

# Generadores de vapor

Balances y ecuaciones de transferencia en superficies

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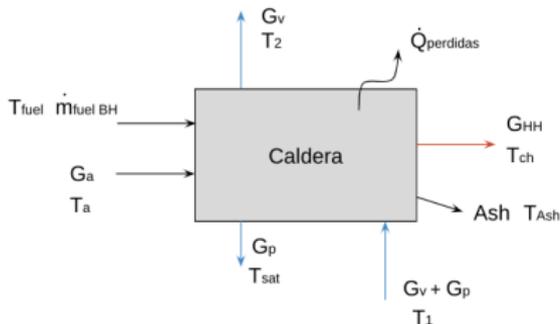
2024

# Balance general

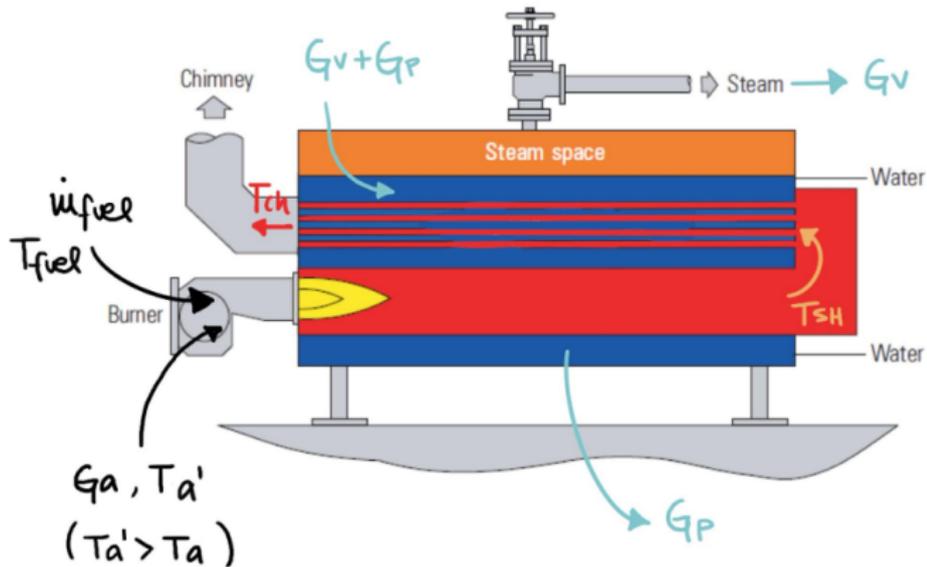
Balance de energía a toda la caldera modelándola como una "caja negra"

**Balance General** (combustible en base total)

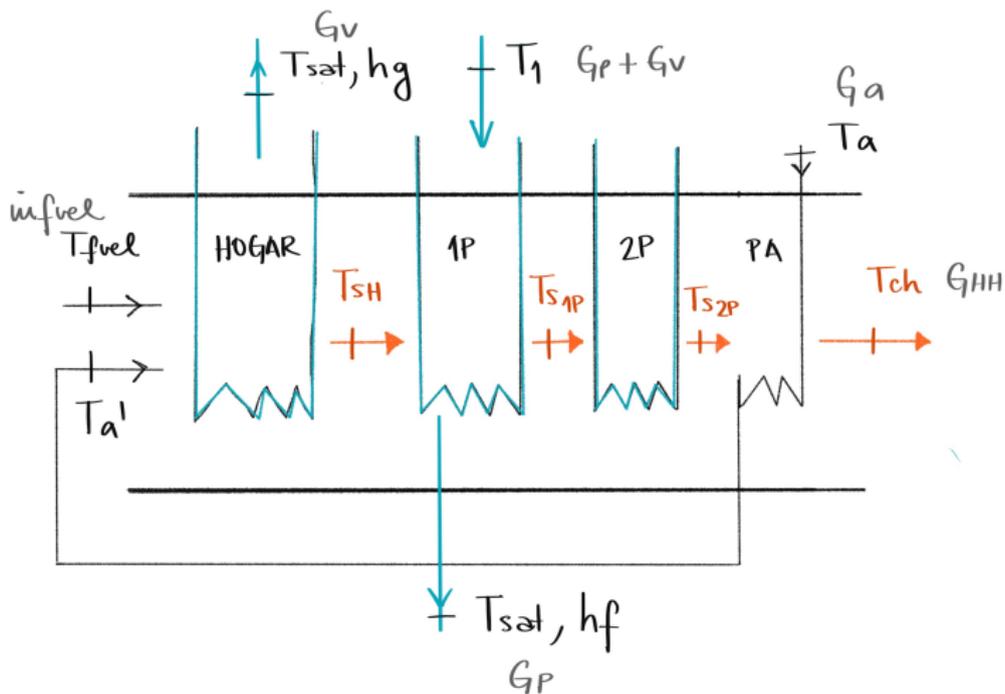
$$\begin{aligned}
 Q_p^s - Q_{perdidas} = & G_v \cdot (h_2 - h_1) + G_{H_2O} \cdot [h_{H_2O}(T_{ch}) - h_{H_2O}(T_o)] + 9H \cdot h_{fg}(T_o) + \\
 & + (H_2O)_{fuel} \cdot [h_{fg}(T_o) + c_{p_{vapor}} \cdot (T_{ch} - T_o) - c_{p_{liq}} \cdot (T_{fuel} - T_o)] + \\
 & - [1 - (H_2O)_{fuel}] \cdot c_{p_{fuel}} \cdot (T_f - T_o) - G_{as} \cdot c_{p_a} \cdot (T_a - T_o) + \\
 & + G_{as} \cdot w_{as} \cdot c_{p_{vapor}} \cdot (T_{ch} - T_a) + G_{purga} \cdot (h_{liq.sat} - h_1) + \\
 & + Ash \cdot c_{p_{ash}} \cdot (T_{ash} - T_o) + H_{qC'}^* + H_{qCO}^*
 \end{aligned}$$



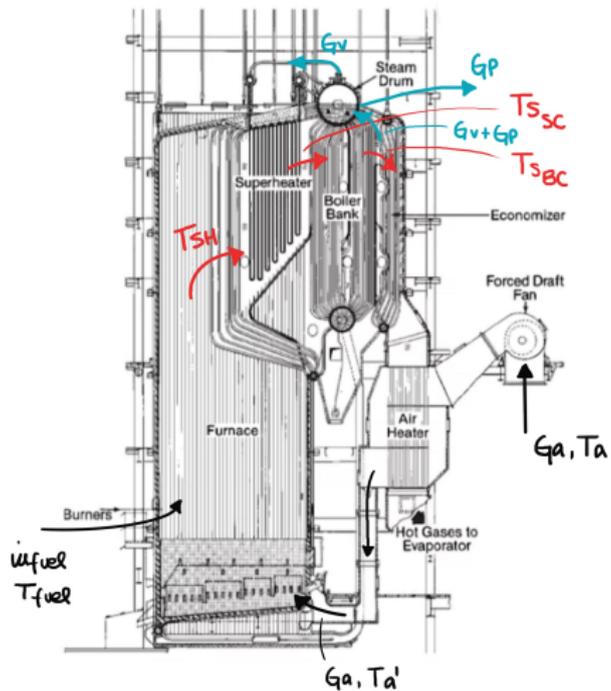
## Humotubular



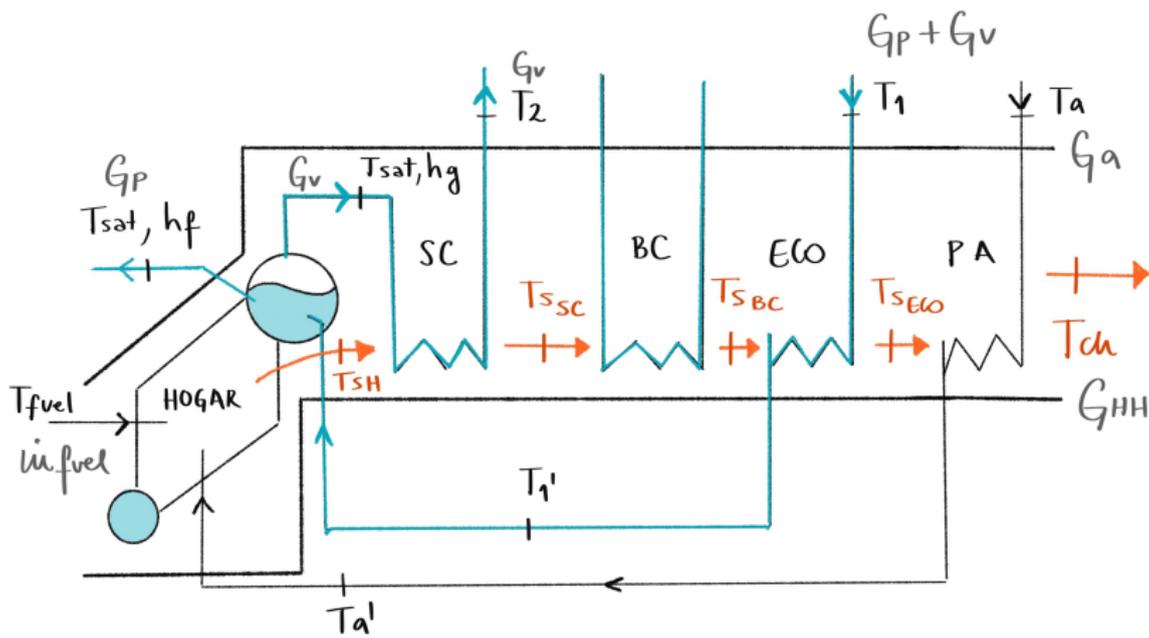
## Diagrama horizontal: Humotubular



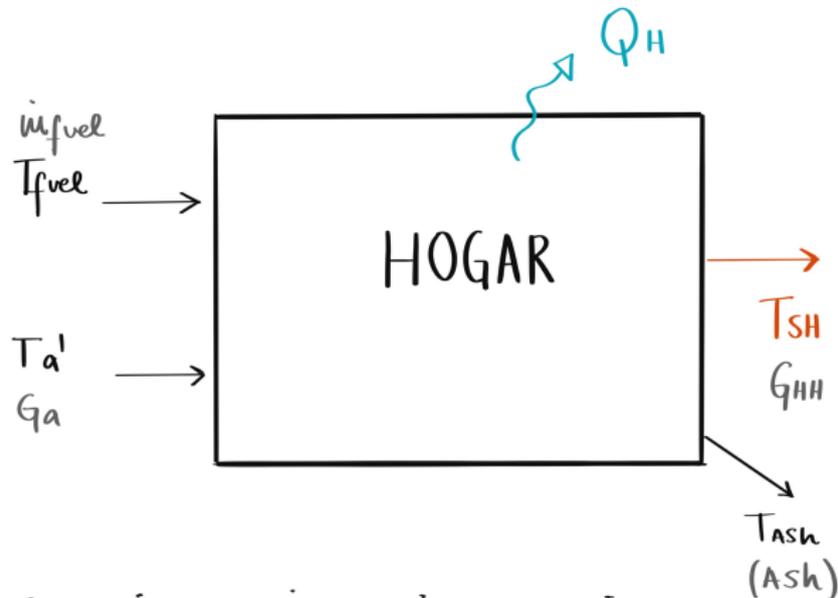
## Acuotubular



## Diagrama horizontal: Acuotubular



# Hogar: modelado como "caja negra"



- $\dot{m}_{fuel,BH} + \dot{m}_{aire} = \dot{m}_{H_2O} + \dot{m}_{H_2O,fuel} + \dot{m}_{ash}$
- $1 + G_a = G_{HH} + (H_2O)_{fuel} + (Ash)$

# Hogar

## ① BALANCE DE ENERGÍA : HOGAR

↳ DEL LADO DE HUMOS

$$* h = h_g + h_s + h_l \rightarrow \dot{m}_f \cdot h_f + \dot{m}_{\text{aire}} \cdot h_a = \dot{Q}_H + \dot{m}_{H_2O} \cdot h_{H_2O} + \dot{m}_{H_2O, f} \cdot h_{H_2O, f} + \dot{m}_{\text{ash}} \cdot h_{\text{ash}}$$

Referencia (ORIGEN) -o H<sub>2</sub>O liq. y T<sub>0</sub>

$$\begin{aligned} \dot{Q}_P^S &= \dot{Q}_H + \dot{C}_{H_2O} \cdot [h_{H_2O}(T_{SH}) - h_{H_2O}(T_0)] + \dot{q} \cdot H \cdot h_{fg} \cdot c_{T_0} \\ &+ (\dot{H}_2O)_{\text{fuel}} \cdot [h_{fg} \cdot c_{T_0} + \dot{C}_v \cdot (T_{SH} - T_0) - \dot{C}_p \cdot \text{liq} \cdot (T_f - T_0)] \\ &- [1 - (\dot{H}_2O)_f] \cdot \dot{C}_p \cdot \text{fuel} \cdot (T_f - T_0) - \dot{C}_a \cdot \dot{C}_{\text{aire}} \cdot (\underline{T_a'} - T_0) \\ &+ \dot{C}_a \cdot \dot{w}_a \cdot \dot{C}_v \cdot (T_{SH} - \underline{T_a'}) \\ &+ (\dot{A}sh) \cdot \dot{C}_{\text{Ash}} \cdot (T_{\text{Ash}} - T_0) + \dot{H}_g \cdot c' + \dot{H}_g \cdot \omega^* \end{aligned}$$

## Hogar

## ② TRANSFERENCIA DE CALOR : HOGAR

Principalmente RADIACIÓN

$$\dot{Q}_H = F_H \epsilon_p \epsilon_{ll} \sigma \cdot (T_g^4 - T_p^4)$$

AL AGUA

$$\hookrightarrow \text{Fuel en masa : } \dot{Q}_H = \dot{Q}_H / \dot{m}_f$$

$$\hookrightarrow \text{" en volumen : } \dot{Q}_H = \dot{Q}_H / \dot{V}_f$$

$$\sigma = 5,67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4} \approx 4,9 \times 10^{-8} \frac{\text{kcal}}{\text{h m}^2 \text{K}^4}$$

$$\rightarrow F_H = A_H \cdot \epsilon_H$$

$$\rightarrow \epsilon_p \text{ entre } 0,8 \text{ y } 0,9$$

$$\rightarrow \epsilon_{ll} \text{ entre } 0,4 \text{ y } 0,6$$

$$\rightarrow T_p \approx T_{\text{sat}} + 20^\circ\text{C}$$

$$\rightarrow T_g = \frac{T_{\text{SH}} + T_{\text{ad}}}{2}$$

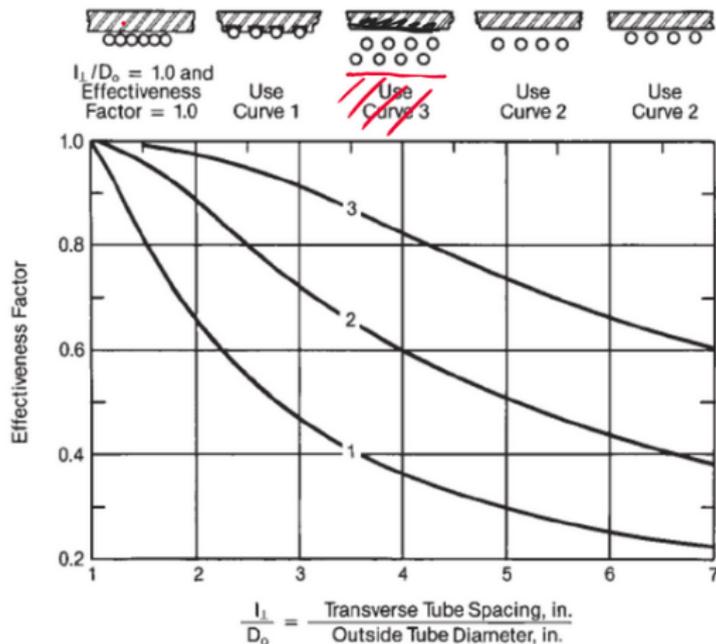
$$\text{con } [A_H] = \text{m}^2, [T] = \text{K}, [\dot{Q}_H] = \frac{\text{kcal}}{\text{h}} \text{ y } [\dot{m}_f] = \frac{\text{kg}}{\text{h}} \quad ([\dot{V}_f] = \frac{\text{kmol}}{\text{h}})$$

$$\dot{Q}_H = \frac{4,9 F_H \epsilon_p \epsilon_{ll}}{\dot{m}_f} \left[ \left( \frac{T_g}{100} \right)^4 - \left( \frac{T_p}{100} \right)^4 \right]$$

# Hogar

- $\varepsilon_p$ : emisividad de pared
- $T_p$ : temperatura de la pared del hogar
- $\varepsilon_{fl}$ : emisividad de llama
- $F_H = A_H \varepsilon_H$ : área del hogar corregida por el factor de vista (factor de Hottel,  $\varepsilon_H$ )
  - En calderas AT con paredes de tubos separados  $\varepsilon_H < 1$  (tabulado)
  - En los demás casos  $F_H = A_H$  ( $\varepsilon_H = 1$ )
- $T_g$ : Temperatura del hogar (llama y humos). Asumimos  $T_g = \frac{T_{SH} + T_{ad}}{2}$ 
  - $T_{ad}$ : temperatura de llamada adiabática. Se obtiene a partir del balance al hogar considerando  $Q_H = 0$  (todo el calor va a los humos)

# Hogar: factor de Hottel



**Fig. 33** Furnace wall area effectiveness factor (1.0 for completely water-cooled surface). A reduced area (equivalent cold surface) is determined from these curves for walls not completely water cooled. (Adapted from Hottel<sup>4</sup>.)

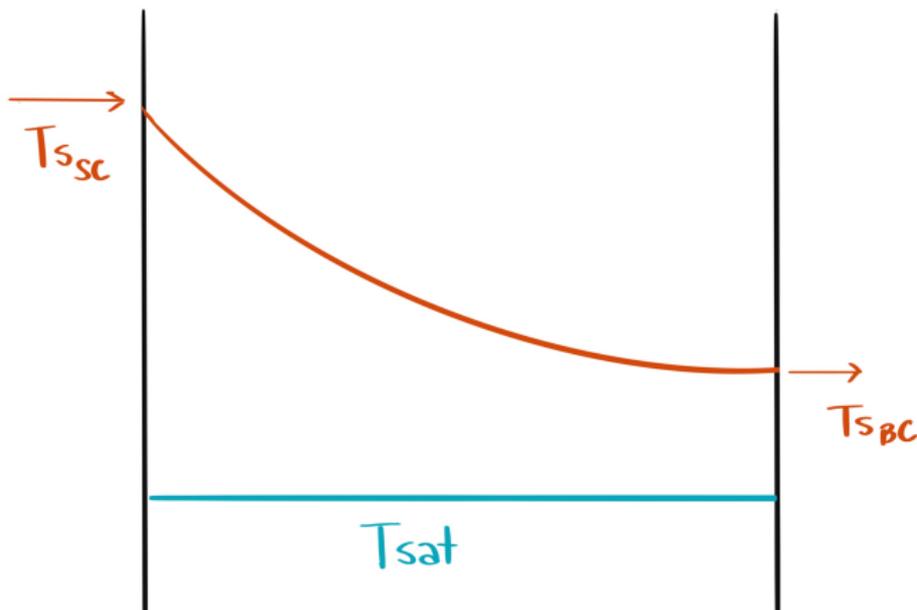
# Hogar: calor liberado por unidad de volumen

## Definición: $q_v$

Calor liberado por unidad de volumen del hogar,  $q_v = \frac{Q_p^S \dot{m}_{fuel}}{Vol_H}$

- Combustibles gaseosos:  $q_v \approx 350 \text{ kW/m}^3$
- Combustibles líquidos:  $q_v \approx 250 \text{ kW/m}^3$
- Combustibles sólidos:  $q_v \approx 110 \text{ kW/m}^3$

# Banco de convección: calderas AT



- $T_p \cong T_{sat} + 10^\circ\text{C}$

## Banco de convección: calderas AT

## ① BALANCE DE ENERGÍA: BANCO DE CONVECCIÓN

↳ DEL LADO DE HUMOS

$$\left( \dot{m}_{HH} \cdot h_{HH} + \dot{m}_a \cdot W_a \cdot h_{H_2O, aire} \right) \Big|_{s_{SC}} = \dot{Q}_{BC} + \left( \dot{m}_{HH} \cdot h_{HH} + \dot{m}_a \cdot W_a \cdot h_{H_2O, aire} \right) \Big|_{s_{BC}}$$

Referencia (ORIGEN) -> H<sub>2</sub>O liq. y T<sub>0</sub>

$$\begin{aligned} \dot{Q}_{BC} = & G_{HH} \cdot [h_{HH}(T_{SC}) - h_{HH}(T_0)] + q \cdot H \cdot h_{fg} e_{T_0} + (H_2O)_{fuel} \cdot [h_{fg} e_{T_0} + C_{pv} \cdot (T_{SC} - T_0)] \\ & + G_a \cdot W_a \cdot C_{pv} \cdot (T_{SC} - T_0) \\ - & \left\{ G_{HH} \cdot [h_{HH}(T_{BC}) - h_{HH}(T_0)] + q \cdot H \cdot h_{fg} e_{T_0} + (H_2O)_f \cdot [h_{fg} e_{T_0} + C_{pv} \cdot (T_{BC} - T_0)] \right. \\ & \left. + G_a \cdot W_a \cdot C_{pv} \cdot (T_{BC} - T_0) \right\} \end{aligned}$$

$$\dot{Q}_{BC} = G_{HH} \cdot [h_{HH}(T_{SC}) - h_{HH}(T_{BC})] + [C_{pv} \cdot ((H_2O)_f + G_a W_a) \cdot (T_{SC} - T_{BC})]$$

\* válido para comb. incompleta (entra H<sub>2</sub>O\* y sale H<sub>2</sub>O\*)

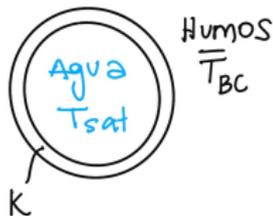
## Banco de convección: calderas AT

## ② TRANSFERENCIA DE CALOR : BANCO DE CONVECCIÓN

Agua en cambio de estado (Tete)  $\rightarrow C_{\text{agua}} \approx \infty \rightarrow \underline{C_r = 0}$

$$C_r = 0 \rightarrow \boxed{\varepsilon = 1 - e^{-NTU}}$$

con  $NTU = \frac{UA}{C_{\min}} = \frac{UA}{C_{\text{humos}}}$



$$R_{\text{TOT}} = \frac{1}{UA} = \frac{1}{\underbrace{h_{\text{ag}} A_{\text{int}}}_{\sim \infty}} + \frac{\ln\left(\frac{r_{\text{ext}}}{r_{\text{int}}}\right)}{\underbrace{2\pi K L}_{\text{despreciable}}} + \frac{1}{h_{\text{H}} A_{\text{ext}}}$$

$$\rightarrow U = h_{\text{H}} = (h_{\text{conv}} + h_{\text{rad}})_{\text{humos}}$$

$$\dot{Q}_{\text{BC}} = \varepsilon \cdot \dot{Q}_{\text{max}}$$

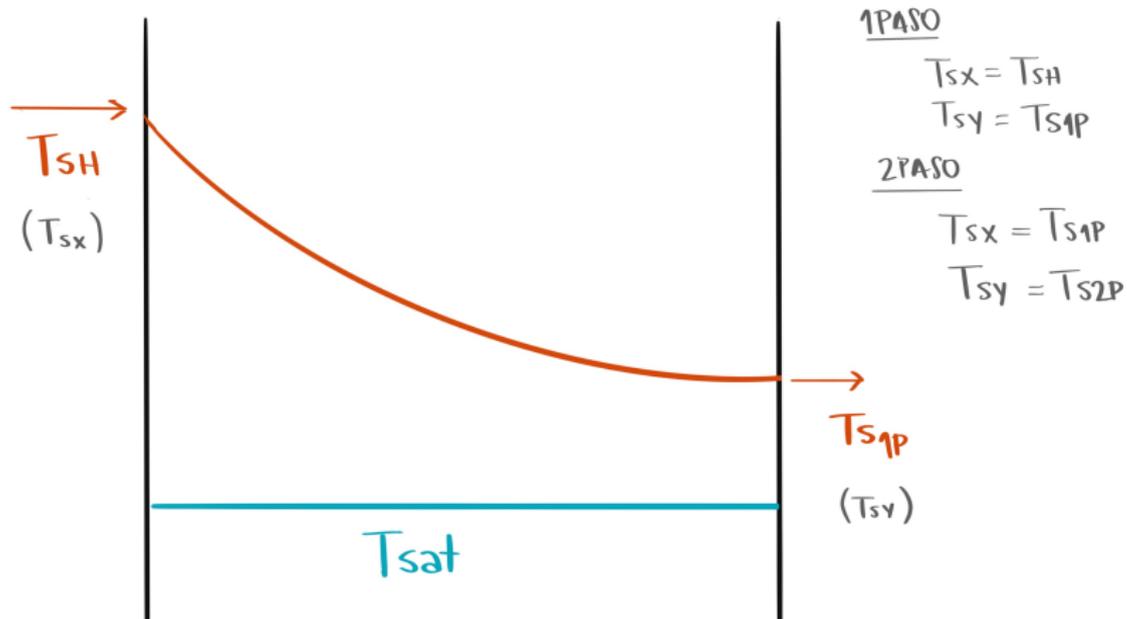
$$C_{\text{humos}} = \frac{\Delta h_{\text{humos}} \cdot \dot{m}_{\text{humos}}}{\Delta T_{\text{humos}}}$$

$$w_{\text{a}} = (\text{H}_2\text{O})_{\text{f}} = 0,$$

$$\Delta h_{\text{humos}} = \Delta h_{\text{HGH}} \quad \uparrow$$

$$\dot{Q}_{\text{BC}} = \varepsilon C_{\text{humos}} \cdot (T_{\text{SSC}} - T_{\text{sat}})$$

## Pasos de tubos: calderas HT



- $T_p \cong T_{sat} + 10^\circ\text{C}$

## Pasos de tubos: calderas HT

## ① BALANCE DE ENERGÍA: 1er PASO DE TUBOS

↳ DEL LADO DE HUMOS

$$\left( \dot{m}_{HH} \cdot h_{HH} + \dot{m}_a \cdot W_a \cdot h_{H_2O, aire} \right) \Big|_{SH} = \dot{Q}_{1P} + \left( \dot{m}_{HH} \cdot h_{HH} + \dot{m}_a \cdot W_a \cdot h_{H_2O, aire} \right) \Big|_{S1P}$$

Referencia (ORIGEN) -> H<sub>2</sub>O liq. y T<sub>0</sub>

$$\begin{aligned} \dot{Q}_{1P} = & G_{H_2O} \cdot [h_{H_2O}(T_{SH}) - h_{H_2O}(T_0)] + q \cdot H \cdot h_{fg} e_{T_0} + (H_2O)_{fuel} \cdot [h_{fg} e_{T_0} + G_v \cdot (T_{SH} - T_0)] \\ & + G_a \cdot W_a \cdot C_{pv} \cdot (T_{SH} - T_0) \\ - & \left\{ G_{H_2O} \cdot [h_{H_2O}(T_{S1P}) - h_{H_2O}(T_0)] + q H h_{fg} e_{T_0} + (H_2O)_f \cdot [h_{fg} e_{T_0} + G_v (T_{S1P} - T_0)] \right. \\ & \left. + G_a W_a \cdot C_{pv} (T_{S1P} - T_0) \right\} \end{aligned}$$

$$\dot{Q}_{1P} = G_{H_2O} \cdot [h_{H_2O}(T_{SH}) - h_{H_2O}(T_{S1P})] + [(H_2O)_f + G_a W_a] \cdot G_v (T_{SH} - T_{S1P})$$

$$\underline{2DO PASO} : \dot{Q}_{2P} = G_{H_2O} \cdot [h_{H_2O}(T_{S1P}) - h_{H_2O}(T_{S2P})] + [G_v \cdot ((H_2O)_f + G_a W_a)] (T_{S1P} - T_{S2P})$$

## Pasos de tubos: calderas HT

② TRANSFERENCIA DE CALOR : 1<sup>er</sup> PASO DE TUBOS

Agua en cambio de estado (T<sub>eb</sub>) → C<sub>agua</sub> ≈ ∞ → C<sub>r</sub> = 0

$$C_r = 0 \rightarrow \boxed{\varepsilon = 1 - e^{-NTU}}$$

con  $NTU = \frac{UA}{C_{\min}} = \frac{UA}{C_{\text{HUMOS}}}$



$$R_{\text{TOT}} = \frac{1}{UA} = \frac{1}{\underbrace{h_{ag} A_{int}}_{\sim \infty}} + \frac{\ln\left(\frac{r_{ext}}{r_{int}}\right)}{\underbrace{2\pi K L}_{\text{despreciable}}} + \frac{1}{h_H \cdot A_{ext}}$$

$$\rightarrow U = h_H = (h_{\text{conv}} + h_{\text{rad}})_{\text{HUMOS}}$$

$$\dot{Q}_{1P} = \varepsilon \cdot \dot{Q}_{\max}$$

$$C_{\text{HUMOS}} = \frac{\Delta h_{\text{HUMOS}} \cdot \dot{m}_{\text{HUMOS}}}{\Delta T_{\text{HUMOS}}}$$

$$w_a = (H_2O)_{f=0},$$

$$\Delta h_{\text{HUMOS}} = \Delta h_{H9H}$$

$$\boxed{\dot{Q}_{1P} = \varepsilon C_{\text{HUMOS}} \cdot (T_{SH} - T_{sat})}$$

# Calor de vaporización

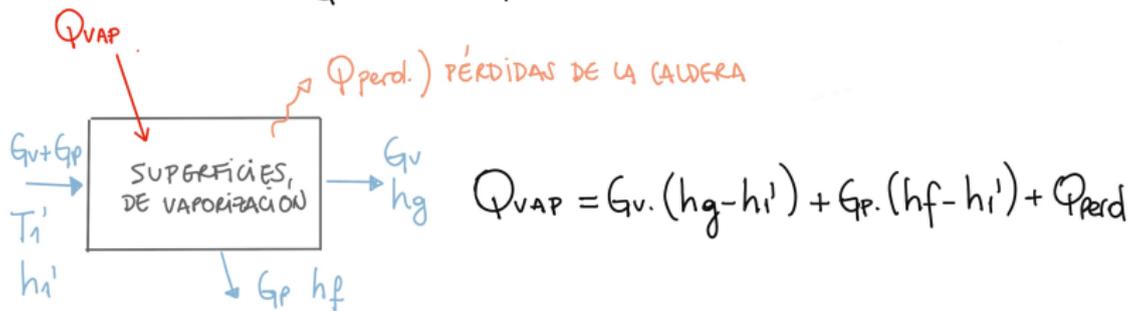
$Q_{VAP}$ : ENERGÍA ENTREGADA POR HUMOS Y LLAMA EN LAS SUPERFICIES DONDE SE GENERA VAPOR

HUMOTUBULAR DE N PASOS DE TUBOS

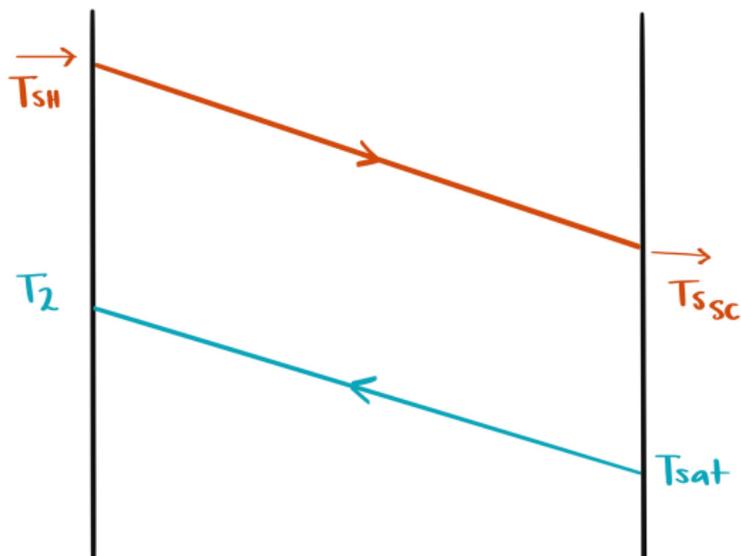
$$Q_{VAP} = Q_H + \sum_{i=1}^N Q_{PASO\ i}$$

ACUOTUBULAR

$$Q_{VAP} = Q_H + Q_{BC}$$



# Sobrecalentador



- $T_p \approx \bar{T}_{vapor} + 50^\circ C$

# Sobrecalentador

## ① BALANCE DE ENERGÍA : SOBRECALENTADOR

↳ DEL LADO DE HUMOS

Referencia (ORIGEN) -o H<sub>2</sub>O liq. y T<sub>0</sub>

$$Q_{sc} = G_{H_2O} \cdot [h_{H_2O}(T_{SH}) - h_{H_2O}(T_{Ssc})] + [(H_2O)_{fuel} + G_a W_a] G_v \cdot (T_{SH} - T_{Ssc})$$

↳ DEL LADO DEL VAPOR

$$Q_{sc} = G_v \cdot (h_2 - h_g)$$

## ② TRANSFERENCIA DE CALOR : SOBRECALENTADOR

$$Q_{sc} = \varepsilon \cdot C_{min} \cdot (T_{SH} - T_{sat}) \quad \text{con} \quad \varepsilon = f(NTU, Cr)$$

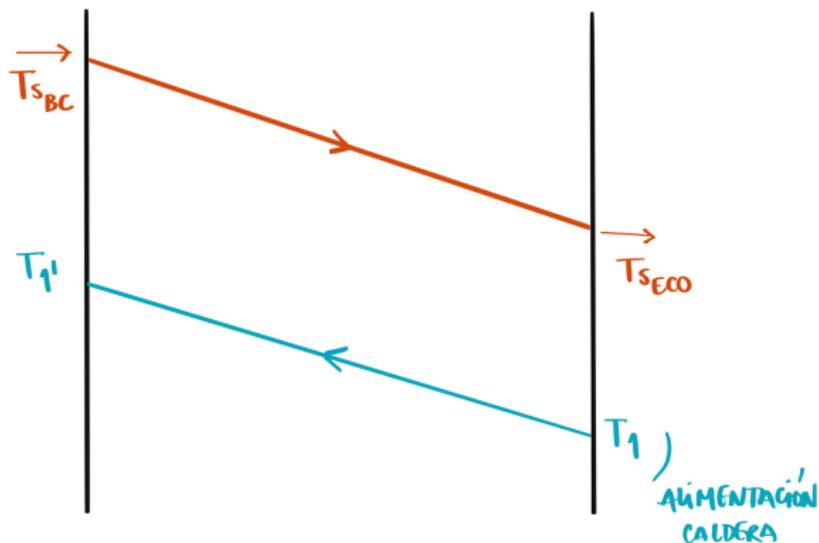
$$NTU = \frac{UA}{C_{min}} \quad \frac{1}{UA} = \frac{1}{h_H A} + \frac{R_{cond}}{r_0} + \frac{1}{h_{vapor} \cdot A}$$

$$Cr = \frac{C_{min}}{C_{max}}$$

$$h_{conv} + h_{rad}$$

↳ se debe contemplar

# Economizador



$$\bullet T_P \approx \bar{T}_{\text{agua}} + 10^\circ\text{C}$$

# Economizador

## ① BALANCE DE ENERGÍA : ECONOMIZADOR

↳ DEL LADO DE HUMOS

Referencia (ORIGEN) -o H<sub>2</sub>O liq. y T<sub>0</sub>

$$\dot{Q}_{ECO} = G_{H_2O} \left[ h_{H_2O}(T_{SBC}) - h_{H_2O}(T_{S_{ECO}}) \right] + \left[ (H_2O)_{fuel} + G_a W_a \right] G_v (T_{SBC} - T_{S_{ECO}})$$

↳ DEL LADO DEL AGUA

$$\dot{Q}_{ECO} = (G_v + \underline{G_p}) \cdot (h_1' - h_1)$$

## ② TRANSFERENCIA DE CALOR : ECONOMIZADOR

$$\dot{Q}_{ECO} = \varepsilon \cdot C_{min} \cdot (T_{SBC} - T_1) \quad \text{con} \quad \varepsilon = f(NTU, Cr)$$

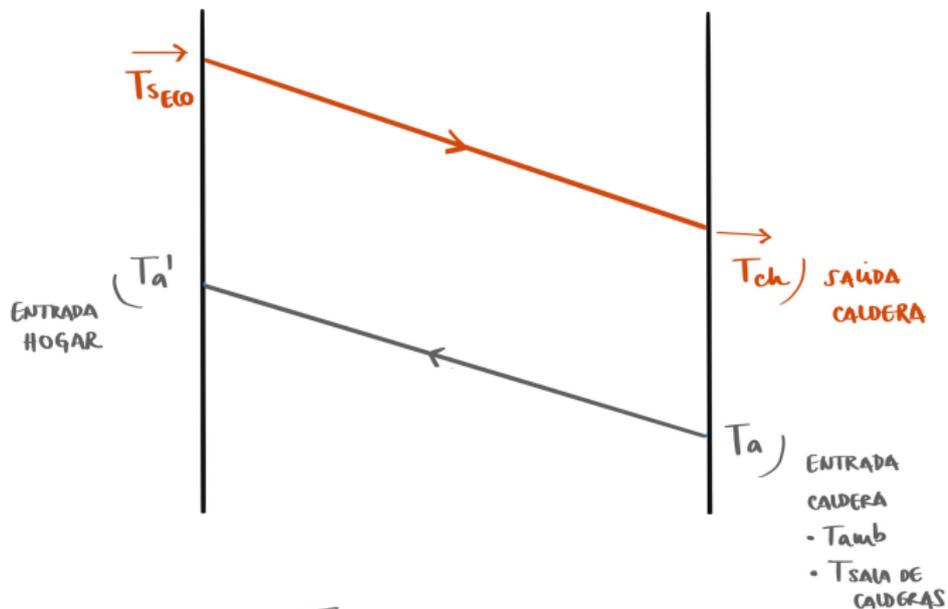
$$NTU = \frac{UA}{C_{min}} \quad \frac{1}{UA} = \frac{1}{h_H A} + \frac{R_{cond}}{20} + \frac{1}{h_{agua} A}$$

$$Cr = C_{min} / C_{max}$$

$$h_{conv} + h_{rad}$$

↳ se debe contemplar

# Pre calentador de aire



$$\bullet T_p \approx \frac{\bar{T}_H + \bar{T}_{aire}}{2}$$

# Precaentador de aire

## ① BALANCE DE ENERGÍA : PRECALENTADOR DE AIRE

↳ DEL LADO DE HUMOS Referencia (ORIGEN) → H<sub>2</sub>O l<sup>iq.</sup> y T<sub>0</sub>

$$\dot{Q}_{PA} = G_{H_2O} \left[ h_{H_2O}(T_{EPA}) - h_{H_2O}(T_{ch}) \right] + \left[ (H_2O)_f + G_a W_a \right] C_{pv} (T_{EPA} - T_{ch})$$

↳ DEL LADO DEL AIRE

$$\dot{Q}_{PA} = G_a \cdot C_{p,aire} \cdot (T_{a'} - T_a)$$

## ② TRANSFERENCIA DE CALOR : PRECALENTADOR DE AIRE

$$\dot{Q}_{PA} = \varepsilon \cdot C_{min} \cdot (T_{EPA} - T_a) \quad \text{con} \quad \varepsilon = f(NTU, Cr)$$

$$\rightarrow C_{aire} = \frac{\Delta h_{aire} \cdot \dot{m}_{aire}}{T_{a'} - T_a}$$

$$\rightarrow C_{humos} = \frac{\Delta h_{humos} \cdot \dot{m}_{humos}}{T_{EPA} - T_{ch}}$$

$$\frac{1}{UA} = \frac{1}{h_H A} + \underbrace{R_{cond}}_{\approx 0} + \frac{1}{h_a A}$$

comparables