Generadores de vapor

Balances y ecuaciones de transferencia en superficies

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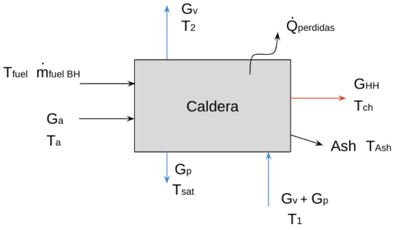
Repaso

Balance general

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

Balance General (combustible en base total)

$$
\begin{aligned}
Q_p^s - Q_{perdidas} = &+ G_v \cdot (h_2 - h_1) + G_{H9H} \cdot [h_{H9H}(T_{ch}) - h_{H9H}(T_o)] + 9H \cdot h_{fg}(T_o) + \\
&+ (H_2O)_{fuel} \cdot [h_{fg}(T_o) + c_{p_{vapor}} \cdot (T_{ch} - T_o) - c_{p_{liq}} \cdot (T_{fuel} - T_o)] + \\
&- [1 - (H_2O)_{fuel}] \cdot c_{p_{fuel}} \cdot (T_f - T_o) - G_{as} \cdot c_{p_a} \cdot (T_a - T_o) + \\
&+ G_{as} \cdot w_{as} \cdot c_{p_{vapor}} \cdot (T_{ch} - T_a) + G_{purga} \cdot (h_{liq.sat} - h_1) + \\
&+ Ash \cdot c_{p_{ash}} \cdot (T_{ash} - T_o) + H^*_{q_{C'}} + H^*_{q_{CO}}
\end{aligned}
$$



Humotubular

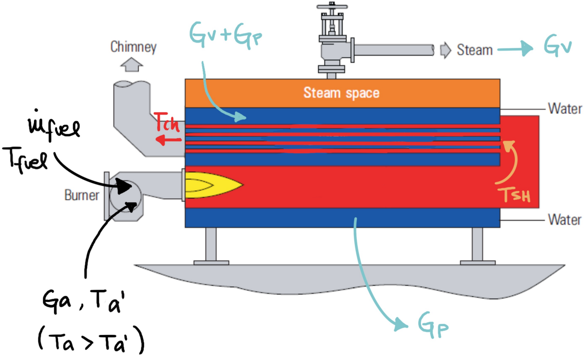
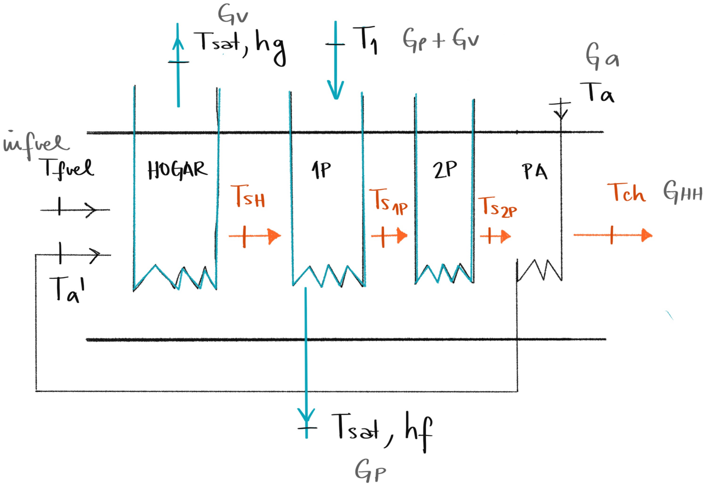


Diagrama horizontal: Humotubular



Acuotubular

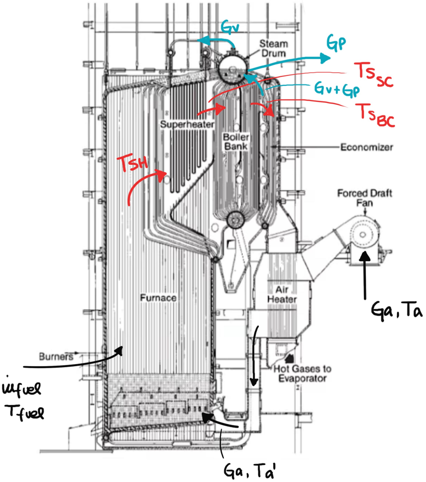
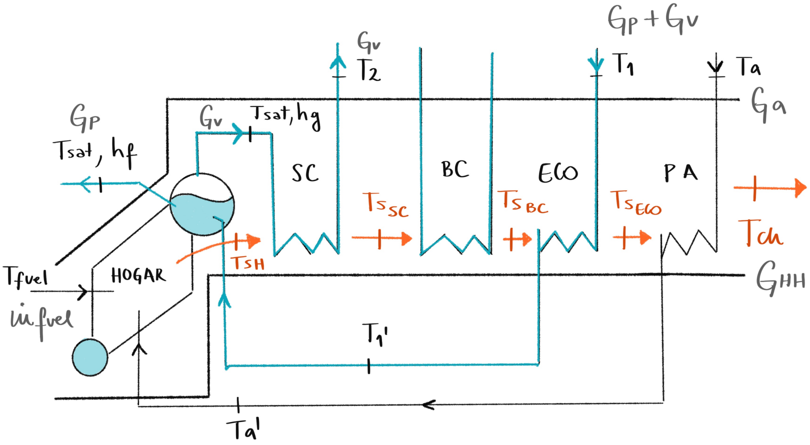
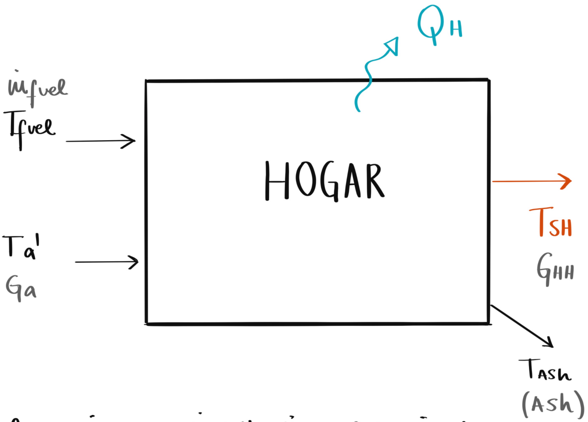


Diagrama horizontal: Acuotubular



Hogar: modelado como "caja negra"



- $\dot{m}_{fuel\,BH} + \dot{m}_{aire} = \dot{m}_{H9H} + \dot{m}_{H_2O,fuel} + \dot{m}_{Ash}$
- $1 + G_a = G_{H9H} + (H_2O)_{fuel} + (Ash)$

Hogar

① BALANCE DE ENERGÍA: HOGAR

↳ DEL LADO DE HUMOS

$$* \; h = h_g + h_s + h_L \rightarrow \dot{m}_f . h_f + \dot{m}_{aire} . h_a = \dot{Q}_H + \dot{m}_{H9H} . h_{H9H} + \dot{m}_{H_2O,f} \, h_{H_2Of} + \dot{m}_{Ash} \, h_{Ash}$$

Referencia (ORIGEN) → H_2O líq. y T_0

$$Q_P^S = Q_H + G_{H9H} . \left[h_{H9H}(T_{SH}) - h_{H9H}(T_0) \right] + 9 . H . h_{fg} @ T_0$$

$$+ (H_2O)_{fuel} . \left[h_{fg} @ T_0 + C_{p_v} . (T_{SH} - T_0) - C_{p,liq} . (T_f - T_0) \right]$$

$$- \left[1 - (H_2O)_f \right] . C_{p,fuel} . (T_f - T_0) - G_a . C_{p\,aire} . (T_a' - T_0)$$

$$+ G_a . W_a . C_{p_v} . (T_{SH} - T_a')$$

$$+ (Ash) . C_{p\,Ash} . (T_{Ash} - T_0) + H_{g,c'}^{*} + H_{g,co}^{*}$$

Hogar

(2) TRANSFERENCIA DE CALOR : HOGAR

principalmente RADIACIÓN

$$\dot{\Phi}_H = F_H \, \varepsilon_p \, \varepsilon_u \, \sigma \cdot \left(T_g^4 - T_p^4 \right)$$

AL AGUA

↳ Fuel en masa : $\varphi_H = \dot{\Phi}_H / \dot{m}_f$

↳ " en volumen : $\varphi_H = \dot{\Phi}_H / \dot{n}_f$

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

→ $F_H = A_H \cdot \varepsilon_H$

→ ε_p entre 0,8 y 0,9

→ ε_u entre 0,4 y 0,6

→ $T_p \cong T_{sat} + 20°C$

→ $T_g = \dfrac{T_{SH} + T_{ad}}{2}$

con $[A_H] = m^2$, $[T] = K$, $[\dot{\Phi}_H] = kcal/h$ y $[\dot{m}_f] = \dfrac{kg}{h}$ $\left([\dot{n}_f] = \dfrac{kmol}{h} \right)$

$$Q_H = \frac{4{,}9 \, F_H \, \varepsilon_p \, \varepsilon_u}{\dot{m}_f} \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_p}{100} \right)^4 \right]$$

Hogar

- ε_p: emisividad de pared
- T_p: temperatura de la pared del hogar
- ε_{ll}: emisividad de llama
- $F_H = A_H \varepsilon_H$: área del hogar corregida por el factor de vista (factor de Hottel, ε_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

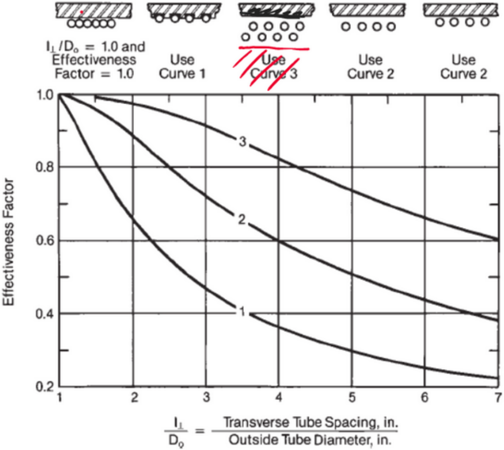


Fig. 33 Furnace wall area effectiveness factor (1.0 for completely water-cooled surface). A reduced area (equivalent cold surface) is determined from these curves for walls not completely water cooled. (Adapted from Hottel[4].)

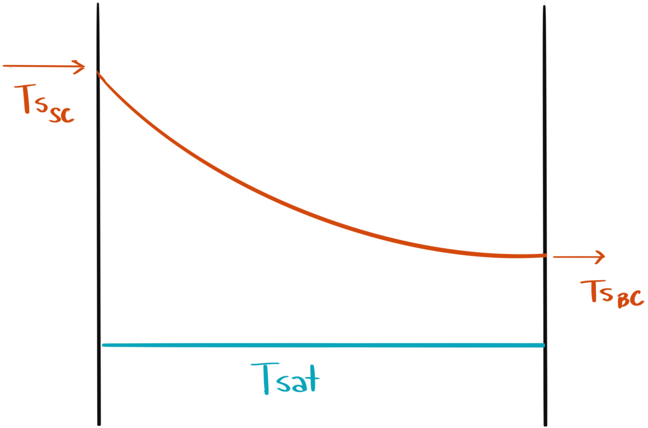
Hogar: calor liberado por unidad de volumen

Definición: q_v

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

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

Banco de convección: calderas AT



- $T_P \cong T_{sat} + 10\,°C$

Banco de convección: calderas AT

① BALANCE DE ENERGÍA: BANCO DE CONVECCIÓN

↳ DEL LADO DE HUMOS

$$\left.\left(\dot{m}_{HH}\cdot h_{HH} + \dot{m}_a \cdot w_a \cdot h_{H_2O,aire}\right)\right|_{SSC} = \dot{Q}_{BC} + \left.\left(\dot{m}_{HH}\cdot h_{HH} + \dot{m}_a \cdot w_a \cdot h_{H_2O,aire}\right)\right|_{SBC}$$

Referencia (ORIGEN) → H_2O líq. y T_0

$$Q_{BC} = G_{HgH}\cdot\left[h_{HgH}(T_{SSC}) - h_{HgH}(T_0)\right] + 9\cdot H\cdot h_{fg}@T_0 + (H_2O)_{fuel}\cdot\left[h_{fg}@T_0 + C_{pv}\cdot(T_{SSC}-T_0)\right]$$
$$+ G_a\cdot W_a\cdot C_{pv}\cdot(T_{SSC}-T_0)$$
$$-\Big\{G_{HgH}\cdot\left[h_{HgH}(T_{SBC}) - h_{HgH}(T_0)\right] + 9H h_{fg}@T_0 + (H_2O)_f\cdot\left[h_{fg}@T_0 + C_{pv}(T_{SBC}-T_0)\right]$$
$$+ G_a W_a\cdot C_{pv}(T_{SBC}-T_0)\Big]$$

$$Q_{BC} = G_{HgH}\cdot\left[h_{HgH}(T_{SSC}) - h_{HgH}(T_{SBC})\right] + \left[C_{pv}\cdot\left((H_2O)_f + G_a W_a\right)\cdot(T_{SSC}-T_{SBC})\right]$$

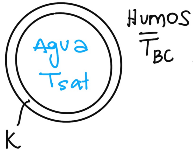
*válido para comb. incompleta (entra Hg^* y sale Hg^*)

Banco de convección: calderas AT

② TRANSFERENCIA DE CALOR : BANCO DE CONVECCIÓN

Agua en cambio de estado (T cte) → $C_{agua} \approx \infty$ → $C_r = 0$

$$C_r = 0 \rightarrow \varepsilon = 1 - e^{-NTU} \quad \text{con} \quad NTU = \frac{UA}{C_{min}} = \frac{UA}{C_{humos}}$$



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

$h_{ag} \approx \infty$; $\frac{\ln(r_{ext}/r_{int})}{2\pi K L}$ despreciable

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

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

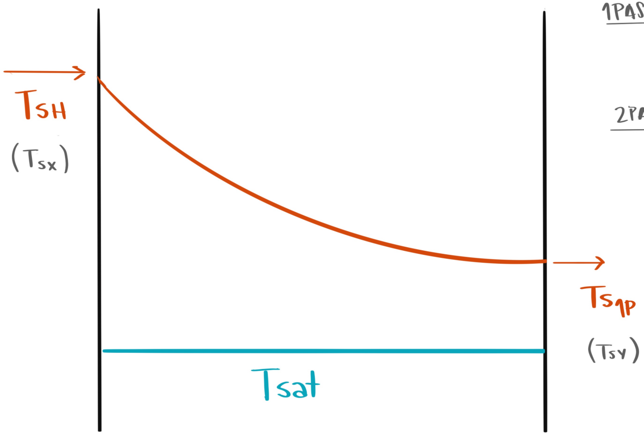
$$C_{humos} = \frac{\Delta h_{humos} \cdot \dot{m}_{humos}}{\Delta T_{humos}}$$

$w_a = (H_2O)_f = 0$,

$\Delta h_{humos} = \Delta h_{HgH}$

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

Pasos de tubos: calderas HT



1 PASO

$T_{sx} = T_{sH}$

$T_{sy} = T_{s1P}$

2 PASO

$T_{sx} = T_{s1P}$

$T_{sy} = T_{s2P}$

- $T_P \cong T_{sat} + 10\,°C$

Pasos de tubos: calderas HT

① BALANCE DE ENERGÍA: 1er PASO DE TUBOS

↳ DEL LADO DE HUMOS

$$\left.\left(\dot m_{HH}\cdot h_{HH} + \dot m_a\cdot w_a\cdot h_{H_2O,aire}\right)\right|_{SH} = \dot Q_{1P} + \left.\left(\dot m_{HH}\cdot h_{HH} + \dot m_a\cdot w_a\cdot h_{H_2O,aire}\right)\right|_{S1P}$$

Referencia (ORIGEN) → H_2O líq. y T_0

$$\dot Q_{1P} = G_{H9H}\cdot\left[h_{H9H}(T_{SH}) - h_{H9H}(T_0)\right] + 9\cdot H\cdot h_{fg}@T_0 + (H_2O)_{fuel}\cdot\left[h_{fg}@T_0 + C_{pv}\cdot(T_{SH}-T_0)\right]$$
$$+ G_a\cdot W_a\cdot C_{pv}\cdot(T_{SH}-T_0)$$
$$-\left\{G_{H9H}\cdot\left[h_{H9H}(T_{S1P}) - h_{H9H}(T_0)\right] + 9H h_{fg}@T_0 + (H_2O)_f\cdot\left[h_{fg}@T_0 + C_{pv}(T_{S1P}-T_0)\right]\right.$$
$$\left. + G_a W_a\cdot C_{pv}(T_{S1P}-T_0)\right]$$

$$\dot Q_{1P} = G_{H9H}\cdot\left[h_{H9H}(T_{SH}) - h_{H9H}(T_{S1P})\right] + \left[\left((H_2O)_f + G_a W_a\right) C_{pv}(T_{SH}-T_{S1P})\right]$$

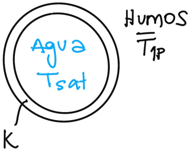
2DO PASO: $\dot Q_{2P} = G_{H9H}\cdot\left[h_{H9H}(T_{S1P}) - h_{H9H}(T_{S2P})\right] + \left[C_{pv}\cdot\left((H_2O)_f + G_a W_a\right)(T_{S1P}-T_{S2P})\right]$

Pasos de tubos: calderas HT

② TRANSFERENCIA DE CALOR : 1er PASO DE TUBOS

Agua en cambio de estado (T cte) → $C_{agua} \approx \infty$ → $C_r = 0$

$C_r = 0$ → $\boxed{\varepsilon = 1 - e^{-NTU}}$ con $NTU = \dfrac{UA}{C_{min}} = \dfrac{UA}{C_{Humos}}$



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

$h_{ag} \to \approx \infty$; $\frac{\ln(r_{ext}/r_{int})}{2\pi K L}$: despreciable

$$\longrightarrow U = h_H = (h_{conv} + h_{rad})_{Humos}$$

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

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

$w_a = (H_2O)_f = 0$,
$\Delta h_{humos} = \Delta h_{H9H}$

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

Calor de vaporización

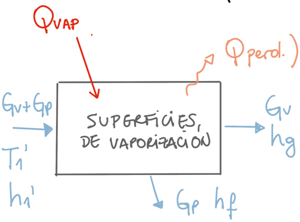
Q_{VAP} : ENERGÍA ENTREGADA POR HUMOS Y LLAMA EN LAS SUPERFICIES DONDE SE GENERA VAPOR

<u>HUMOTUBULAR DE N PASOS DE TUBOS</u>

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

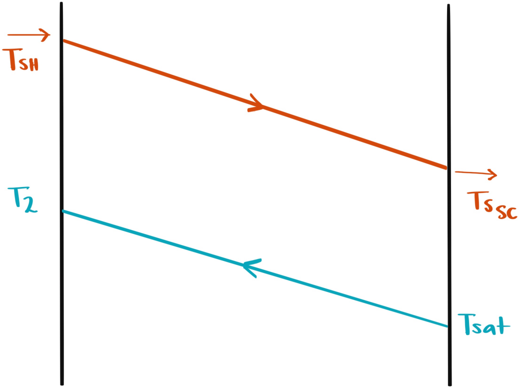
<u>ACUOTUBULAR</u>

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



$$Q_{VAP} = G_v \cdot (h_g - h_1') + G_p \cdot (h_f - h_1') + Q_{perd}$$

Sobrecalentador



- $T_p \cong T_{vapor} + 50\,°C$

Sobrecalentador

① BALANCE DE ENERGÍA: SOBRECALENTADOR

↳ DEL LADO DE HUMOS

Referencia (ORIGEN) → H_2O líq. y To

$$\dot{Q}_{SC} = G_{H9H} \cdot \left[h_{H9H}(T_{SH}) - h_{H9H}(T_{SSC}) \right] + \left[\left((H_2O)_{fuel} + G_a w_a \right) c_{pv} \cdot (T_{SH} - T_{SSC}) \right]$$

↳ DEL LADO DEL VAPOR $\dot{Q}_{SC} = G_v \cdot (h_2 - h_g)$

② TRANSFERENCIA DE CALOR: SOBRECALENTADOR

$$\dot{Q}_{SC} = \varepsilon \cdot C_{min} \cdot (T_{SH} - T_{sat}) \quad \text{con} \quad \varepsilon = f(NTU, C_r)$$

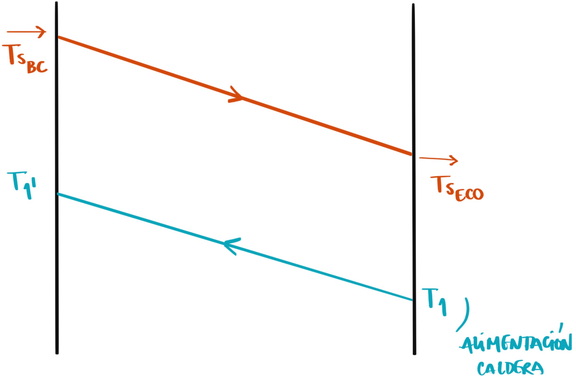
$$NTU = \frac{UA}{C_{min}} \qquad \frac{1}{UA} = \frac{1}{h_H A} + \underbrace{R_{cond}}_{\simeq 0} + \frac{1}{h_{vapor} \cdot A}$$

$$C_r = C_{min} / C_{máx}$$

h_H: $h_{conv} + h_{rad}$

$h_{vapor} \cdot A$ ↳ se debe contemplar

Economizador



- $T_P \cong \overline{T}_{agua} + 10\,°C$

Economizador

① BALANCE DE ENERGÍA : ECONOMIZADOR

↳ DEL LADO DE HUMOS

Referencia (ORIGEN) → H_2O líq. y T_o

$$Q_{ECO} = G_{HqH} \cdot \left[h_{HqH}(Ts_{BC}) - h_{HqH}(Ts_{ECO}) \right] + \left[\left((H_2O)_{fuel} + G_a w_a \right) c_{pv} \cdot \left(Ts_{BC} - Ts_{ECO} \right) \right]$$

↳ DEL LADO DEL AGUA

$$Q_{ECO} = (G_v + G_p) \cdot (h_1' - h_1)$$

② TRANSFERENCIA DE CALOR : ECONOMIZADOR

$$\dot{Q}_{ECO} = \varepsilon \cdot C_{min} \cdot (Ts_{BC} - T_1) \quad \text{con} \quad \varepsilon = f(NTU, C_r)$$

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

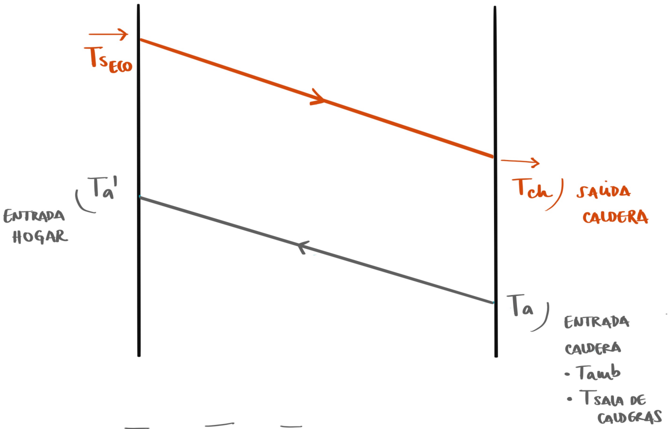
$R_{cond} \approx 0$

h_H: $h_{conv} + h_{rad}$

$h_{agua} A$ ↳ se debe contemplar

$$C_r = C_{min} / C_{máx}$$

Precalentador de aire



- $T_P \cong \dfrac{\overline{T}_H + \overline{T}_{aire}}{2}$

Precalentador de aire

① BALANCE DE ENERGÍA: PRECALENTADOR DE AIRE

↳ DEL LADO DE HUMOS   Referencia (ORIGEN) → H_2O líq. y To

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

↳ 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

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

→ $C_{aire} = \dfrac{\Delta h_{aire} \cdot \dot{m}_{aire}}{T_a' - T_a}$

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

$$\frac{1}{UA} = \frac{1}{h_H A} + R_{cond} + \frac{1}{h_a \cdot A}$$

$R_{cond} \approx 0$; $\frac{1}{h_H A}$ y $\frac{1}{h_a \cdot A}$ → comparables