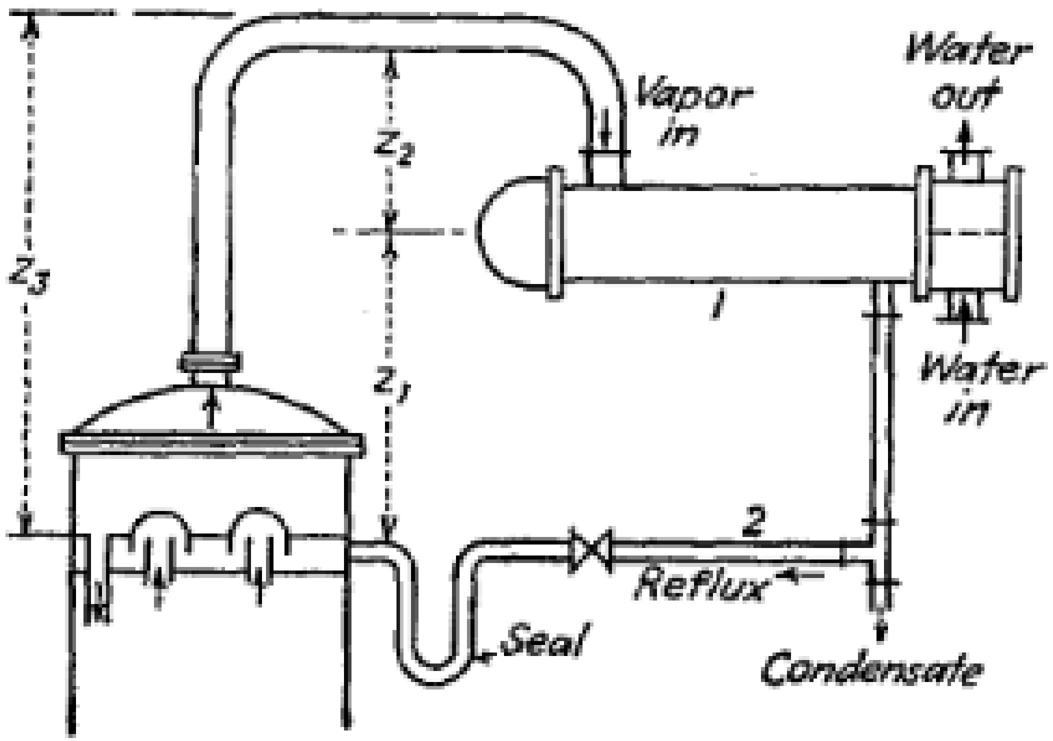


FIG. 12.10. Condenser with gravity return of reflux.

VERTICAL CONDENSER

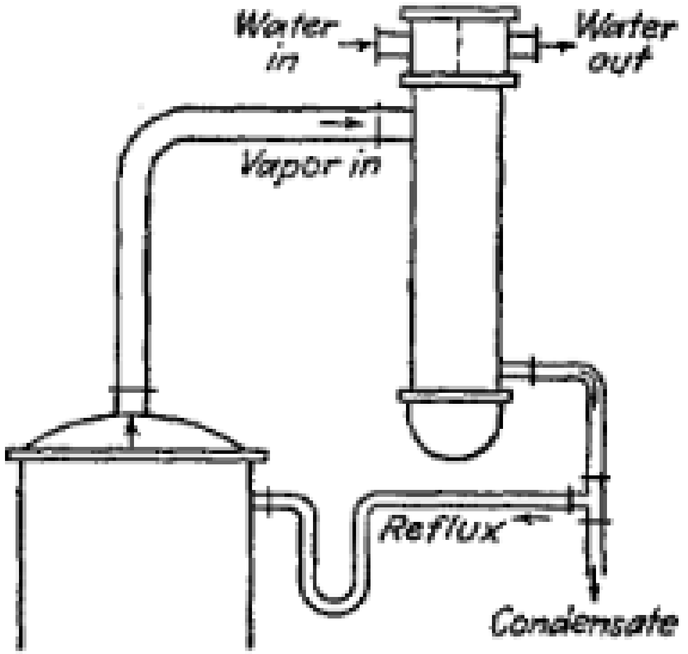
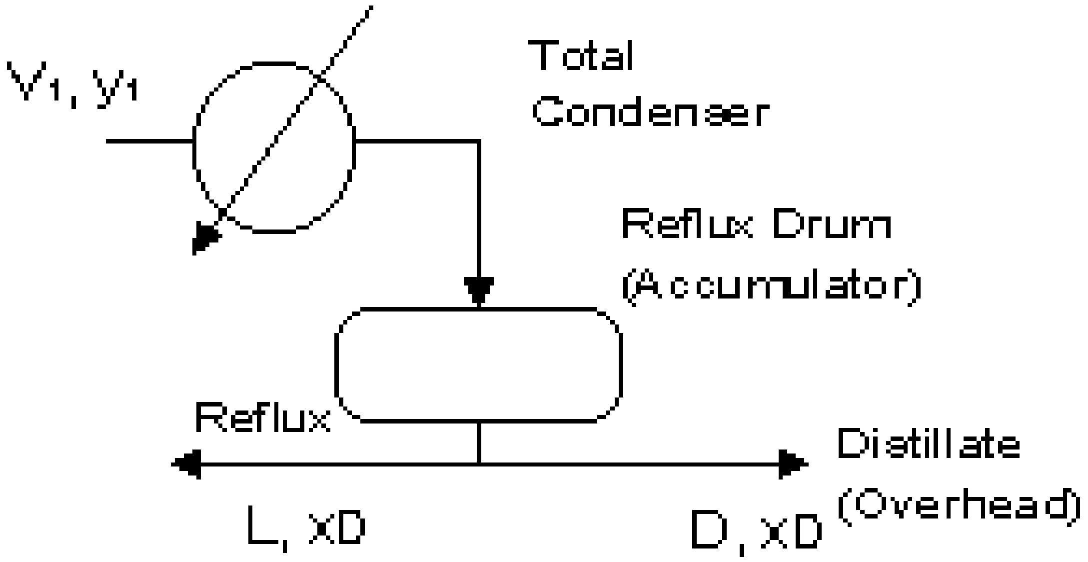
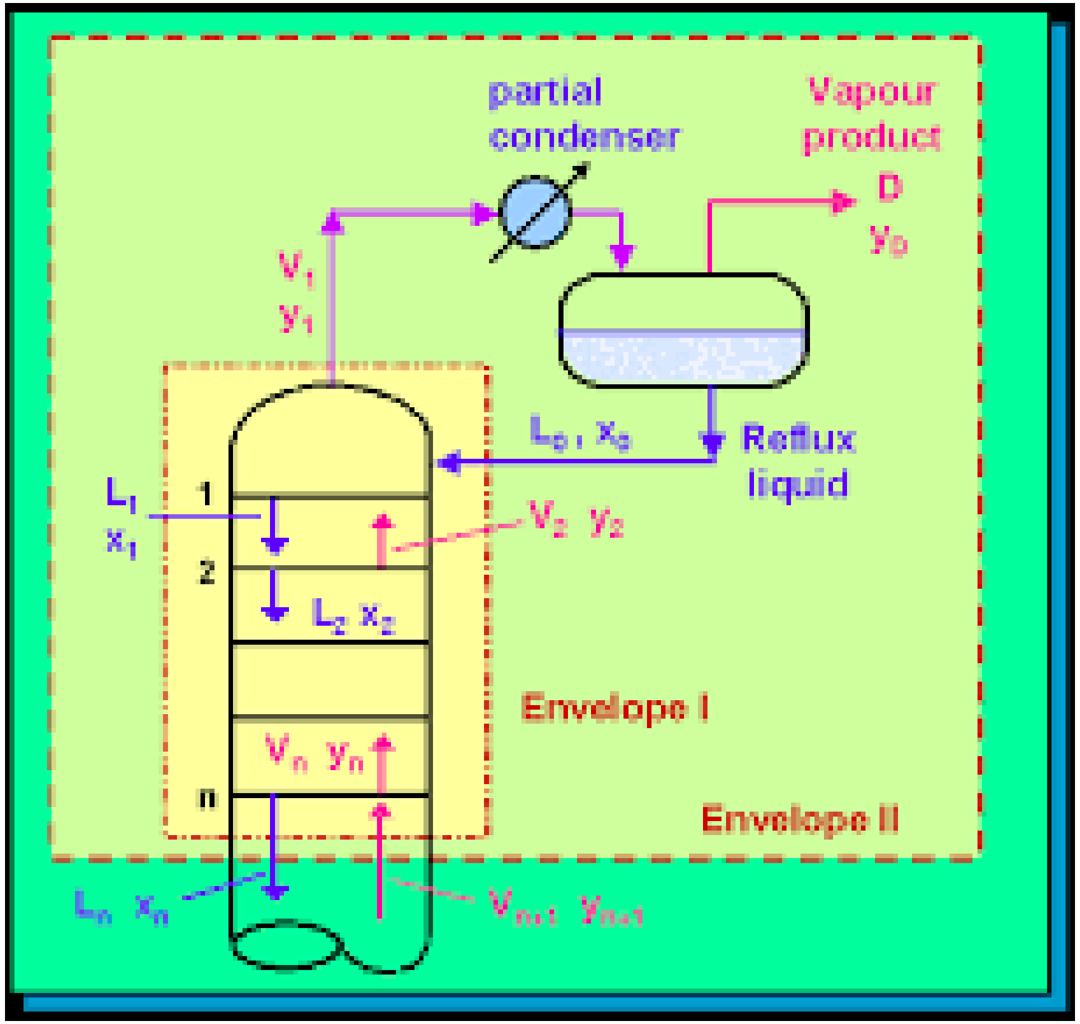


FIG. 12.11. Vertical condenser with condensation in shell and gravity return of reflux.

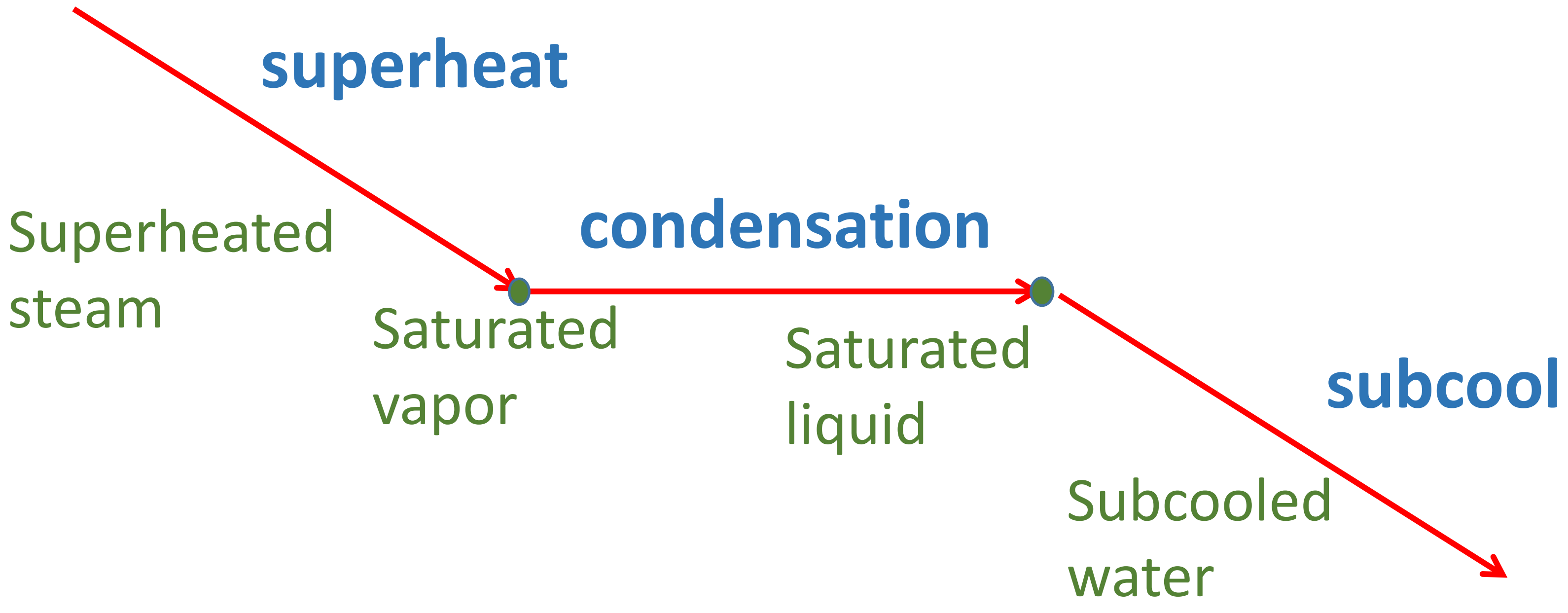
KONDENSER TOTAL



KONDENSER PARSIAL



Perubahan fasa uap-cair



Fungsi kondenser

- Condensing
- Desuperheating-condensing
- Condensing-subcooling
- Desuperheating-condensing-subcooling

Kondenser

- Horisontal

Kondensasi lebih efektif bila berlangsung di luar tube (dalam shell)

- Vertikal

Sebagian besar uap terkondensasi di bagian atas tube

Ketinggiannya harus tertentu agar kondensat dapat di-refluks secara gravitasi

Cocok digunakan untuk condensing sekaligus subcooling

Kondensasi single vapor

- Saturated vapor

- Superheated vapors

- Total / parsial condensation outside tubes
- Condensation & subcooling outside tubes

- Desuperheating & condensation outside tubes

- Condensation inside tubes

- Condensation of steam

- Desuperheating, condensing, subcooling

Kondensasi vapor mixtures

- Binary mixture
- Vapor mixture with long condensing range
- Vapor mixture forming immiscible condensates

- Single vapor / vapors with noncondensable gas
- Vapor mixtures & noncondensable gases forming immiscible condensates

KERN'S INDEX TO THE PRINCIPAL APPARATUS CALCULATIONS

CONDENSERS (TUBULAR)

ADDITIONAL THEORY

CONDENSATION HEAT TRANSFER

Occurs when a vapor contacts a surface which is at a temperature below the saturation temperature of the vapor.
When the liquid condensate forms on the surface, it will flow under the influence
of gravity.

Film condensation

- The condensate wets the surface and forms a liquid film.
- The surface is blanketed by a liquid film which serves as a *resistance* to heat transfer.

Dropwise condensation

- The condensed vapor forms droplets on the surface.
- The droplets slide down when they reach a certain size.
- No liquid film to resist heat transfer.
- As a result, heat transfer rates that are more than 10 times larger than with film condensation can be achieved.

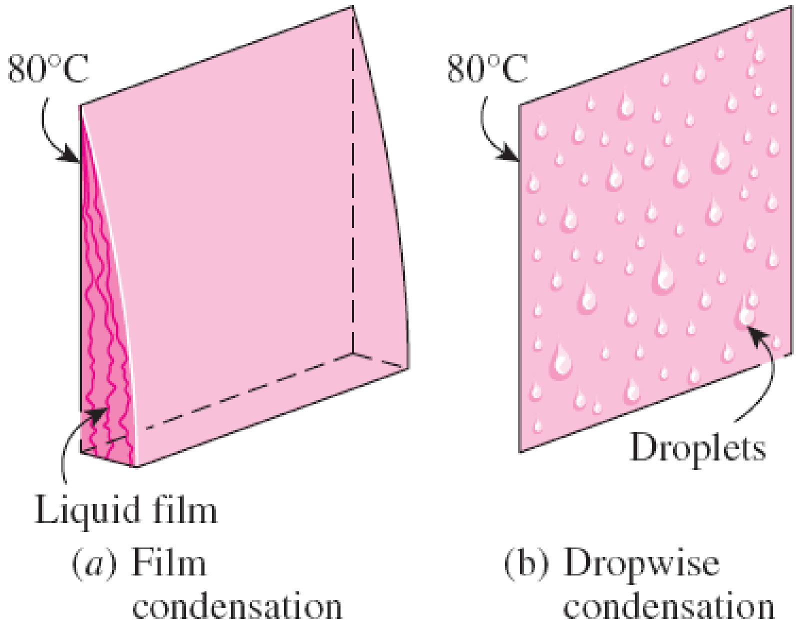


FIGURE 10–20
When a vapor is exposed to a surface at a temperature below T_{sat}, condensation in the form of a liquid film or individual droplets occurs on the surface.

FILM CONDENSATION

- Liquid film starts forming at the top of the plate and flows downward under the influence of gravity.
- δ *increases* in the flow direction x
- Heat in the amount h_{fg} is released during condensation and is *transferred* through the film to the plate surface.
- T_s must be below the saturation temperature for condensation.
- The *temperature* of the condensate is T_{sat} at the interface and decreases gradually to T_s at the wall.

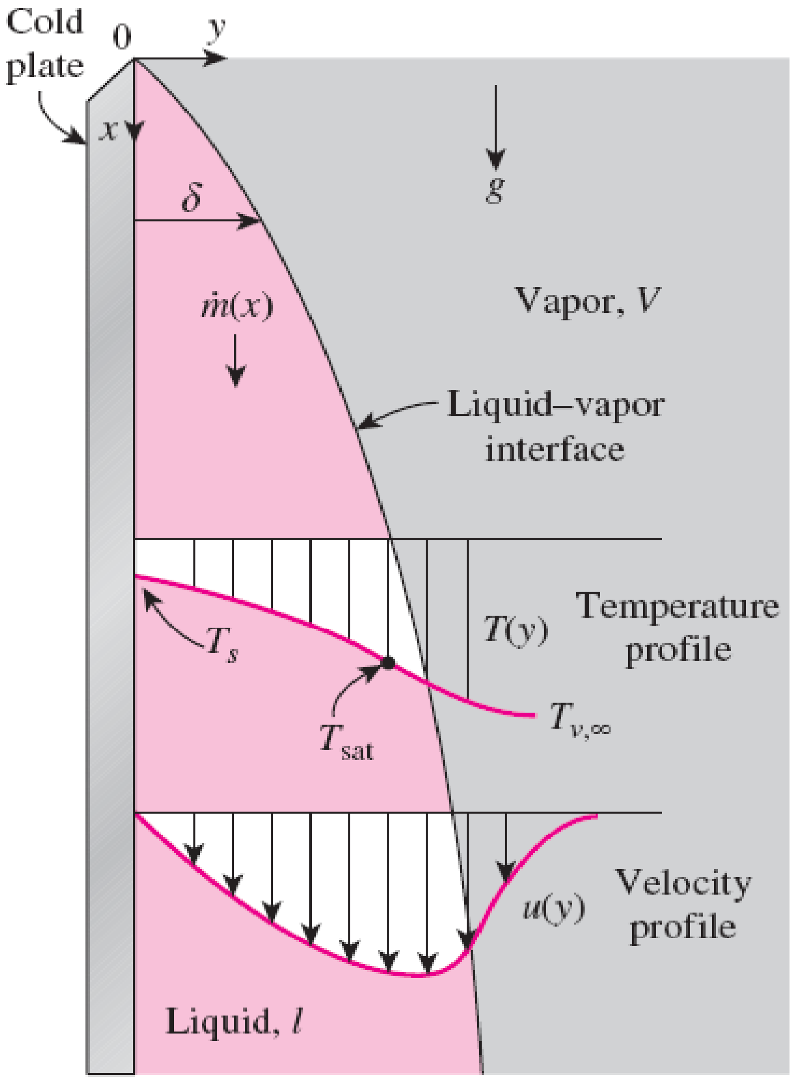


FIGURE 10–21
Film condensation on a vertical plate.

$$\mathrm{Re} = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 \rho_l V_l \delta}{\mu_l} = \frac{4\dot{m}}{p \mu_l}$$

$D_h = 4A_c/p = 4\delta$ = hydraulic diameter of the condensate flow, m
p = wetted perimeter of the condensate, m
$A_c = -p\delta$ = wetted perimeter × film thickness, m^2, cross-sectional area of the condensate flow at the lowest part of the flow
ρ_l = density of the liquid, kg/m^3
μ_l = viscosity of the liquid, kg/m·s
V_l = average velocity of the condensate at the lowest part of the flow, m/s
$\dot{m} = \rho_l V_l A_c$ = mass flow rate of the condensate at the lowest part, kg/s

Heat transfer in condensation depends on whether the condensate flow is *laminar* or *turbulent*. The criterion for the flow regime is provided by the Reynolds number.

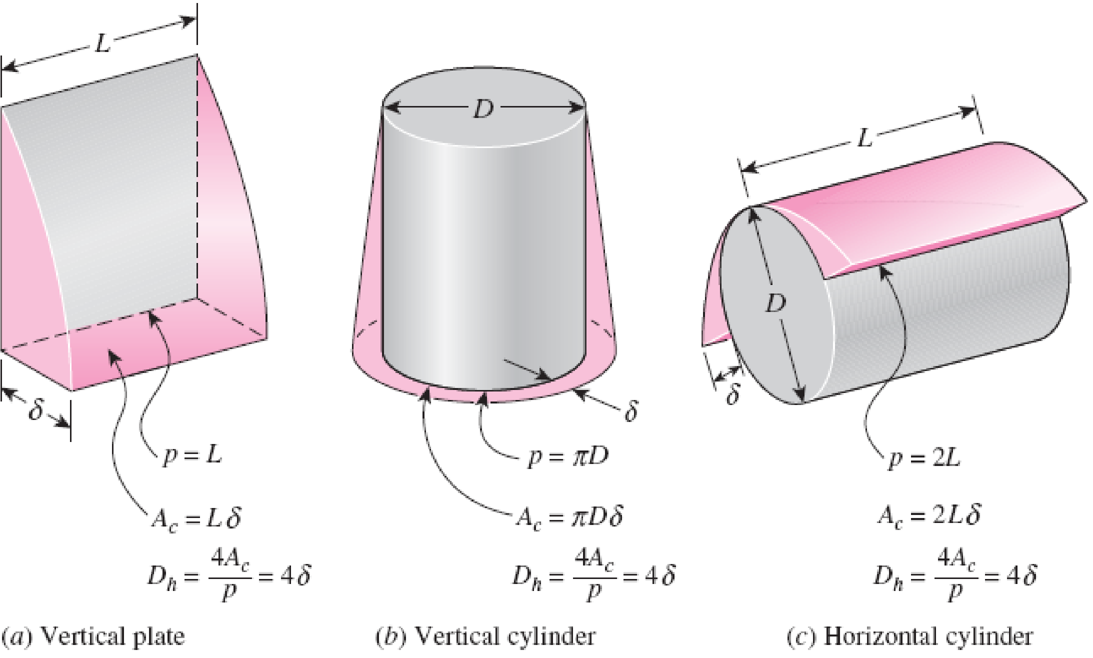


FIGURE 10–22
The wetted perimeter p, the condensate cross-sectional area A_c, and the hydraulic diameter D_h for some common geometries.

When the final state is subcooled liquid instead of saturated liquid:

$$h^*_{fg} = h_{fg} + 0.68c_{pl}\,(T_{\text{sat}} - T_s)$$ Modified latent heat of vaporization

For vapor that enters the condenser as superheated vapor at a temperature T_v instead of as saturated vapor:

$$h^*_{fg} = h_{fg} + 0.68c_{pl}\,(T_{\text{sat}} - T_s) + c_{pv}\,(T_v - T_{\text{sat}})$$

$$\dot{Q}_{\text{conden}} = hA_s(T_{\text{sat}} - T_s) = \dot{m}\,h^*_{fg}$$ Rate of heat transfer

$$\text{Re} = \frac{4\dot{Q}_{\text{conden}}}{p\mu_l\,h^*_{fg}} = \frac{4A_s\,h(T_{\text{sat}} - T_s)}{p\mu_l\,h^*_{fg}}$$

This relation is convenient to use to determine the Reynolds number when the condensation heat transfer coefficient or the rate of heat transfer is known.

$$T_f = (T_{\text{sat}} + T_s)/2$$

The properties of the liquid should be evaluated at the *film temperature*

The h_{fg} should be evaluated at T_{sat}

Flow Regimes

- The dimensionless parameter controlling the transition between regimes is the Reynolds number defined as:

$$\mathrm{Re} = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 \rho_l V_l \delta}{\mu_l} = \frac{4 \dot{m}}{p \mu_l}$$

  - Re < 30 – Laminar (wave-free)
  - 30 < Re < 1800 – Laminar (wavy)
  - Re > 1800 – Turbulent
- The Reynolds number increases in the flow direction.

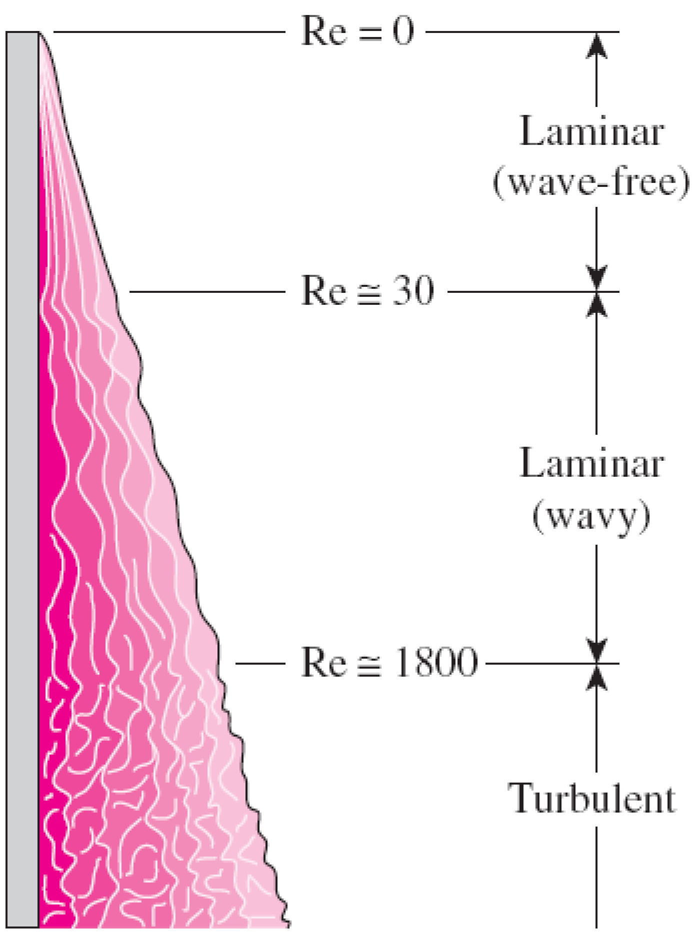


FIGURE 10–23
Flow regimes during film condensation on a vertical plate.

Heat Transfer Correlations for Film Condensation

1 Vertical Plates

Assumptions:

1. Both the plate and the vapor are maintained at *constant temperatures* of T_s and T_{sat}, respectively, and the temperature across the liquid film varies *linearly*.

2. Heat transfer across the liquid film is by pure *conduction*.

3. The velocity of the vapor is low (or zero) so that it exerts *no drag* on the condensate (no viscous shear on the liquid–vapor interface).

4. The flow of the condensate is *laminar* (Re<30) and the properties of the liquid are constant.

5. The acceleration of the condensate layer is negligible.

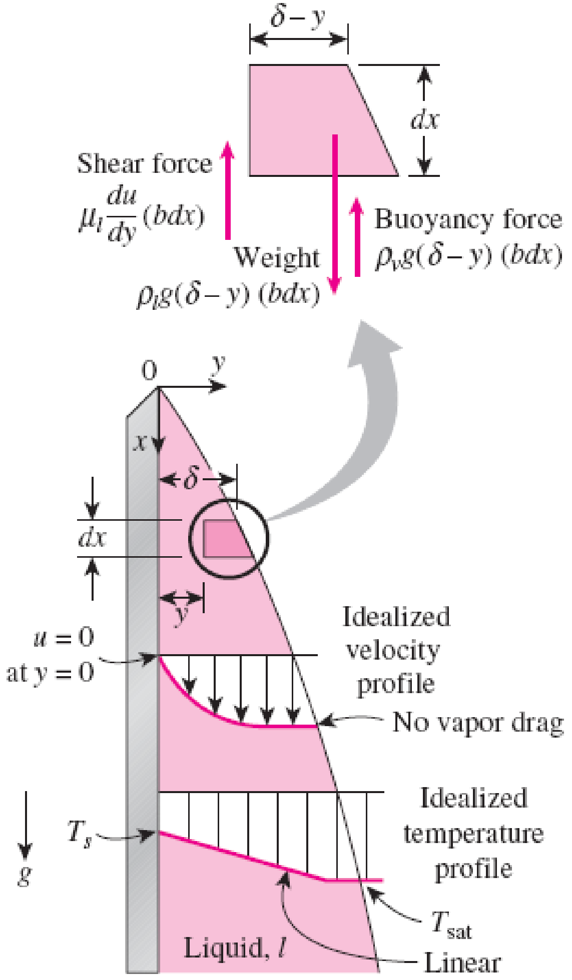


FIGURE 10–24
The volume element of condensate on a vertical plate considered in Nusselt's analysis.

Then Newton's second law of motion for the volume element shown in Fig. 10–24 in the vertical x-direction can be written as

$$\sum F_x = ma_x = 0$$

since the acceleration of the fluid is zero. Noting that the only force acting downward is the weight of the liquid element, and the forces acting upward are the viscous shear (or fluid friction) force at the left and the buoyancy force, the force balance on the volume element becomes

$$F_{\text{downward}\downarrow} = F_{\text{upward}\uparrow}$$

$$\text{Weight} = \text{Viscous shear force} + \text{Buoyancy force}$$

$$\rho_l g(\delta - y)(bdx) = \mu_l \frac{du}{dy}(bdx) + \rho_v\, g(\delta - y)(bdx)$$

Canceling the plate width b and solving for du/dy gives

$$\frac{du}{dy} = \frac{g(\rho_l - \rho_v)g(\rho - y)}{\mu_l}$$

Integrating from $y = 0$ where $u = 0$ (because of the no-slip boundary condition) to $y = y$ where $u = u(y)$ gives

$$u(y) = \frac{g(\rho_l - \rho_v)g}{\mu_l}\left(y\delta - \frac{y^2}{2}\right) \tag{10–12}$$

The mass flow rate of the condensate at a location x, where the boundary layer thickness is δ, is determined from

$$\dot{m}(x) = \int_A \rho_l u(y)dA = \int_{y=0}^{\delta} \rho_l u(y)bdy \tag{10–13}$$

Substituting the $u(y)$ relation from Equation 10–12 into Eq. 10–13 gives

$$\dot{m}\,(x) = \frac{gb\rho_l(\rho_l - \rho_v)\delta^3}{3\mu_l} \tag{10–14}$$

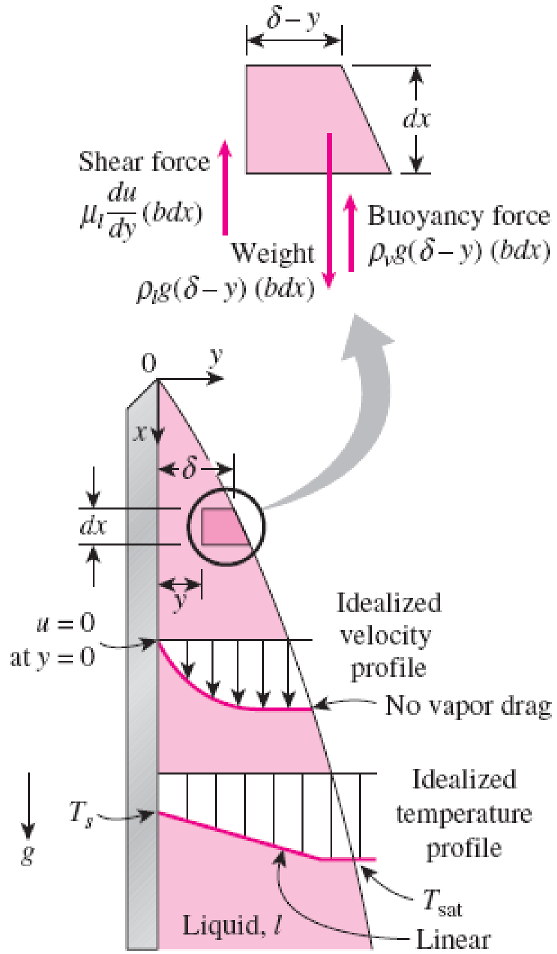


FIGURE 10–24

The volume element of condensate on a vertical plate considered in Nusselt's analysis.

whose derivative with respect to x is

$$\frac{d\dot{m}}{dx} = \frac{gb\rho_l(\rho_l - \rho_v)\delta^2}{\mu_l}\frac{d\delta}{dx} \tag{10–15}$$

which represents the rate of condensation of vapor over a vertical distance dx. The rate of heat transfer from the vapor to the plate through the liquid film is simply equal to the heat released as the vapor is condensed and is expressed as

$$d\dot{Q} = h_{fg}d\dot{m} = k_l(bdx)\frac{T_{sat} - T_s}{\delta} \rightarrow \frac{d\dot{m}}{dx} = \frac{k_l\, b}{h_{fg}}\frac{T_{sat} - T_s}{\delta} \tag{10–16}$$

Equating Eqs. 10–15 and 10–16 for $d\dot{m}/dx$ to each other and separating the variables give

$$\delta^3 d\delta = \frac{\mu_l\, k_l(T_{sat} - T_s)}{g\rho_l\,(\rho_l - \rho_v)h_{fg}}\,dx \tag{10–17}$$

Integrating from $x = 0$ where $\delta = 0$ (the top of the plate) to $x = x$ where $\delta = \delta(x)$, the liquid film thickness at any location x is determined to be

$$\delta(x) = \left[\frac{4\mu_l\, k_l(T_{sat} - T_s)x}{g\rho_l\,(\rho_l - \rho_v)h_{fg}}\right]^{1/4} \tag{10–18}$$

The heat transfer rate from the vapor to the plate at a location x can be expressed as

$$\dot{q}_x = h_x(T_{sat} - T_s) = k_l\frac{T_{sat} - T_s}{\delta} \rightarrow h_x = \frac{k_l}{\delta(x)} \tag{10–19}$$

Substituting the $\delta(x)$ expression from Eq. 10–18, the local heat transfer coefficient h_x is determined to be

$$h_x = \left[\frac{g\rho_l(\rho_l - \rho_v)h_{fg}\, k_l^3}{4\mu_l\,(T_{sat} - T_s)x}\right]^{1/4} \tag{10–20}$$

The average heat transfer coefficient over the entire plate is determined from its definition by substituting the h_x relation and performing the integration. It gives

$$h = h_{vert} = \frac{1}{L}\int_0^L h_x\, dx = \frac{4}{3}h_{x=L} = 0.943\left[\frac{g\rho_l(\rho_l - \rho_v)h_{fg}\, k_l^3}{\mu_l\,(T_{sat} - T_s)L}\right]^{1/4} \tag{10–21}$$

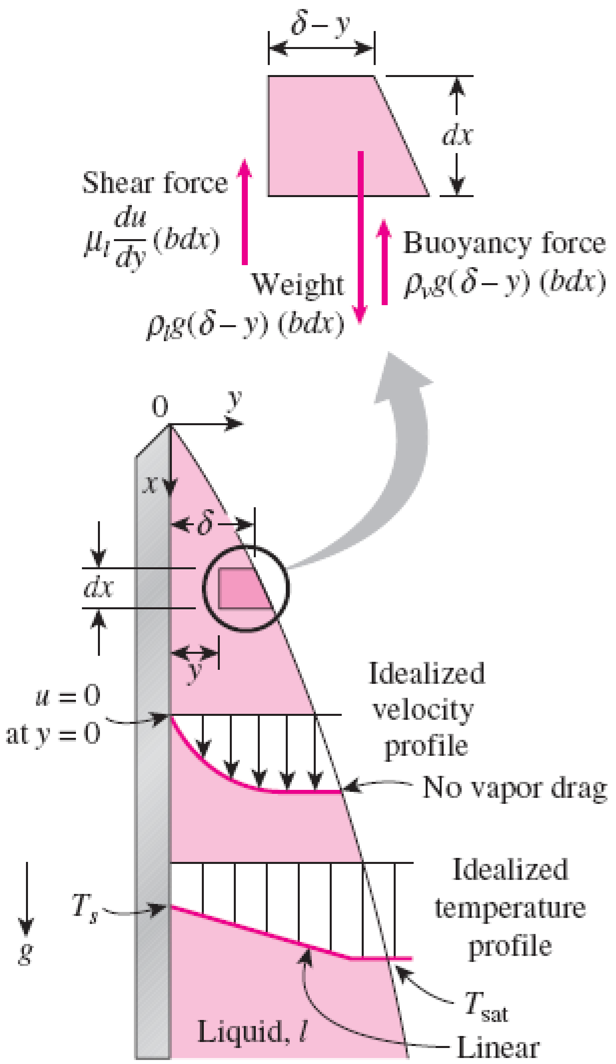


FIGURE 10–24
The volume element of condensate on a vertical plate considered in Nusselt's analysis.

The *average heat transfer coefficient* for laminar film condensation over a vertical flat plate of height L is

$$h_{vert} = 0.943 \left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg} k_l^3}{\mu_l (T_{sat} - T_s)L}\right]^{1/4} \quad (\mathrm{W/m^2 \cdot K}), \qquad 0 < \mathrm{Re} < 30 \qquad \text{(10-22)}$$

g = gravitational acceleration, m/s²
ρ_l, ρ_v = densities of the liquid and vapor, respectively, kg/m³
μ_l = viscosity of the liquid, kg/m·s
$h^*_{fg} = h_{fg} + 0.68c_{pl}(T_{sat} - T_s)$ = modified latent heat of vaporization, J/kg
k_l = thermal conductivity of the liquid, W/m·K
L = height of the vertical plate, m
T_s = surface temperature of the plate, °C
T_{sat} = saturation temperature of the condensing fluid, °C

$$\mathrm{Re} \cong \frac{4g\rho_l(\rho_l - \rho_v)\delta^3}{3\mu_l^2} = \frac{4g\rho_l^2}{3\mu_l^2}\left(\frac{k_l}{h_{x=L}}\right)^3 = \frac{4g}{3\nu_l^2}\left(\frac{k_l}{3h_{vert}/4}\right)^3$$

$$h_{vert} \cong 1.47 k_l \mathrm{Re}^{-1/3}\left(\frac{g}{\nu_l^2}\right)^{1/3}, \qquad 0 < \mathrm{Re} < 30, \quad \rho_v \ll \rho_l$$

$$T_f = (T_{sat} + T_s)/2$$

All properties of the liquid are to be evaluated at the film temperature. The h_{fg} and ρ_v are to be evaluated at the saturation temperature T_{sat}.

$$h_{vert} = \left(\frac{\frac{\mathrm{m}}{\mathrm{s^2}}\frac{\mathrm{kg}}{\mathrm{m^3}}\frac{\mathrm{kg}}{\mathrm{m^3}}\frac{\mathrm{J}}{\mathrm{kg}}\left(\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right)^3}{\frac{\mathrm{kg}}{\mathrm{m\cdot s}}\cdot \mathrm{K\cdot m}}\right)^{1/4}$$
$$= \left[\frac{\mathrm{m}}{\mathrm{s}}\frac{1}{\mathrm{m^6}}\frac{\mathrm{W^3}}{\mathrm{m^3\cdot K^3}}\frac{\mathrm{J}}{\mathrm{K}}\right]$$
$$= \left(\frac{\mathrm{W^4}}{\mathrm{m^8\cdot K^4}}\right)^{1/4}$$
$$= \mathrm{W/m^2\cdot K}$$

FIGURE 10–25
Equation 10–22 gives the condensation heat transfer coefficient in W/m²·K when the quantities are expressed in the units specified in their descriptions.

Wavy Laminar Flow on Vertical Plates

The average heat transfer coefficient in wavy laminar condensate flow for $\rho_v \ll \rho_l$ and $30 < \text{Re} < 1800$

$$h_{\text{vert, wavy}} = \frac{\text{Re}\, k_l}{1.08\, \text{Re}^{1.22} - 5.2} \left(\frac{g}{\nu_l^2}\right)^{1/3}, \qquad \begin{array}{l} 30 < \text{Re} < 1800 \\ \rho_v \ll \rho_l \end{array}$$

$$h_{\text{vert, wavy}} = 0.8\, \text{Re}^{0.11}\, h_{\text{vert (smooth)}}$$

A simpler alternative to the relation above

$$\text{Re}_{\text{vert, wavy}} = \left[4.81 + \frac{3.70\, L k_l (T_{\text{sat}} - T_s)}{\mu_l\, h_{fg}^*} \left(\frac{g}{\nu_l^2}\right)^{1/3}\right]^{0.820}, \qquad \rho_v \ll \rho_l$$

Turbulent Flow on Vertical Plates

Turbulent flow of condensate on *vertical plates:*

$$h_{\text{vert, turbulent}} = \frac{\text{Re}\, k_l}{8750 + 58\,\text{Pr}^{-0.5}\,(\text{Re}^{0.75} - 253)}\left(\frac{g}{\nu_l^2}\right)^{1/3}, \qquad \begin{array}{l}\text{Re} > 1800 \\ \rho_v \ll \rho_l\end{array}$$

$\rho_v \ll \rho_l$

The physical properties of the condensate are again to be evaluated at the film temperature $T_f = (T_{sat} + T_s)/2$.

$$\text{Re}_{\text{vert, turbulent}} = \left[\frac{0.0690\, L k_l\, \text{Pr}^{0.5}\,(T_{\text{sat}} - T_s)}{\mu_l\, h_{fg}^*}\left(\frac{g}{\nu_l^2}\right)^{1/3} - 151\,\text{Pr}^{0.5} + 253\right]^{4/3}$$

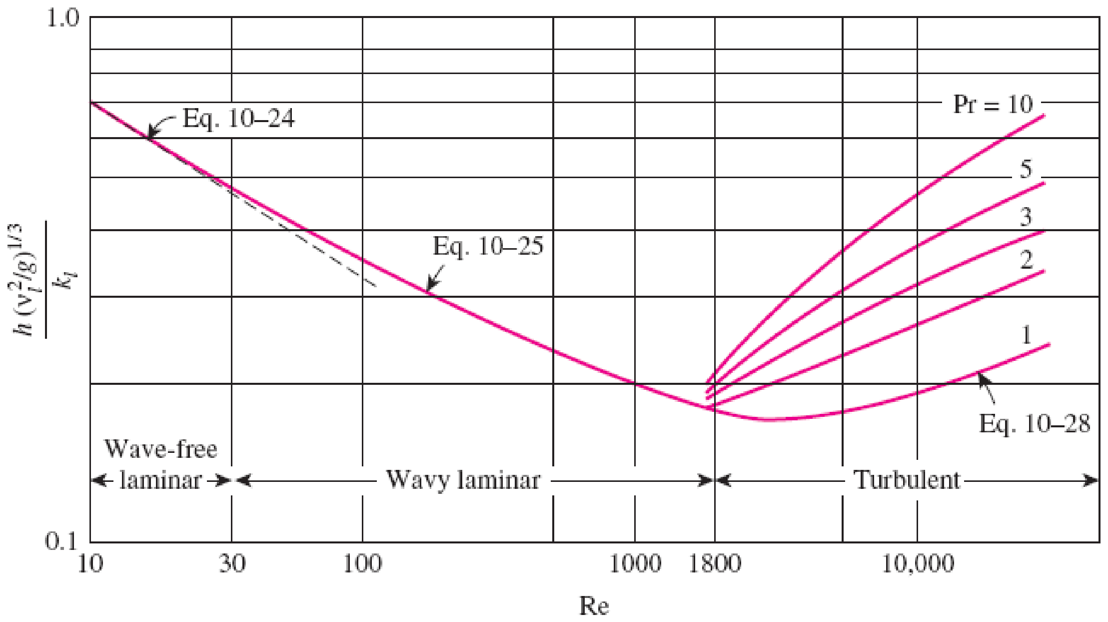


FIGURE 10–26
Nondimensionalized heat transfer coefficients for the wave-free laminar, wavy laminar, and turbulent flow of condensate on vertical plates.

2 Inclined Plates

Equation 10–22 was developed for vertical plates, but it can also be used for laminar film condensation on the upper surfaces of plates that are *inclined* by an angle θ from the *vertical,* by replacing *g* in that equation by $g \cos\theta$.

$$h_{\text{inclined}} = h_{\text{vert}} (\cos\theta)^{1/4} \qquad \text{(laminar)}$$

$$h_{\text{vert}} = 0.943 \left[\frac{g \rho_l (\rho_l - \rho_v) h^*_{fg} k_l^3}{\mu_l (T_{\text{sat}} - T_s) L} \right]^{1/4} \qquad (\text{W/m}^2 \cdot \text{K}), \qquad 0 < \text{Re} < 30$$

(10-22)

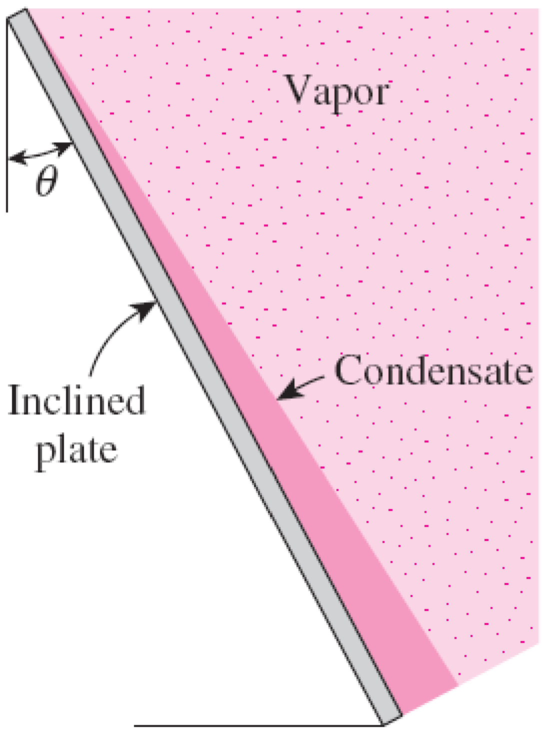


FIGURE 10–27
Film condensation on an inclined plate.

3 Vertical Tubes

Equation 10–22 for vertical plates can also be used to calculate the average heat transfer coefficient for laminar film condensation on the outer surfaces of vertical tubes provided that the tube diameter is large relative to the thickness of the liquid film.

4 Horizontal Tubes and Spheres

The average heat transfer coefficient for film condensation on the outer surfaces of a *horizontal tube* is

$$h_{\text{horiz}} = 0.729 \left[\frac{g\rho_l(\rho_l - \rho_v)\, h^*_{fg}\, k_l^3}{\mu_l(T_{\text{sat}} - T_s)D}\right]^{1/4} \quad (\text{W/m}^2\cdot\text{K})$$

For a *sphere,* replace the constant 0.729 by 0.815.

A comparison of the heat transfer coefficient relations for a vertical tube of height *L* and a horizontal tube of diameter *D* yields

$$\frac{h_{\text{vert}}}{h_{\text{horiz}}} = 1.29\left(\frac{D}{L}\right)^{1/4}$$

Setting $h_{\text{vert}} = h_{\text{horiz}}$ gives $L = 1.29^4 D = 2.77D$.

For a tube whose length is 2.77 times its diameter, the average heat transfer coefficient for laminar film condensation will be the *same* whether the tube is positioned horizontally or vertically.

For $L > 2.77D$, the heat transfer coefficient is higher in the horizontal position.

Considering that the length of a tube in any practical application is several times its diameter, it is common practice to place the tubes in a condenser *horizontally* to maximize the condensation heat transfer coefficient on the outer surfaces of the tubes.

5 Horizontal Tube Banks

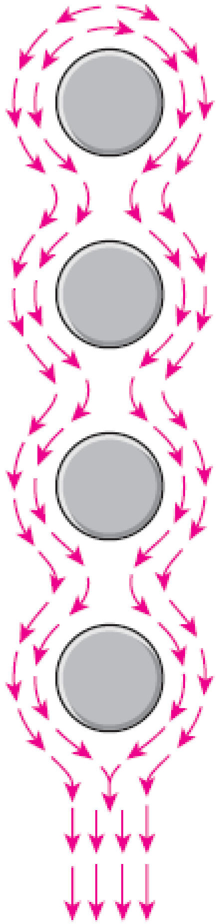


FIGURE 10–28
Film condensation on a vertical tier of horizontal tubes.

The average thickness of the liquid film at the lower tubes is much larger as a result of condensate falling on top of them from the tubes directly above.

Therefore, the average heat transfer coefficient at the lower tubes in such arrangements is smaller.

Assuming the condensate from the tubes above to the ones below drain smoothly, the average film condensation heat transfer coefficient for all tubes in a vertical tier can be expressed as

$$\boxed{h_{\text{horiz, } N \text{ tubes}} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)\,h_{fg}^{*}\,k_l^3}{\mu_l(T_{\text{sat}} - T_s)\,ND}\right]^{1/4} = \frac{1}{N^{1/4}}\,h_{\text{horiz, 1 tube}}}$$

$$h_{\text{horiz}} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)\,h_{fg}^{*}\,k_l^3}{\mu_l(T_{\text{sat}} - T_s)D}\right]^{1/4} \quad (\text{W/m}^2\cdot\text{K})$$

This relation does not account for the increase in heat transfer due to the ripple formation and turbulence caused during drainage, and thus generally yields conservative results.

Effect of Vapor Velocity

In the analysis above we assumed the vapor velocity to be small and thus the vapor drag exerted on the liquid film to be negligible, which is usually the case.

However, when the vapor velocity is high, the vapor will "pull" the liquid at the interface along since the vapor velocity at the interface must drop to the value of the liquid velocity.

If the vapor flows downward (i.e., in the same direction as the liquid), this additional force will increase the average velocity of the liquid and thus decrease the film thickness.

This, in turn, will decrease the thermal resistance of the liquid film and thus increase heat transfer.

Upward vapor flow has the opposite effects: the vapor exerts a force on the liquid in the opposite direction to flow, thickens the liquid film, and thus decreases heat transfer.

The Presence of Noncondensable Gases in Condensers

Experimental studies show that the presence of noncondensable gases in the vapor has a detrimental effect on condensation heat transfer.

Even small amounts of a noncondensable gas in the vapor cause significant drops in heat transfer coefficient during condensation.

It is common practice to periodically vent out the noncondensable gases that accumulate in the condensers to ensure proper operation.

Heat transfer in the presence of a noncondensable gas strongly depends on the nature of the vapor flow and the flow velocity.

A *high flow velocity* is more likely to remove the stagnant noncondensable gas from the vicinity of the surface, and thus *improve* heat transfer.

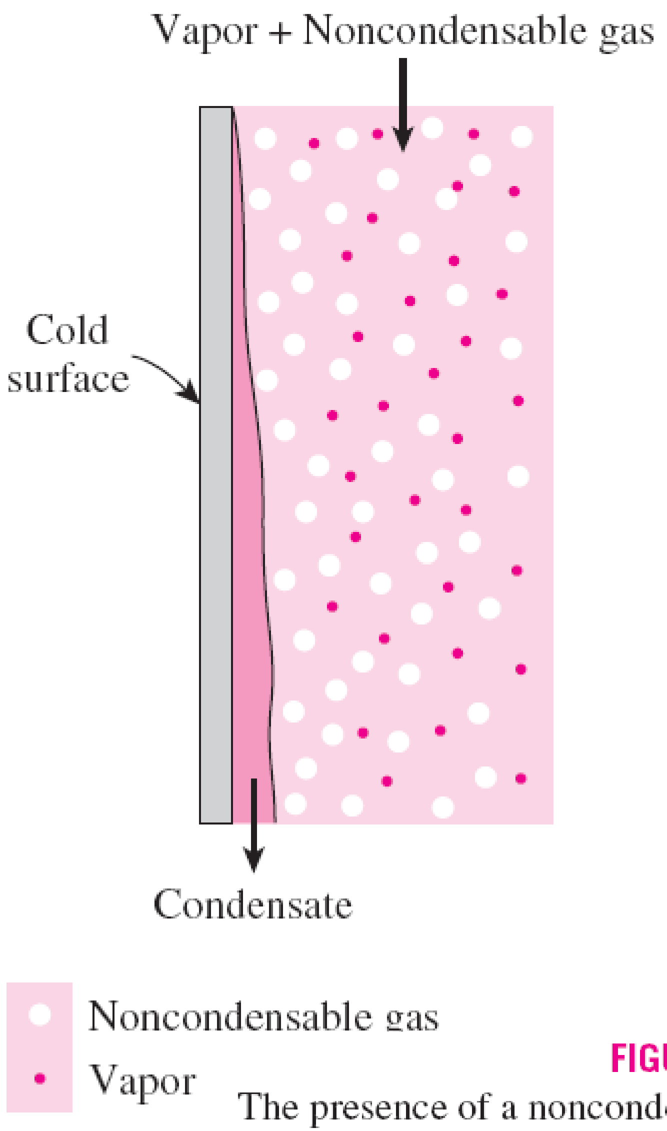


FIGURE 10–29
The presence of a noncondensable gas in a vapor prevents the vapor molecules from reaching the cold surface easily, and thus impedes condensation heat transfer.

FILM CONDENSATION INSIDE HORIZONTAL TUBES

Most condensation processes encountered in refrigeration and air-conditioning applications involve condensation on the *inner surfaces* of horizontal or vertical tubes.

Heat transfer analysis of condensation inside tubes is complicated by the fact that it is strongly influenced by the vapor velocity and the rate of liquid accumulation on the walls of the tubes.

For *low vapor velocities:*

$$h_{\text{internal}} = 0.555\left[\frac{g\rho_l(\rho_l - \rho_v)k_l^3}{\mu_l(T_{\text{sat}} - T_s)D}\left(h_{fg} + \frac{3}{8}c_{pl}(T_{\text{sat}} - T_s)\right)\right]^{1/4}$$

$$\text{Re}_{\text{vapor}} = \left(\frac{\rho_v V_v D}{\mu_v}\right)_{\text{inlet}} < 35{,}000$$

The Reynolds number of the vapor is to be evaluated at the tube *inlet* conditions using the internal tube diameter as the characteristic length.

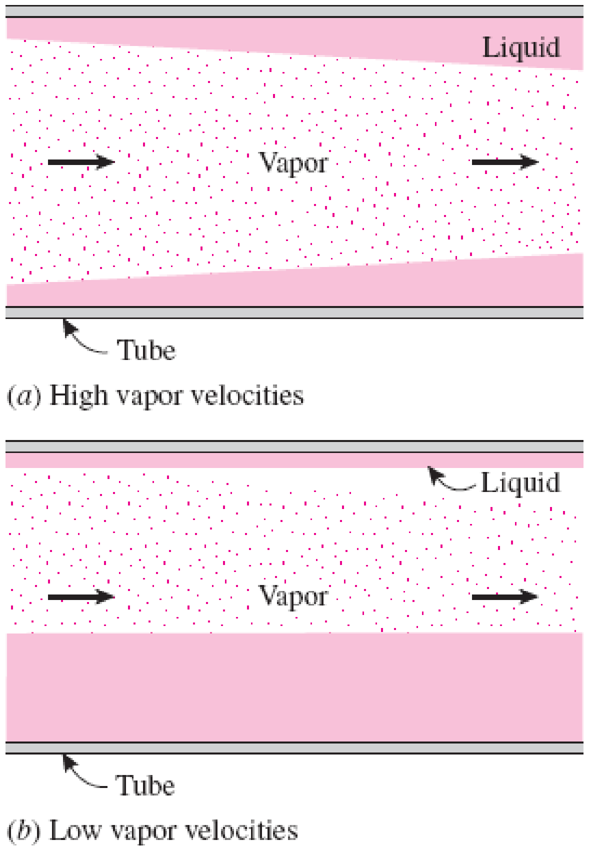


FIGURE 10–34
Condensate flow in a horizontal tube with high and low vapor velocities.

DROPWISE CONDENSATION

Dropwise condensation, characterized by countless droplets of varying diameters on the condensing surface instead of a continuous liquid film and extremely large heat transfer coefficients can be achieved with this mechanism.

The small droplets that form at the nucleation sites on the surface grow as a result of continued condensation, coalesce into large droplets, and slide down when they reach a certain size, clearing the surface and exposing it to vapor. There is no liquid film in this case to resist heat transfer.

As a result, with dropwise condensation, heat transfer coefficients can be achieved that are more than 10 times larger than those associated with film condensation.

The challenge in dropwise condensation is not to achieve it, but rather, to *sustain* it for prolonged periods of time.

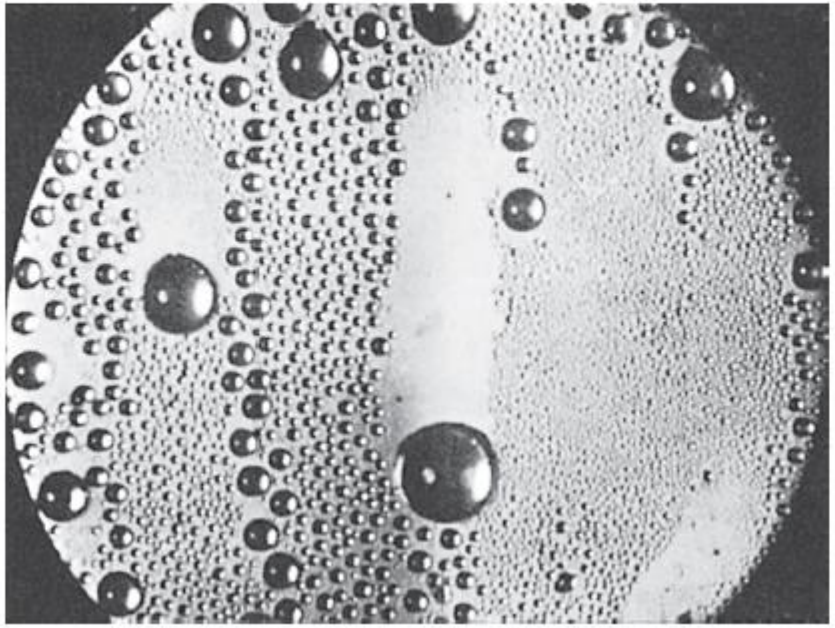


FIGURE 10–35
Dropwise condensation of steam on a vertical surface.

Dropwise condensation of *steam* on *copper surfaces:*

$$h_{\text{dropwise}} = \begin{cases} 51{,}104 + 2044T_{\text{sat}}, & 22^\circ\text{C} < T_{\text{sat}}, 100^\circ\text{C} \\ 255{,}310 & T_{\text{sat}} > 100^\circ\text{C} \end{cases}$$

Data

- Perry's Chemical Handbook, Section 11, Heat transfer equipment,
  - **TABLE 11-12 Characterstics of Tubing (From *Standards of the Tubular Exchanger Manufacturers Association, 8th Ed., 1999)***