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Condensation (Chapter 13)

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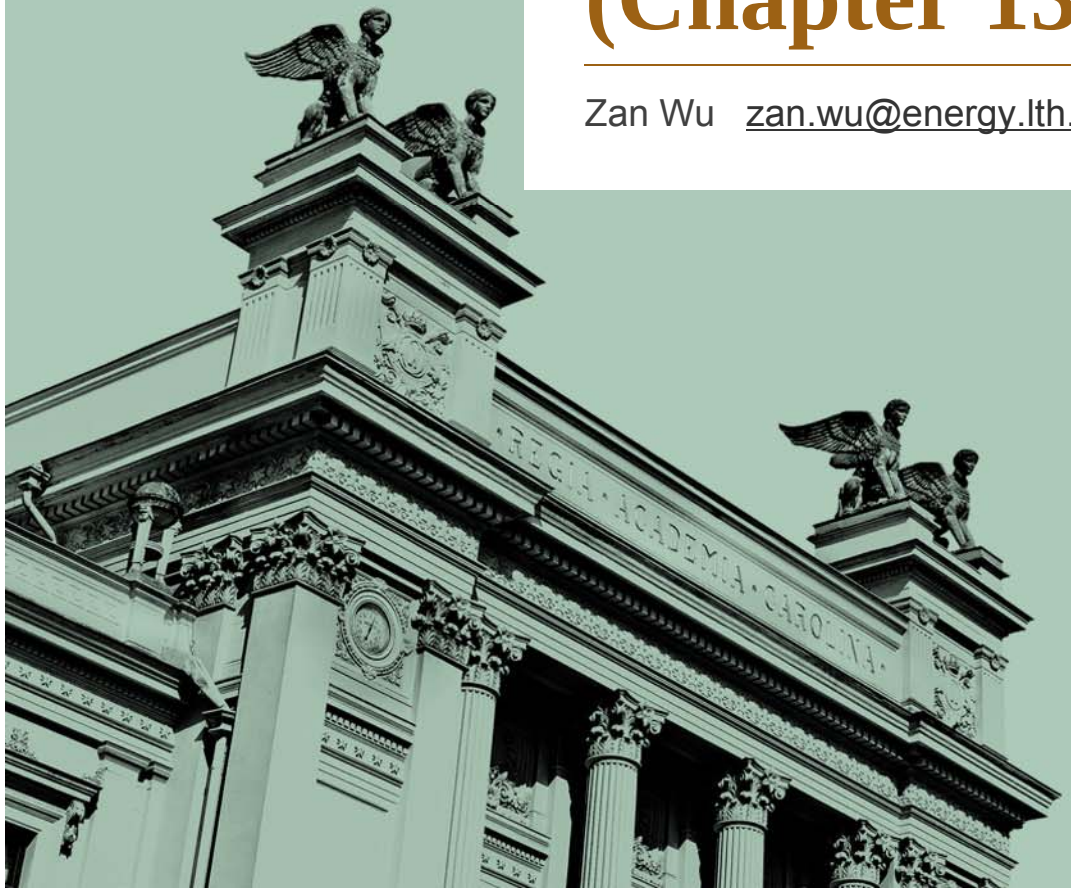
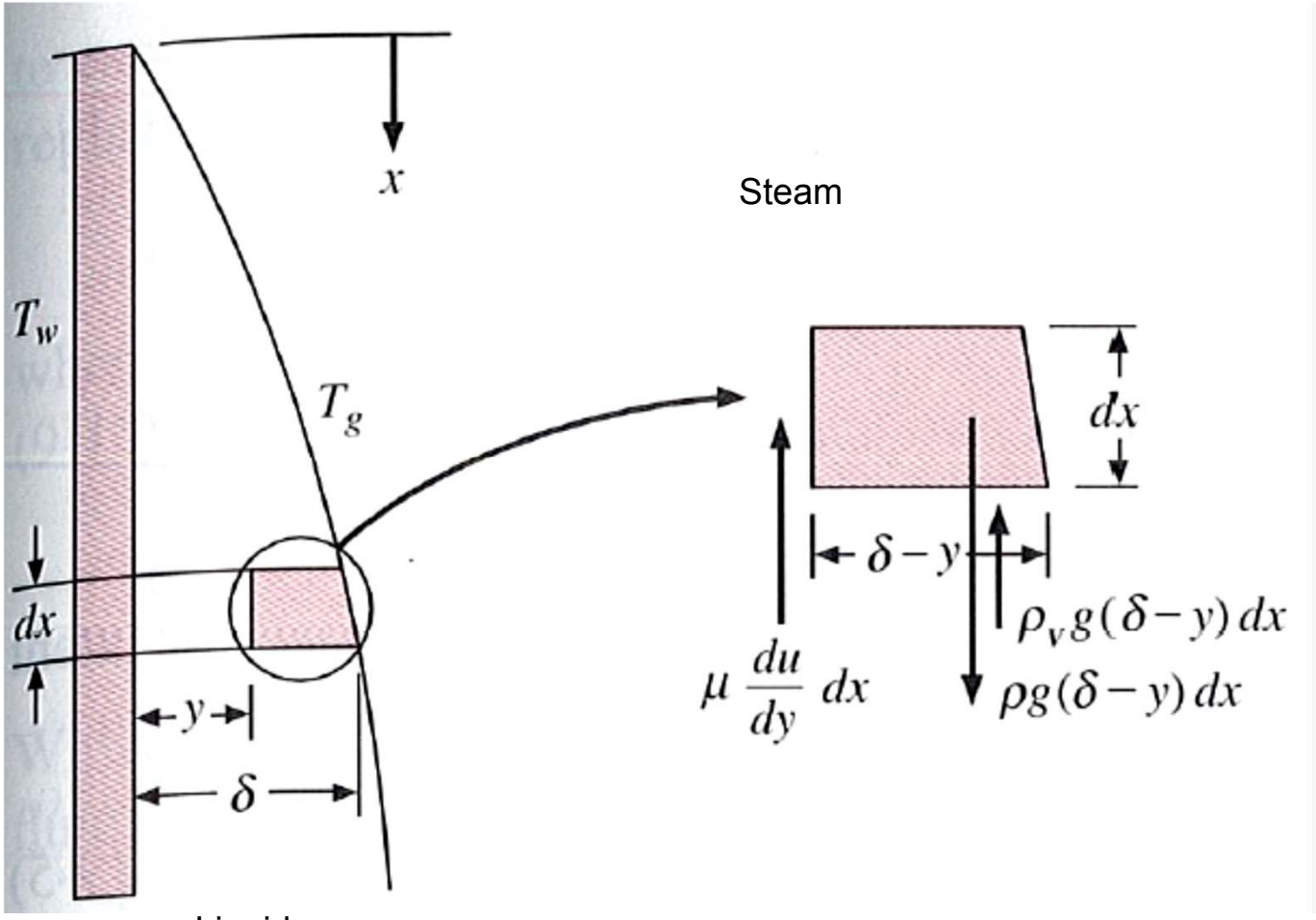


Film condensation along a vertical wall



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Condensation - Nusselt's film theory; assumptions

- Neglected convective transport in both the liquid and vapor layers
- Pure heat conduction through the film
- Constant temperature in the vapor layer
- Laminar condensate flow
- Fluid properties are constant

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Condensation – force balance

$$\rho_f g(\delta_f - y)dx = \mu_f \frac{du_f}{dy}dx + \rho_v g(\delta_f - y)dx$$

weight of the liquid element	viscous shear at y	buoyancy force due to displaced vapor

Integrating and using the B.C. $u_f = 0$ at $y = 0$

$$u_f = \frac{(\rho_f - \rho_v)g}{\mu_f}\left(\delta_f y - \frac{1}{2}y^2\right)$$

Velocity profile in the liquid film, largest at $y = \delta_f$

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Nusselt's film theory

The mass flow of condensate per unit width through any x position of the film:

$$\text{Mass flow per unit width} = \dot{m} = \int_0^{\delta_f} \rho_f u_f dy = \frac{\rho_f (\rho_f - \rho_v) g \delta_f^3}{3\mu}$$

The heat transfer at the wall per unit width in the area *dx* is:

i.e., Heat balance for an element *dx*

$$Q = -\lambda_f \left.\frac{\partial t}{\partial y}\right|_{y=0} dx = \lambda_f \frac{t_s - t_w}{\delta_f} dx = h_{fg} d\dot{m}$$

$$d\dot{m} = d\left[\frac{\rho_f (\rho_f - \rho_v) g \delta_f^3}{3\mu}\right] = \frac{d}{d\delta_f}\left[\frac{\rho_f (\rho_f - \rho_v) g \delta_f^3}{3\mu}\right] d\delta_f = \frac{\rho_f (\rho_f - \rho_v) g \delta_f^2}{\mu} d\delta_f$$

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Nusselt's film theory

$$\lambda_f \frac{t_s - t_w}{\delta_f} dx = h_{fg} \frac{\rho_f (\rho_f - \rho_v) g \delta_f^2}{\mu} d\delta_f$$

Integrating and using the B.C. $\delta_f = 0$ at $x = 0$

$$\delta_f = \left(\frac{4\mu_f \lambda_f (t_s - t_w) x}{h_{fg} g \rho_f^2} \right)^{1/4}$$

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Nusselt's film theory

$$\alpha = \frac{\lambda_f}{\delta_f}$$

$$\alpha = \left(\frac{h_{fg} g \rho_f^2 \lambda_f^3}{4 \mu_f (t_s - t_w) x} \right)^{1/4}$$

$$\bar{\alpha} = \frac{1}{L} \int_0^L \alpha \, dx = \frac{4}{3} \alpha_{x=L}$$

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Nusselt's film theory cont.

$$\overline{\alpha} = 0.943\left(\frac{h_{fg} g \rho_f^2 \lambda_f^3}{\mu_f (t_s - t_w) L}\right)^{1/4} \qquad \textbf{(13-16)}$$

$$\mathrm{Re}_{\delta_f} = \frac{u_m \delta_f}{\nu_f} = \frac{\rho_f u_m \delta_f}{\mu_f} = \frac{\dot{m}}{\mu_f}$$

$$\mathrm{Re}_{\delta_f} = \frac{1}{3}\frac{\rho_f^2 g}{\mu_f^2}\left(\frac{4\mu_f \lambda_f (t_s - t_w) x}{h_{fg} g \rho_f^2}\right)^{3/4} = 0.943\left(\frac{\rho_f^{2/3} g^{1/3} \lambda_f (t_s - t_w) x}{h_{fg} \mu_f^{5/3}}\right)^{3/4}$$

Nusselt's film theory valid to $\mathrm{Re}_{\delta_f} \sim 6$

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Condensation - empirical correlations

$$\overline{\alpha}_L = \frac{\lambda_f}{(\nu_f^2/g)^{1/3}}\left(1.47\,\mathrm{Re}_{\delta_f}^{0.22} - \frac{1.3}{\mathrm{Re}_{\delta_f}}\right)^{-1} \qquad 6 < \mathrm{Re}_{\delta_f} \le 450$$

Turbulent flow

$$\overline{\alpha}_L = \frac{\lambda_f}{(\nu_f^2/g)^{1/3}} \frac{\mathrm{Re}_{\delta_f}}{(2188 + 41(\mathrm{Re}_{\delta_f}^{0.75} - 89.5)/\mathrm{Pr}_f^{0.5})} \qquad \mathrm{Re}_{\delta_f} > 450$$

$$\overline{\alpha} = 0.0077\,\mathrm{Re}'^{0.4}_{\delta_f}\left(\frac{\lambda_f^3 \rho_f^2 g}{\mu_f^2}\right)^{1/3}$$

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Condensation – alternate Reynolds number

$$\mathrm{Re}'_{\delta_f} = \frac{4\dot{m}_{tot}}{\mu_f \mathrm{P}}$$

$$\mathrm{P} = \begin{cases} b & \text{width for a vertical plate} \\ \pi D & \text{for a vertical pipe} \end{cases}$$

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Condensation – improvements of Nusselt's film theory

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

$$\mathrm{Ja} = \frac{c_{\mathrm{p_f}}(t_{\mathrm{s}} - t_{\mathrm{w}})}{h_{\mathrm{fg}}}$$

due to subcooling of the liquid layer

The constant 0.943 is replaced by 1.13

$$\overline{\alpha} = 1.13\left(\frac{h'_{\mathrm{fg}} g \rho_{\mathrm{f}}^2 \lambda_{\mathrm{f}}^3}{\mu_{\mathrm{f}}(t_{\mathrm{s}} - t_{\mathrm{w}})L}\right)^{1/4} \qquad \mathrm{Re}_{\delta_{\mathrm{f}}} < 450$$

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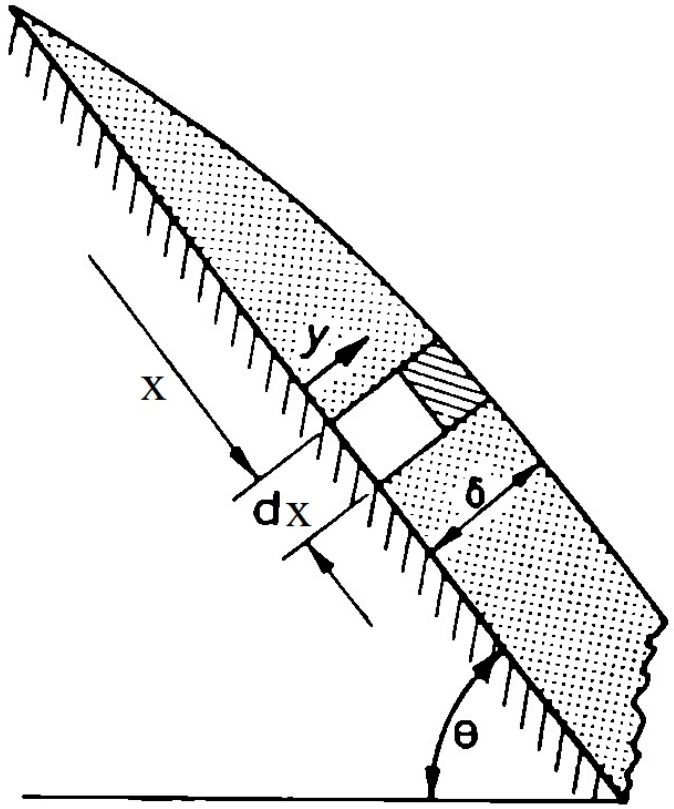
Condensation – Inclined plate



$$g' = g \sin\theta$$

Applicable range for finite plate?

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Reference temperature for physical properties

- Liquid properties: $(t_s+t_w)/2$
- Vapor properties: t_s
- Latent heat of vaporization: t_s

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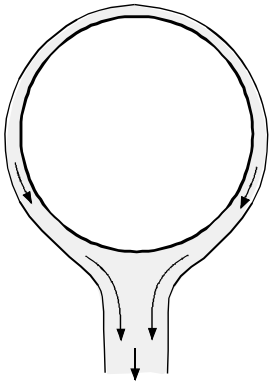
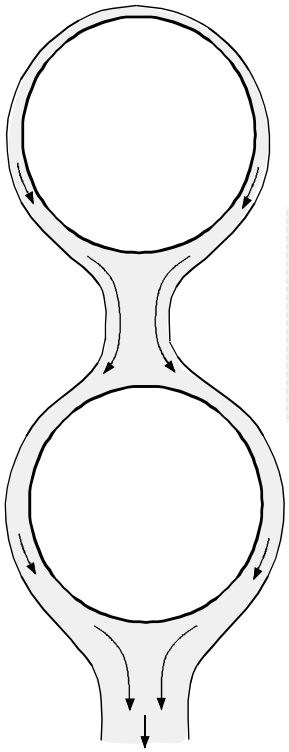
Film condensation along a vertical tube?

Condensation on the outer surface of tubes (pipes)



(a)



(b)

$$\overline{\alpha} = 0.728\left(\frac{h'_{fg} g \rho_f^2 \lambda_f^3}{\mu_f (t_s - t_w) D}\right)^{1/4}$$

$$\overline{\alpha} = 0.728\left(\frac{h'_{fg} g \rho_f^2 \lambda_f^3}{N \mu_f (t_s - t_w) D}\right)^{1/4}$$

$$t_{ref} = \frac{t_s + t_w}{2}$$

$$\rho_f (\rho_f - \rho_v) \approx \rho_f^2$$

Latent heat of vaporization evaluated at t_s

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Condensation inside tubes (pipes)

low flow velocities

$$\mathrm{Re}_{\mathrm{v,i}} = \left(\frac{\rho_{\mathrm{v}} u_{\mathrm{m_v}} D}{\mu_{\mathrm{v}}} \right)_{\mathrm{i}} < 35 \times 10^3$$

$$\bar{\alpha}_D = 0.555 \left(\frac{h'_{\mathrm{fg}} g \rho_{\mathrm{f}} (\rho_{\mathrm{f}} - \rho_{\mathrm{v}}) \lambda_{\mathrm{f}}^3}{\mu_{\mathrm{f}} (t_{\mathrm{s}} - t_{\mathrm{w}}) D} \right)^{1/4}$$

If t_w is unkown?

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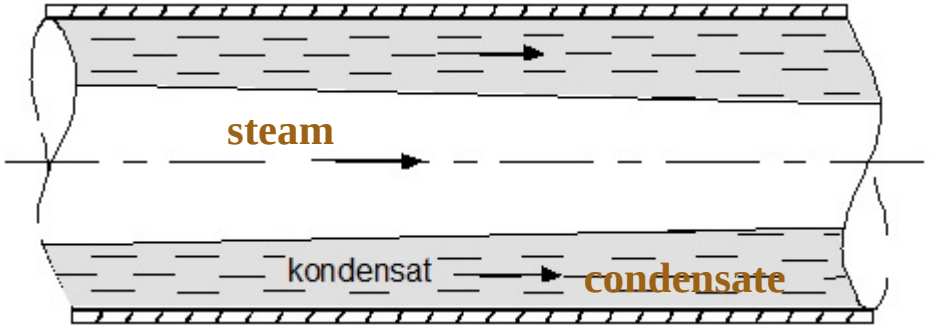
Condensation-inside horizontal tubes (pipes)



high flow velocities

$$\overline{\mathrm{Nu}} = \frac{\bar{\alpha} D}{\lambda_\mathrm{f}} = 0.026\,\mathrm{Pr}_\mathrm{f}^{1/3}\left(\frac{D}{\mu_\mathrm{f}}\left(G_v\left(\rho_\mathrm{f}/\rho_\mathrm{v}\right)^{1/2} + G_\mathrm{f}\right)\right)^{0.8}$$

$$G_v = \dot{m}_v / A \qquad G_\mathrm{f} = \dot{m}_\mathrm{f} / A$$

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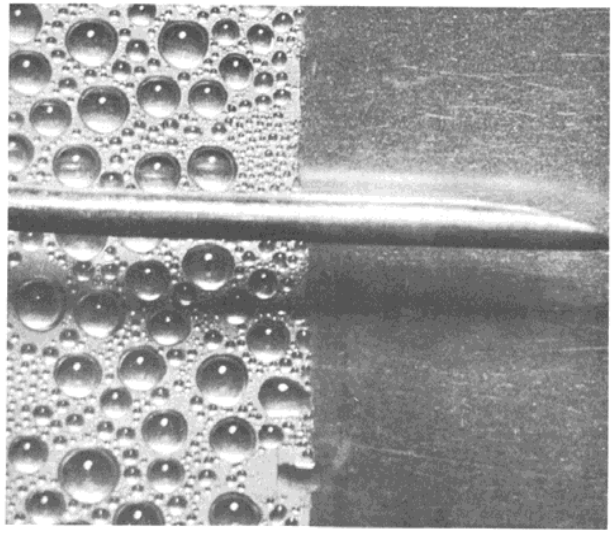
Dropwise condensation



The mechanism is still a mystery.
Significant progress recently

By adding chemicals to the vapor
Treat the surface with appropriate chemicals
Apply a teflon layer on the surface
Apply a thin layer of gold or any other noble metal on the surface (controversy?)

Disadvantages?

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Non-condensable gases

- **Non-condensable gas presents an additional thermal resistance which reduces the heat transfer coefficient**

- **As vapor condenses, the noncondensable gases are accumulated at the surface and the vapor has to diffuse across the vapor-gas mixture**

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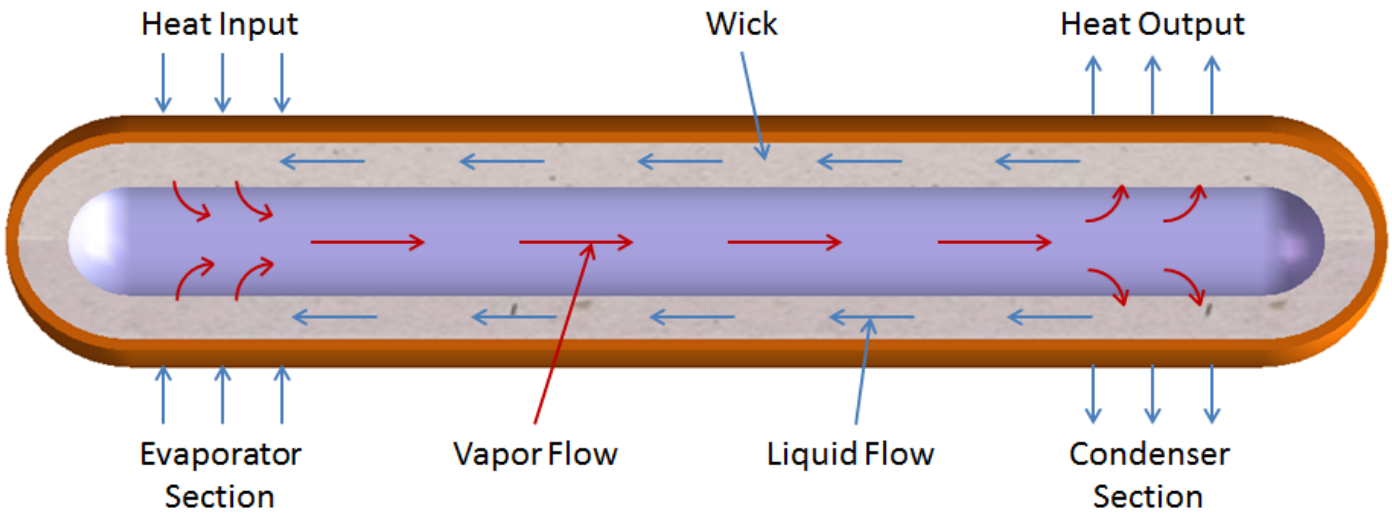
Heat pipe



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