Condensation Heat Transfer

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CONDENSATION

CONDENSERS

Power plant – water is boiled in boiler and condensed in condenser

Oil refinery - oil is evaporated in distillation column and condensed into liquid fuels like gasoline and kerosene

Desalination plant – water vapor is produced by evaporation from brine and condensed as pure water

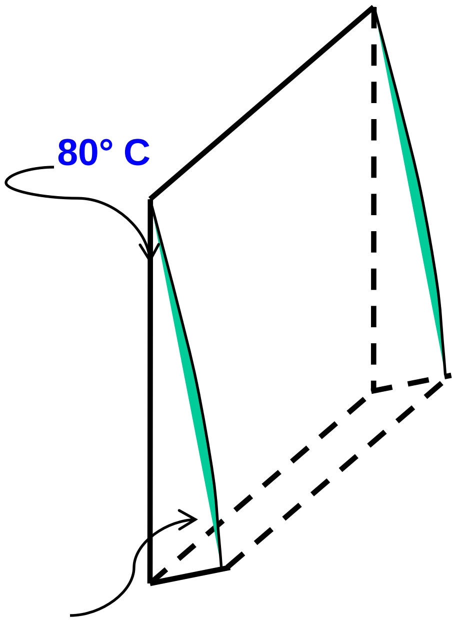
Condensation – enthalpy of phase change to be removed by a coolant

Enthalpy of phase change is relatively large, for water (2.5×10^6 J/kg) and associated heat transfer rates are also large

Heat transfer to phase interface – convective process – complicated by an irregular surface – bubbles and drops

CONDENSATION HEAT TRANSFER

- **Film condensation**
- **Dropwise condensation**



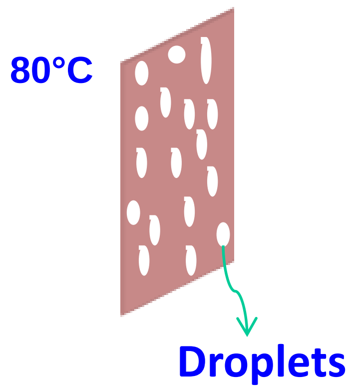
FILM CONDENSATION

Condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity.

Surface is blanketed by a liquid film of increasing thickness, and this "liquid wall" between the solid surface and the vapor serves as a *resistance* to heat transfer

- Condensate film thickness are thin – heat transfer coefficients are large
- Example - steam at a saturation temperature of 305 K condenses on a 2 cm – O.D tube with a wall temperature of 300 K
- Average film thickness - 50μm (0.05 mm) and the average heat transfer coefficient – 11,700 $W/m^2.K$
- If the condensate flow rate is small, the surface of the film will be smooth and the flow laminar because
    - Temperature difference is small
    - Wall is short
- If the condensate flow rate is high, waves will form on the surface to give wavy laminar flow
- If the condensate flow rate is yet higher, the flow becomes turbulent

DROPWISE CONDENSATION



If the condensate does not wet the wall, because either it is dirty or it has been treated with a non-wetting agent, droplets of condensate nucleate at small pits and other imperfections on the surface, and they grow rapidly by direct vapor condensation upon them and by coalescence

When the droplets become sufficiently large, they flow down the surface under the action of gravity and expose bare metal in their tracks, where further droplet nucleation is initiated

THIS IS CALLED DROPWISE CONDENSATION

Droplets 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.

Heat transfer rates that are more than 10 times larger than those associated with film condensation can be achieved with dropwise condensation

Most of the heat transfer is through drops of less than 100μm diameter

Thermal resistance of such drops is small; hence, heat transfer coefficients for dropwise condensation are large; values of upto 30000 $W/m^2.K$ have been measured.

Hence, dropwise condensation is preferred over filmwise condensation

Considerable efforts are put for non-wetting heat exchanger surfaces

If the surface is treated with non-wetting agent (stearic acid) to promote dropwise condensation, the effect lasts only few days, until the promoter is washed off or oxidised.

Continuous adding of the promoter to the vapour is expensive and contaminates the condensate.

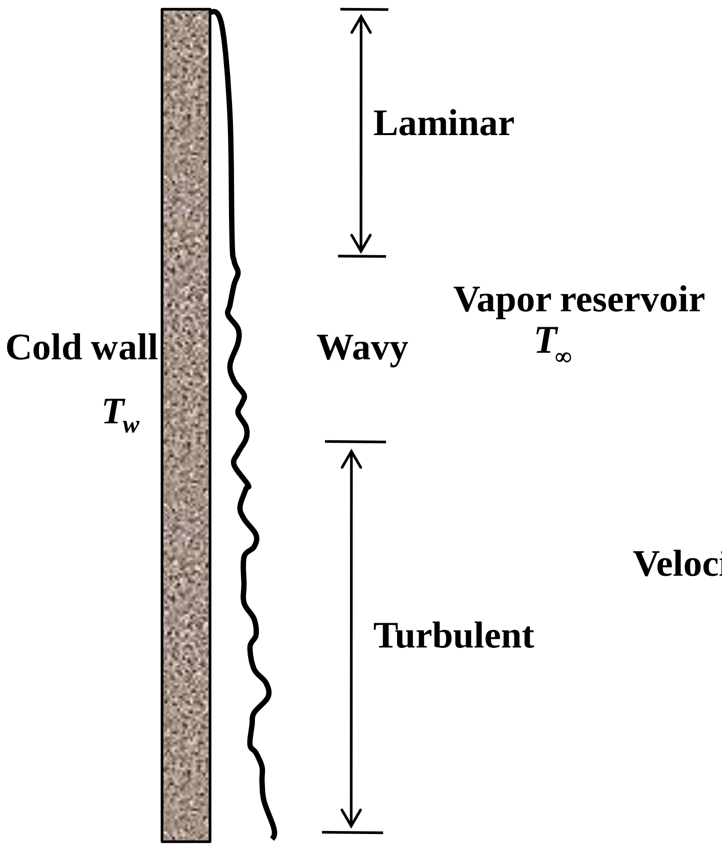
Bonding a polymer such as teflon to the surface is expensive and adds additional thermal resistance

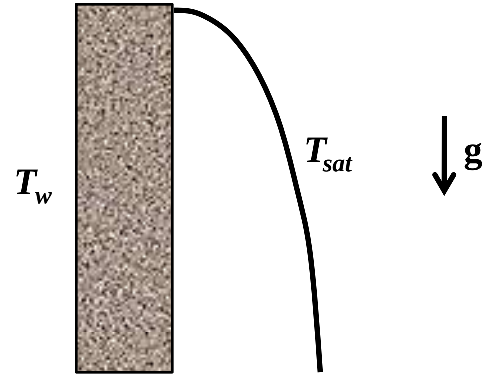
Gold plating is also expensive

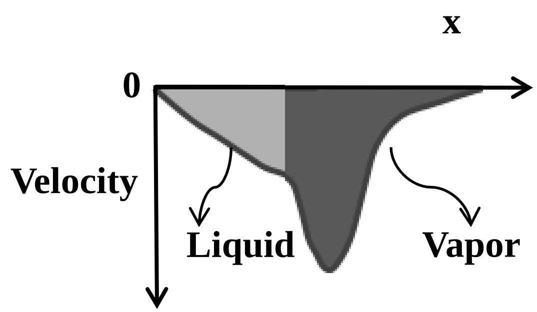
Because of lack of sustainability of dropwise condensation, present day condensers are designed based on filmwise condensation

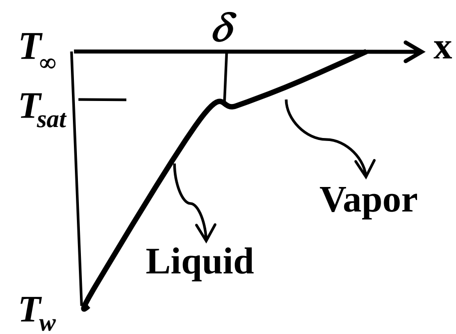
Filmwise condensation – conservative estimate

LAMINAR FLOW CONDENSATION ON A VERTICAL WALL









Temperature of the liquid-vapour interface is the saturation temperature that corresponds to T_{sat}

Vapour in the descending jet is colder than the vapour reservoir and warmer than the liquid in the film attached to the wall

LAMINAR FLOW CONDENSATION ON A VERTICAL WALL

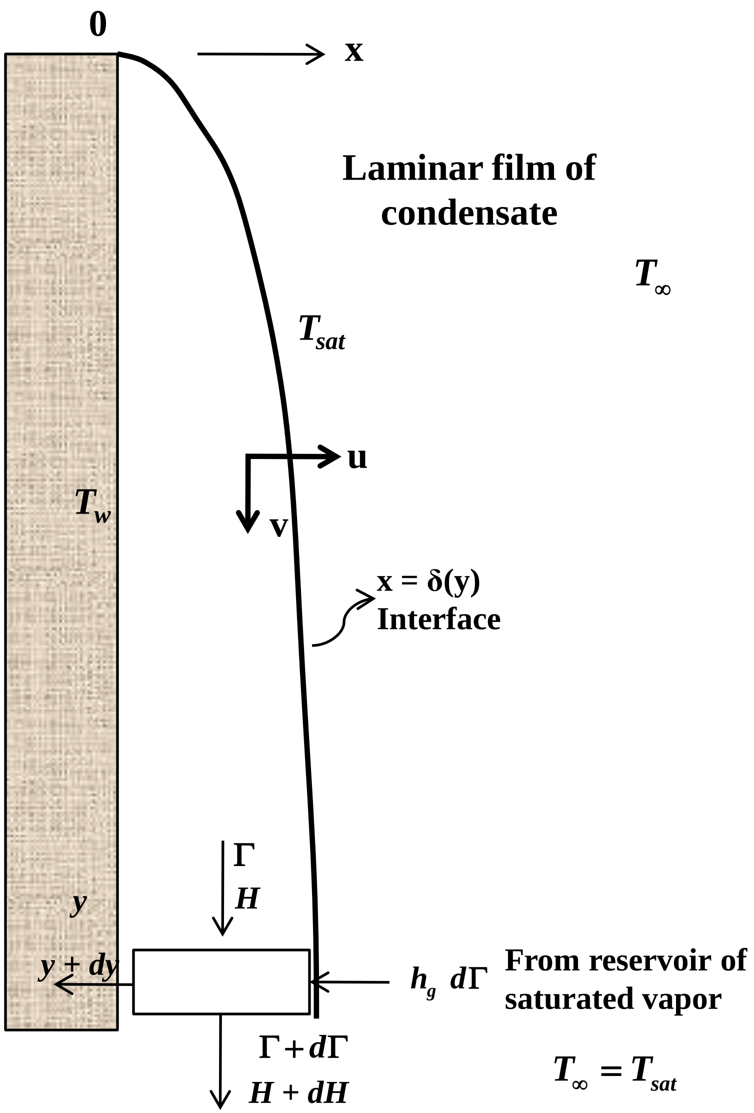
Consider a vertical wall exposed to a saturated vapour at pressure p and saturation temperature $T_{sat} = T_{sat}(P)$.

The wall could be flat or could be the outside surface of a vertical tube

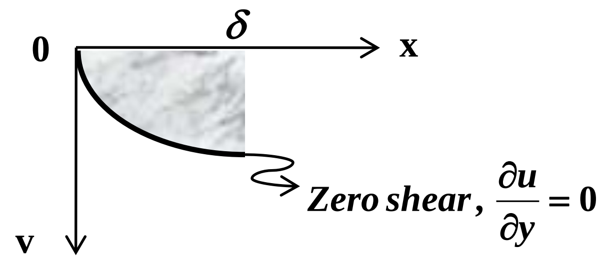
If the surface is maintained at a temperature $T_w < T_{sat}$, vapour will continuously condense on the wall, and if the liquid phase wets the surface well, will flow down the wall in a thin film

Provided the condensation rate is not too large, there will be no discernable waves on the film surface, and the flow in the film will be laminar

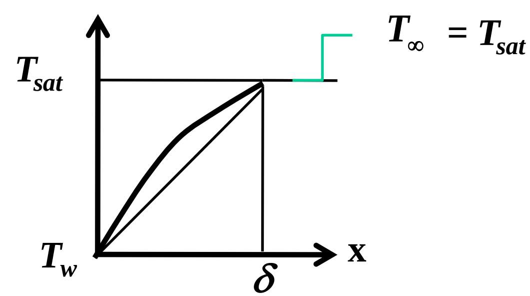
- **Fluid dynamics of the flow of a thin liquid film**
- **Heat transfer during the flow of a thin liquid film**



0
x
Laminar film of condensate
T_∞
T_{sat}
u
v
T_w
x = δ(y)
Interface
Γ
H
y
$y + dy$
$h_g \; d\Gamma$
From reservoir of saturated vapor
$\Gamma + d\Gamma$
$H + dH$
$T_\infty = T_{sat}$



0
δ
x
v
$Zero\,shear,\ \frac{\partial u}{\partial y} = 0$



$T_\infty = T_{sat}$
T_{sat}
T_w
x
δ

ASSUMPTIONS

- **Laminar flow and constant properties are assumed for the liquid film**
- **Gas is assumed to be pure vapour and at a uniform temperature equal to $T_{sat.}$ The merit of this simplification is that it allows us to focus exclusively on the flow of the liquid film and to neglect the movement of the nearest layers of vapour**
- **Shear stress at the liquid-vapour interface is assumed to be negligible**
- **With no temperature gradient in the vapour, heat transfer to the liquid-vapour interface can occur only by condensation at the interface and not by conduction from the vapour**

Steady state two dimensional incompressible flow

$$\rho_L\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+\mu_L\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right]$$

$$\rho_L\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\mu_L\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right]+\rho_L g$$

$$x\sim\delta;\ y\sim L$$

$$u<<<v,\ \ Hence,\ x-momentum\ \ equation\ \ vanishes$$

Neglected, *y<<x*

$$\rho_L\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{dP}{dy}+\mu_L\left[\frac{\partial^2 v}{\partial x^2}+\cancel{\frac{\partial^2 v}{\partial y^2}}\right]+\rho_L g$$

$$\frac{dP}{dy}=pressure\ \ imposed\ \ from\ the\ inviscid\ \ potion=\rho_v g=Hydrostatic\ \ pressure$$

$$\rho_L\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=(\rho_L-\rho_v)g+\mu_L\frac{\partial^2 v}{\partial x^2}$$

$$\underbrace{\rho_L\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)}_{INERTIA} = \underbrace{(\rho_L-\rho_v)g}_{SINKING\ EFFECT} + \underbrace{\mu_L\frac{\partial^2 v}{\partial x^2}}_{FRICTION}$$

Assuming inertia is negligible

$$\mu_L\frac{\partial^2 v}{\partial x^2}+(\rho_L-\rho_v)g=0$$

Boundary conditions

$$x=0 \quad v=0$$

$$x=\delta \quad \frac{\partial v}{\partial x}=0$$

Integrating

$$\mu_L\frac{\partial v}{\partial x}+g(\rho_L-\rho_v)x=C_1$$

$$\mu_L v+g(\rho_L-\rho_v)\frac{x^2}{2}=C_1x+C_2$$

$$x=0 \quad v=0\Rightarrow C_2=0$$

$$x=\delta \quad \frac{\partial v}{\partial x}=0\Rightarrow \mu_L\frac{\partial v}{\partial x}+g(\rho_L-\rho_v)x=C_1\Rightarrow g(\rho_L-\rho_v)\delta=C_1$$

$$\mu_L v + g(\rho_L - \rho_v)\frac{x^2}{2} = C_1 x + C_2$$

$$C_2 = 0$$

$$C_1 = g(\rho_L - \rho_v)\delta$$

$$\mu_L v + g(\rho_L - \rho_v)\frac{x^2}{2} = g(\rho_L - \rho_v)\delta\, x$$

$$v = \frac{g(\rho_L - \rho_v)}{\mu_L}\left(\delta x - \frac{x^2}{2}\right)$$

$$\boxed{v(x,y) = \frac{g(\rho_L - \rho_v)}{\mu_L}\delta^2\left(\frac{x}{\delta} - \frac{1}{2}\left(\frac{x}{\delta}\right)^2\right)}$$

Film thickness is unknown function of δ(y)

Local mass flow rate per unit width $\Gamma(y)$

$$\Gamma(y)=\int_0^{\delta}\rho_L v\,dx \qquad \delta=\delta(y)$$

$$\Gamma(y)=\int_0^{\delta}\rho_L\frac{g(\rho_L-\rho_v)}{\mu_L}\delta^2\left(\frac{x}{\delta}-\frac{1}{2}\left(\frac{x}{\delta}\right)^2\right)dx$$

$$\Gamma(y)=\rho_L\frac{g(\rho_L-\rho_v)}{\mu_L}\delta^2\left[\frac{x^2}{2\delta}-\frac{1}{6}\left(\frac{x^3}{\delta^3}\right)\right]\Bigg|_0^{\delta}$$

$$\Gamma(y)=\frac{\rho_L g(\rho_L-\rho_v)}{\mu_L}\delta^2\left[\frac{\delta}{2}-\frac{\delta}{6}\right]$$

$$\Gamma(y)=\frac{\rho_L g(\rho_L-\rho_v)}{\mu_L}\delta^2\frac{\delta}{3}$$

$$\Gamma(y)=\frac{\rho_L g(\rho_L-\rho_v)}{\mu_L}\frac{\delta^3}{3}$$

$$\Gamma(y) = \frac{\rho_L g(\rho_L - \rho_v)}{\mu_L}\frac{\delta^3}{3}$$

$$\dot{m} = b\Gamma(y) = \frac{b\rho_L g(\rho_L - \rho_v)}{\mu_L}\frac{\delta^3}{3}$$

B – width of the plate perpendicular to the plane of paper

Flow rate is proportional to the sinking effect - $g(\rho_L-\rho_v)$

Flow rate is inversely proportional to the liquid viscosity (Friction)

HEAT TRANSFER PROBLEM

Film velocity is low

Temperature gradients in the y-direction are negligible since both wall and film surface are isothermal

$$\frac{d^2T}{dx^2} = 0$$

$$\frac{dT}{dx} = C_1; T = C_1 x + C_2$$

$$T = C_1 x + C_2$$

$$x = \delta \quad T = T_{sat}$$

$$x = 0 \quad T = T_w \Rightarrow C_2 = T_w$$

$$T = C_1 x + T_w \Rightarrow T_{sat} = C_1 \delta + T_w \Rightarrow C_1 = \frac{T_{sat} - T_w}{\delta}$$

$$T = \left(T_{sat} - T_w\right)\frac{x}{\delta} + T_w$$

This is a linear temperature profile similar to the conduction in a plane wall

Heat flux into the wall = Heat flux across the film

$$k_l \left.\frac{dT}{dx}\right|_w = h\left(T_{sat} - T_w\right) = \frac{\dot{Q}}{A} = \frac{k_l\left(T_{sat} - T_w\right)}{\delta}$$

$$h = \frac{k_l \left.\frac{dT}{dx}\right|_w}{\left(T_{sat} - T_w\right)} = \frac{\frac{k_l\left(T_{sat} - T_w\right)}{\delta}}{\left(T_{sat} - T_w\right)} = \frac{k_l}{\delta}$$

$$h = \frac{k_l}{\delta}$$

Determination of film thickness

$$\Gamma(y) = \frac{\rho_L g\left(\rho_L - \rho_v\right)}{\mu_L}\frac{\delta^3}{3};$$

$$\dot{m} = b\Gamma(y) = \frac{b\rho_L g\left(\rho_L - \rho_v\right)}{\mu_L}\frac{\delta^3}{3}$$

$$\boxed{\frac{d\dot{m}}{dy} = b\Gamma(y) = \frac{b\rho_L g\left(\rho_L - \rho_v\right)}{\mu_L}\frac{3\delta^2}{3}\frac{d\delta}{dy}}$$

Rate of condensation of vapour over a vertical distance dy

Rate of heat transfer from the vapour to the plate through the liquid film = Heat releasead as vapour is condensed

$$d\dot{Q} = d\dot{m}h_{fg} = k_l\left(b\,dy\right)\frac{T_{sat}-T_w}{\delta}$$

$$\boxed{\frac{d\dot{m}}{dy} = \frac{k_l b}{h_{fg}}\frac{T_{sat}-T_w}{\delta}}$$

$$\frac{d\dot{m}}{dy} = b\Gamma\left(y\right) = \frac{b\rho_L g\left(\rho_L-\rho_v\right)}{\mu_L}\frac{3\delta^2}{3}\frac{d\delta}{dy} = \frac{k_l b}{h_{fg}}\frac{T_{sat}-T_w}{\delta}$$

$$\frac{\rho_L g\left(\rho_L-\rho_v\right)}{\mu_L}\frac{3\delta^2}{3}\frac{d\delta}{dy} = \frac{k_l}{h_{fg}}\frac{T_{sat}-T_w}{\delta}$$

$$\delta^3 d\delta = \frac{\mu_L k_l\left(T_{sat}-T_w\right)}{\rho_L g\left(\rho_L-\rho_v\right)h_{fg}}dy$$

$$\frac{\delta^4}{4} = \frac{\mu_L k_l\left(T_{sat}-T_w\right)}{\rho_L g\left(\rho_L-\rho_v\right)h_{fg}}y + C \qquad y=0, \quad \delta=0 \Rightarrow C=0$$

$$\frac{\delta^4}{4} = \frac{\mu_L k_l \left(T_{sat} - T_w\right)}{\rho_L g \left(\rho_L - \rho_v\right) h_{fg}} y$$

$$\boxed{\delta(y) = \left[\frac{4\mu_L k_l^4 \left(T_{sat} - T_w\right)}{\rho_L g \left(\rho_L - \rho_v\right) h_{fg}} y\right]^{\frac{1}{4}}}$$

$$h = \frac{k_l}{\delta} = \left(\frac{\rho_L g \left(\rho_L - \rho_v\right) h_{fg} k_l^4}{4\mu_L k_l \left(T_{sat} - T_w\right) y}\right)^{\frac{1}{4}}$$

$$\overline{h}_L = \frac{1}{L}\int_0^L \left(\frac{\rho_L g \left(\rho_L - \rho_v\right) h_{fg} k_l^3}{4\mu_L \left(T_{sat} - T_w\right) y}\right)^{\frac{1}{4}} dy = \left(\frac{g\rho_L \left(\rho_L - \rho_v\right) h_{fg} k_l^3}{4\mu_L \left(T_{sat} - T_w\right)}\right)^{\frac{1}{4}} \frac{1}{L}\int_0^L y^{-\frac{1}{4}} dy$$

$$\boxed{\bar{h}_L = 0.943\left(\frac{g\rho_L(\rho_L-\rho_v)h_{fg}k_l^3}{4\mu_L(T_{sat}-T_w)L}\right)^{\frac{1}{4}}}$$

$$\dot{m} = b\Gamma(y) = \frac{b\rho_L g(\rho_L-\rho_v)}{\mu_L}\frac{\delta^3}{3}$$

$$\delta(y) = \left[\frac{4\mu_L k_l^4(T_{sat}-T_w)}{\rho_L g(\rho_L-\rho_v)h_{fg}}y\right]^{\frac{1}{4}}$$

$$\boxed{\dot{m} = \frac{b\rho_L g(\rho_L-\rho_v)}{3\mu_L}\left[\frac{4\mu_L k_l^4(T_{sat}-T_w)}{\rho_L g(\rho_L-\rho_v)h_{fg}}y\right]^{\frac{3}{4}}}$$

All liquid properties evaluated at

$$T_f = \frac{T_{sat}+T_w}{2}$$

Effect of subcooling

Rohsenow refined

- **avoided linear temperature profile**
- **Integral analysis of temperature distribution across the film**

Temperature profile whose curvature increases with the degree of subcooling

$C_{p,L}(T_{sat}-T_w)$

$$h'_{fg} = h_{fg} + 0.68 C_{p,L}\left(T_{sat} - T_w\right)$$

Replace in previous equations h_{fg} *by* h'_{fg}

All liquid properties evaluated at

$$T_f = \frac{T_{sat} + T_w}{2}$$

h_{fg} **and** ρ_v **are evaluated at the saturation temperature** T_{sat}

JAKOB NUMBER

Is a measure of degree of subcooling experienced by the liquid film

$$Ja = \frac{C_{p,L}\left(T_{sat} - T_w\right)}{h_{fg}}$$

$$h'_{fg} = h_{fg} + 0.68C_{p,L}\left(T_{sat} - T_w\right)$$

$$h'_{fg} = h_{fg}\left(1 + 0.68Ja\right)$$

Reynolds Number

$$Re = \frac{\rho_L u_m D_h}{\mu_L}\ ;\ u_m = \frac{\Gamma}{\rho_L \delta}\ ;\ D_h = \frac{4A_c}{P} = \frac{4\delta b}{b} = 4\delta$$

$$Re = \rho_L \frac{\Gamma}{\rho_L \delta}\frac{4\delta}{\mu_L} = \frac{4\Gamma}{\mu_L}$$

$$Re = \frac{4\Gamma}{\mu_L}$$

$$\Gamma(y) = \frac{\rho_L g(\rho_L - \rho_v)}{\mu_L}\frac{\delta^3}{3}$$

$$Re = \frac{4\Gamma}{\mu_L} = \frac{4\rho_L g(\rho_L - \rho_v)}{3\mu_L}\frac{\delta^3}{\mu_L}$$

$$\rho_L >> \rho_v \Rightarrow \boxed{Re = \frac{4\rho_L^2 g\delta^3}{3\mu_L^2} = \frac{4g\delta^3}{3\nu_L^2}}$$

$$\rho_L >> \rho_v \Rightarrow Re = \frac{4\rho_L^2 g\delta^3}{3\mu_L^2}$$

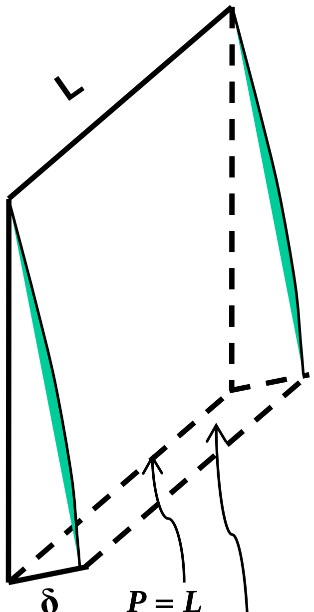
$$\delta = \frac{k_l}{h} \Rightarrow \delta(x = L) = \frac{k_l}{h_{x=L}}$$

$$h_{x=L} = \frac{3}{4} h_{avg}$$

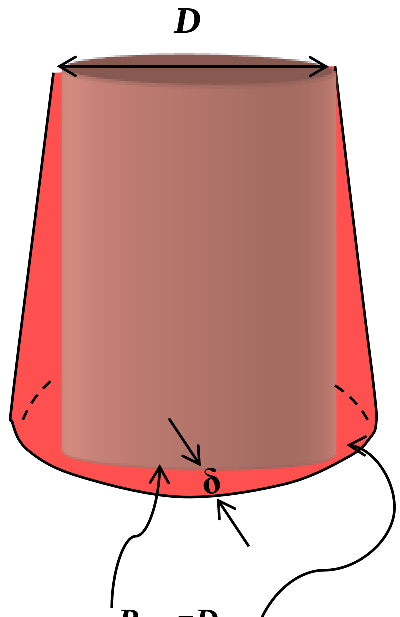
$$Re = \frac{4g\rho_L^2}{3\mu_L^2}\left(\frac{k_L}{h_{x=L}}\right)^3 = \frac{4g\rho_L^2}{3\mu_L^2}\left(\frac{k_L}{\frac{3}{4}h_{avg}}\right)^3$$

$$\boxed{h_{avg} = 1.47 k_l \, Re^{-\frac{1}{3}}\left(\frac{g}{\nu_l^2}\right)^{\frac{1}{3}}}$$

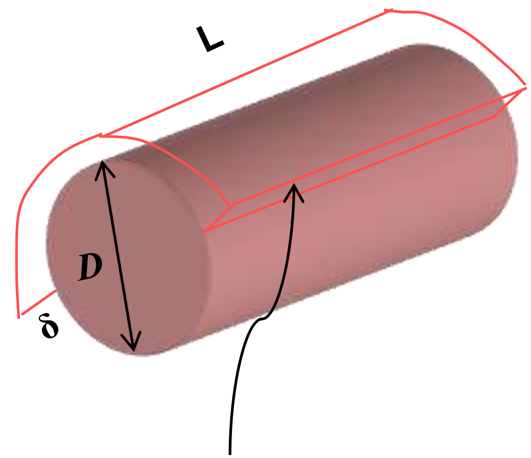
Hydraulic diameter



$$P = L$$
$$A_c = L\delta$$
$$Dh = \frac{4A_c}{P} = 4\delta$$



$$P = \pi D$$
$$A_c = \pi D\delta$$
$$Dh = \frac{4A_c}{P} = 4\delta$$



$$P = 2L$$
$$A_c = 2L\delta$$
$$Dh = \frac{4A_c}{P} = 4\delta$$

Wavy Laminar flow over vertical plates

At Reynolds number greater than about 30, it is observed that waves form at the liquid vapour interface although the flow in liquid film remains laminar. The flow in this case is Wavy Laminar

Kutateladze (1963) recommended the following relation for wavy laminar condensation over vertical plates

$$h_{vert,wavy} = \frac{Re\, k_l}{1.08\, Re^{1.22} - 5.2}\left(\frac{g}{\nu_l^2}\right)^{\frac{1}{3}}$$

$$30 < Re < 1800, \quad \rho_v << \rho_l$$

$$Re_{vert,wavy} = \left[4.81 + \frac{3.70\, L k_l (T_{sat} - T_w)}{\mu_l h'_{fg}}\left(\frac{g}{\nu_l^2}\right)^{\frac{1}{3}}\right]^{0.82}$$

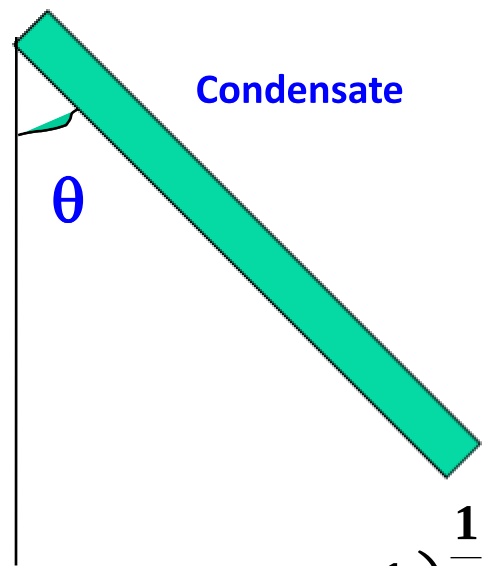
Turbulent flow over vertical plates (Re > 1800)

Labuntsov proposed the following relation

$$h_{vert,turbulent} = \frac{Re\,k_l}{8750 + 58\,Pr^{-0.5}\left(Re^{0.75} - 253\right)}\left(\frac{g}{\nu_l^2}\right)^{\frac{1}{3}}$$

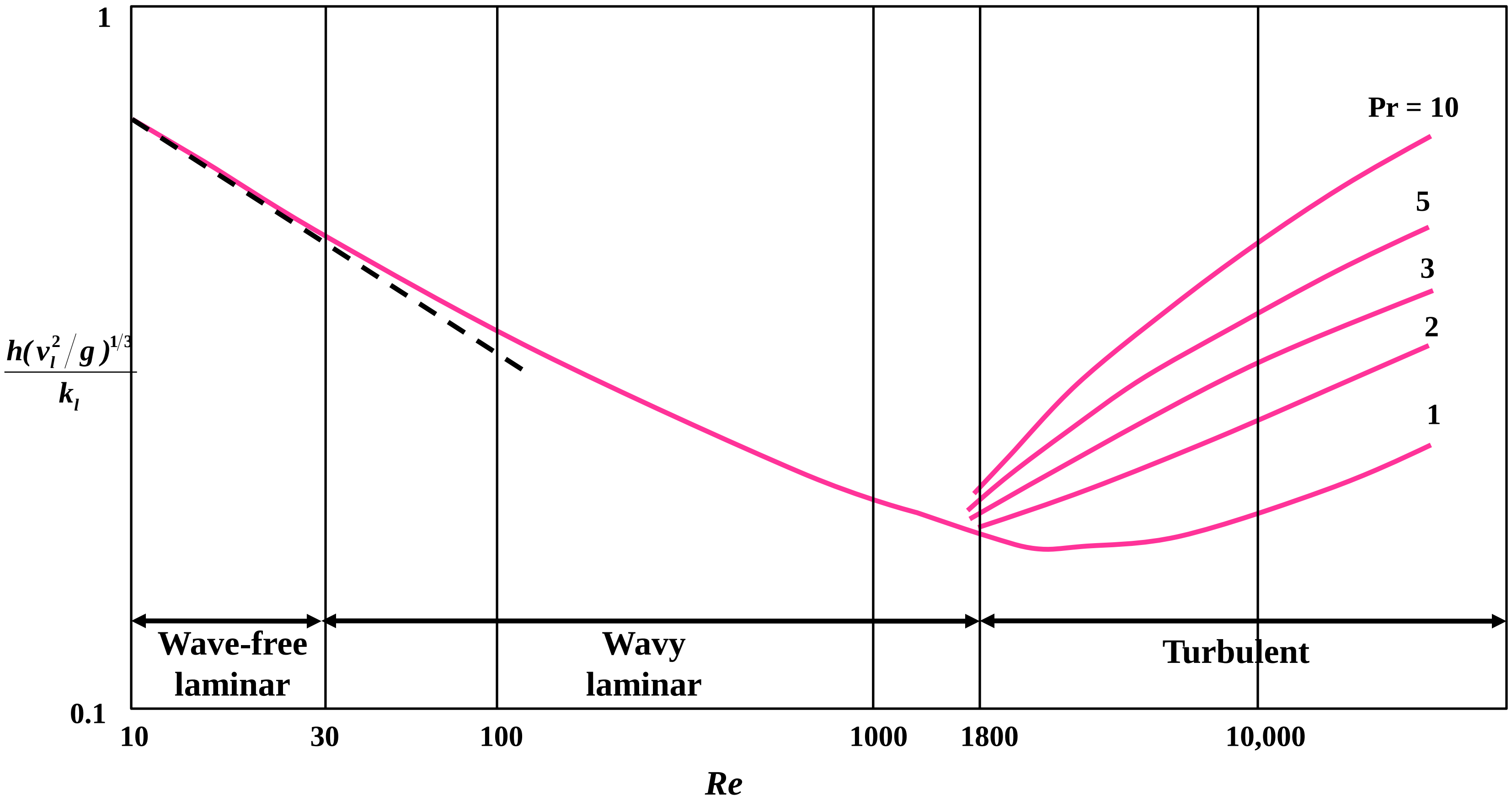
Film condensation on an inclined Plates

$$h_{inclined} = h_{vert}\cos\theta$$



$$\frac{\bar{h}_L}{k_l}\left(\frac{\nu_l^2}{g}\right)^{\frac{1}{3}} = \left(Re_L^{-0.44} + \left(5.82\times 10^{-6}\right)Re_L^{0.88}\,Pr_L^{\frac{1}{3}}\right)^{\frac{1}{2}}$$

Non-dimensionalised heat transfer coefficients for the wave-free laminar and turbulent flow of condensate on vertical plates



Problem: Saturated steam at atmospheric pressure condenses on a 2 m high and 3 m wide vertical plate that is maintained at 80°C by circulating cooling water through the other side. Determine (a) the rate of heat transfer by condensation to the plate (b) the rate at which the condensate drips off the plate at the bottom

Solution: saturated steam at 1 atm condenses on a vertical plate. The rats of heat transfer and condensation are to be determined

Assumptions: 1. steady operating conditions exist 2. The plate is isothermal. 3. The condensate flow is wavy laminar over the entire plate (will be verified). 4. The density of vapour is much smaller than the density of the liquid $\rho_v \ll \rho_l$

Properties: The properties of water at the saturation temperature of 100°C are h_{fg} = 2257 10^3 J/g and ρ_v = 0.6 kg/m³. The properties of liquid water at the film temperature 90°C are

$$T_f = \frac{T_{sat} + T_w}{2} = \frac{100 + 80}{2} = 90$$

$$\rho_l = 965.3\ kg/m^3$$

$$\mu_l = 0.315 \times 10^{-3}\ Pa.s$$

$$\nu_l = \frac{\mu_l}{\rho_l} = 0.326 \times 10^{-6}\ m^2/s$$

$$C_{pl} = 4206\ J/kg.K$$

$$k_l = 0.675\ W/m.K$$

$$Pr = 1.9628$$

$$h'_{fg} = h_{fg} + 0.68 C_{p,L}\left(T_{sat} - T_w\right)$$

$$h'_{fg} = 2257 \times 10^3 + 0.68 \times 4206 \times (100 - 80)$$

$$h'_{fg} = 2314 \times 10^3\ J/kg$$

$$\bar{h}_L = 0.943\left(\frac{g\rho_L(\rho_L-\rho_v)h_{fg}k_l^3}{4\mu_L(T_{sat}-T_w)L}\right)^{\frac{1}{4}} = 0.943\left(\frac{9.81\times 965.3\times(965.3)(2314\times 1000)0.675^3}{4\times 0.315\times 10^{-3}(100-80)4}\right)^{\frac{1}{4}}$$

$$\bar{h}_L = 2656.2\frac{W}{m^2K}$$

$$\dot{Q} = \bar{h}_L A_s(T_{sat}-T_w) = 2562.2\times 2\times 3\times(100-80) = 307464\ W$$

$$\dot{Q} = \dot{m}h_{sf} \Rightarrow 307464 = \dot{m}\times 2314\times 10^3 \Rightarrow \dot{m} = 0.1329\ kg/s$$

$$Re = \frac{4\Gamma}{\mu_L} = \frac{4}{\mu_L}\left(\frac{\dot{m}}{b}\right) = \frac{4}{0.315\times 10^{-3}}\left(\frac{0.1329}{3}\right) = 562.5$$

$$\frac{\bar{h}_L}{k_l}\left(\frac{\nu_l^2}{g}\right)^{\frac{1}{3}} = \left(Re_L^{-0.44} + \left(5.82\times10^{-6}\right)Re_L^{0.88}\,Pr_L^{\frac{1}{3}}\right)^{\frac{1}{2}}$$

$$\frac{\bar{h}_L}{0.675}\left(\frac{\left(0.326\times10^{-6}\right)^2}{9.81}\right)^{\frac{1}{3}} = \left(562.5^{-0.44} + \left(5.82\times10^{-6}\right)\times562.5^{0.88}\times1.9628^{\frac{1}{3}}\right)^{\frac{1}{2}}$$

$$\bar{h}_L = 7691.4\frac{W}{m^2K}$$

$$\dot{Q} = \bar{h}_L A_s\left(T_{sat} - T_w\right) = 7691.4\times2\times3\times\left(100-80\right) = 2307420\ W$$

$$\dot{Q} = \dot{m}h_{sf} \Rightarrow 2307420 = \dot{m}\times2314\times10^3 \Rightarrow \dot{m} = 0.9972\ kg/s$$

$$Re = \frac{4\Gamma}{\mu_L} = \frac{4}{\mu_L}\left(\frac{\dot{m}}{b}\right) = \frac{4}{0.315\times10^{-3}}\left(\frac{0.9972}{3}\right) = 4221$$

This confirms that condensation is in turbulent region

Comments: This Reynolds number confirms that condensation is in Wavy laminar domain

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