Ingeniería Térmica y de Fluidos (II)

T18.- Intercambiadores de Calor. Método de la Eficiencia

Las trasparencias son el material de apoyo del profesor para impartir la clase. No son apuntes de la asignatura. Al alumno le pueden servir como guía para recopilar información (libros, …) y elaborar sus propios apuntes

Departamento: **Ingeniería Eléctrica y Energética**
Area: **Máquinas y Motores Térmicos**

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XVIII.- INTERCAMBIADORES DE CALOR MÉTODO DE LA EFICIENCIA

XVIII.1.- EFICACIA DE LOS INTERCAMBIADORES DE CALOR, ε (I)

Se conoce la descripción del intercambiador y las T^as^ de entrada, desconociendo las de salida

ε compara transferencia térmica en el fluido frío

$$\varepsilon = \frac{\text{Velocidad real de transferencia de calor en un intercambiador determinado}}{\text{Velocidad máxima posible de transferencia de calor}}$$

$Q_{máx}$ intercambiador en contracorriente, A infinita

$$Q = C_C\,(T_{C1} - T_{C2}) = C_F\,(T_{F2} - T_{F1})$$

Supuesto sin pérdidas térmicas:

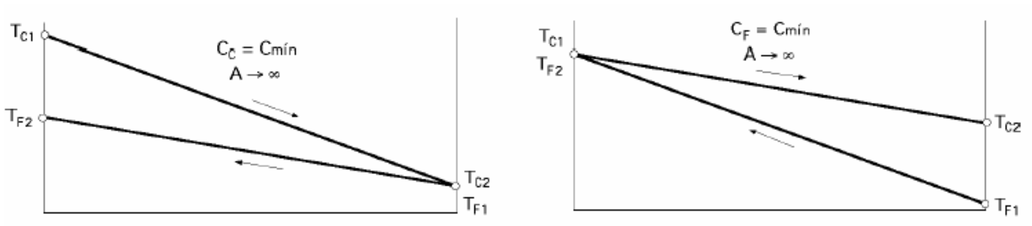
Si $C_C < C_F \Rightarrow \Delta T_C > \Delta T_F \Rightarrow T_{C2mín} = T_{F1}$ y $Q_{máx} = C_C\,(T_{C1} - T_{F1})$

Si $C_F < C_C \Rightarrow \Delta T_F > \Delta T_C \Rightarrow T_{F2máx} = T_{C1}$ y $Q_{máx} = C_F\,(T_{C1} - T_{F1})$

En cualquier caso:

$$\boxed{Q_{máx} = C_{mín}\,(T_{C1} - T_{F1})}$$

XVIII.1.- EFICACIA DE LOS INTERCAMBIADORES DE CALOR, ε (II)



$$\varepsilon = \frac{Q}{Q_{máx}} = \frac{Q}{C_{mín}\,(T_{C1} - T_{F1})} = \frac{C_F\,(T_{F2} - T_{F1})}{C_{mín}\,(T_{C1} - T_{F1})} = \frac{C_C\,(T_{C1} - T_{C2})}{C_{mín}\,(T_{C1} - T_{F1})}$$

$$\boxed{Q = \varepsilon\, C_{mín}\,(T_{C1} - T_{F1})} = C_F\,(T_{F2} - T_{F1}) = C_C\,(T_{C1} - T_{C2})$$

XVIII.- INTERCAMBIADORES DE CALOR MÉTODO DE LA EFICIENCIA

XVIII.2.- EFICACIA, CASO FLUJOS PARALELOS EN EQUICORRIENTE (I)

$$Q = \varepsilon\, C_{mín}\,(T_{C1} - T_{F1}) = U A\, \frac{\Delta T_2 - \Delta T_1}{\ln \dfrac{\Delta T_2}{\Delta T_1}} = \left|\begin{array}{l} \Delta T_2 = T_{C1} - T_{F1} \\ \Delta T_1 = T_{C2} - T_{F2} \end{array}\right| = U A\, \frac{(T_{C1} - T_{F1}) - (T_{C2} - T_{F2})}{\ln \dfrac{T_{C1} - T_{F1}}{T_{C2} - T_{F2}}}$$

$$\boxed{\ln \frac{T_{C1} - T_{F1}}{T_{C2} - T_{F2}} = U A\, \frac{(T_{C1} - T_{C2}) - (T_{F1} - T_{F2})}{\varepsilon\, C_{mín}\,(T_{C1} - T_{F1})}} \qquad (\ast\ast) = (\ast)$$

$$(\ast)\quad U A\, \frac{(T_{C1} - T_{C2}) - (T_{F1} - T_{F2})}{\varepsilon\, C_{mín}\,(T_{C1} - T_{F1})} =$$

$$= \frac{U A}{\varepsilon\, C_{mín}} \left(\frac{T_{C1} - T_{C2}}{T_{C1} - T_{F1}} + \frac{T_{F2} - T_{F1}}{T_{C1} - T_{F1}}\right) =$$

$$\varepsilon = \frac{C_F\,(T_{F2} - T_{F1})}{C_{mín}\,(T_{C1} - T_{F1})} = \frac{C_C\,(T_{C1} - T_{C2})}{C_{mín}\,(T_{C1} - T_{F1})}$$

$$\frac{T_{F2} - T_{F1}}{T_{C1} - T_{F1}} = \frac{\varepsilon\, C_{mín}}{C_F}$$

$$\Longleftarrow \quad \frac{T_{C1} - T_{C2}}{T_{C1} - T_{F1}} = \frac{\varepsilon\, C_{mín}}{C_C}$$

$$= \frac{U A}{\varepsilon\, C_{mín}} \left(\frac{\varepsilon\, C_{mín}}{C_C} + \frac{\varepsilon\, C_{mín}}{C_F}\right) =$$

$$= U A \left(\frac{1}{C_C} + \frac{1}{C_F}\right) \quad (\ast)$$

XVIII.2.- EFICACIA, CASO FLUJOS PARALELOS EN EQUICORRIENTE (II)

(✱✱)

$$\ln \frac{T_{C1} - T_{F1}}{T_{C2} - T_{F2}} = \left| \begin{array}{l} \varepsilon\, C_{mín} (T_{C1} - T_{F1}) = C_C (T_{C1} - T_{C2}) \rightarrow T_{C2} = T_{C1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_C} \\ \varepsilon\, C_{mín} (T_{C1} - T_{F1}) = C_F (T_{F2} - T_{F1}) \rightarrow T_{F2} = T_{F1} + (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_F} \end{array} \right|$$

$$= \ln \frac{T_{C1} - T_{F1}}{T_{C1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_C} - T_{F1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_F}} =$$

$$= \ln \frac{T_{C1} - T_{F1}}{T_{C1} (1 - \dfrac{\varepsilon\, C_{mín}}{C_C} - \dfrac{\varepsilon\, C_{mín}}{C_F}) - T_{F1} (1 - \dfrac{\varepsilon\, C_{mín}}{C_C} - \dfrac{\varepsilon\, C_{mín}}{C_F})} =$$

$$= \ln \frac{1}{1 - \varepsilon\, C_{mín} (\dfrac{1}{C_C} + \dfrac{1}{C_F})} = - \ln \{1 - \varepsilon\, C_{mín} (\frac{1}{C_C} + \frac{1}{C_F})\} \quad (✱✱)$$

XVIII.- INTERCAMBIADORES DE CALOR MÉTODO DE LA EFICIENCIA

XVIII.2.- EFICACIA, CASO FLUJOS PARALELOS EN EQUICORRIENTE (III)

$$\boxed{\ln \frac{T_{C1} - T_{F1}}{T_{C2} - T_{F2}} = U A \frac{(T_{C1} - T_{C2}) - (T_{F1} - T_{F2})}{\varepsilon\, C_{mín} (T_{C1} - T_{F1})}} \qquad (✱✱) = (✱)$$

$$\left| \begin{array}{ll} U A \dfrac{(T_{C1} - T_{C2}) - (T_{F1} - T_{F2})}{\varepsilon\, C_{mín} (T_{C1} - T_{F1})} = U A (\dfrac{1}{C_C} + \dfrac{1}{C_F}) & (✱) \\ \ln \dfrac{T_{C1} - T_{F1}}{T_{C2} - T_{F2}} = - \ln \{1 - \varepsilon\, C_{mín} (\dfrac{1}{C_C} + \dfrac{1}{C_F})\} & (✱✱) \end{array} \right.$$

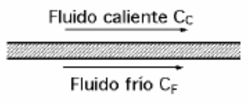
$$- \ln \{1 - \varepsilon\, C_{mín} (\frac{1}{C_C} + \frac{1}{C_F})\} = U A (\frac{1}{C_C} + \frac{1}{C_F}) \qquad \frac{U A}{C_{mín}} = NTU$$

$$1 - \varepsilon (\frac{C_{mín}}{C_C} + \frac{C_{mín}}{C_F}) = e^{- U A (\frac{1}{C_C} + \frac{1}{C_F})}$$

$$\varepsilon = \frac{1 - e^{- U A (\frac{1}{C_C} + \frac{1}{C_F})}}{\dfrac{C_{mín}}{C_C} + \dfrac{C_{mín}}{C_F}} = \frac{1 - e^{- \frac{U A}{C_{mín}} (\frac{C_{mín}}{C_{máx}} + 1)}}{\dfrac{C_{mín}}{C_{máx}} + 1}$$

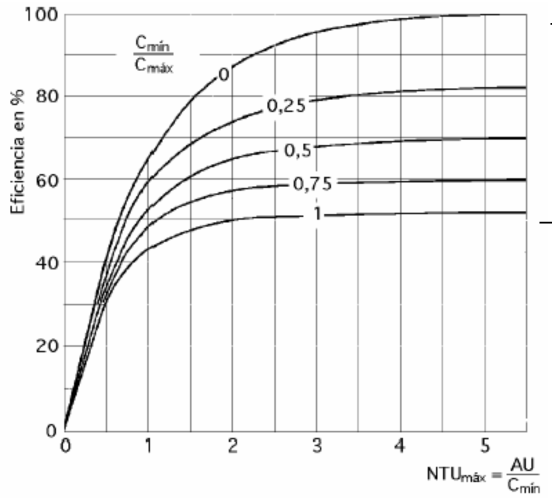
$$\boxed{\varepsilon = \frac{1 - e^{- NTU (\frac{C_{mín}}{C_{máx}} + 1)}}{\dfrac{C_{mín}}{C_{máx}} + 1}}$$

XVIII.2.- EFICACIA, CASO FLUJOS PARALELOS EN EQUICORRIENTE (IV)



$$\frac{UA}{C_{mín}} = NTU$$

$$\varepsilon = \frac{1 - e^{-NTU\left(\frac{C_{mín}}{C_{máx}} + 1\right)}}{\frac{C_{mín}}{C_{máx}} + 1}$$



$\rightarrow$ $\left.\begin{matrix} A \rightarrow \infty \\ C_{min} << C_{max} \end{matrix}\right] \Rightarrow T_{C2} = T_{F1}$ o $T_{F2} = T_{C1} \Rightarrow \varepsilon \approx 1$

Tª de un fluido cte: condensación, evaporación, sist. calef., ...

$\rightarrow$ $\left.\begin{matrix} A \rightarrow \infty \\ C_{min} = C_{max} \end{matrix}\right] \Rightarrow T_{C2} = T_{F2} = \frac{(T_{C1} + T_{F1})}{2} \Rightarrow \varepsilon = 0{,}5$

XVIII.3.- EFICACIA, CASO FLUJOS PARALELOS EN CONTRACORRIENTE (I)

$$Q = \varepsilon\, C_{mín}\,(T_{C1} - T_{F1}) = UA\,\frac{\Delta T_2 - \Delta T_1}{\ln\frac{\Delta T_2}{\Delta T_1}} = \left|\begin{matrix} \Delta T_2 = T_{C1} - T_{F2} \\ \Delta T_1 = T_{C2} - T_{F1} \end{matrix}\right| = UA\,\frac{(T_{C1} - T_{F2}) - (T_{C2} - T_{F1})}{\ln\frac{T_{C1} - T_{F2}}{T_{C2} - T_{F1}}}$$

$$\boxed{\ln\frac{T_{C1} - T_{F2}}{T_{C2} - T_{F1}} = UA\,\frac{(T_{C1} - T_{C2}) - (T_{F2} - T_{F1})}{\varepsilon\, C_{mín}\,(T_{C1} - T_{F1})}}\ (**) = (*)$$

$$(*)\quad UA\,\frac{(T_{C1} - T_{C2}) - (T_{F2} - T_{F1})}{\varepsilon\, C_{mín}\,(T_{C1} - T_{F1})} =$$

$$= \frac{UA}{\varepsilon\, C_{mín}}\left(\frac{T_{C1} - T_{C2}}{T_{C1} - T_{F1}} - \frac{T_{F2} - T_{F1}}{T_{C1} - T_{F1}}\right) =$$

$$= \frac{UA}{\varepsilon\, C_{mín}}\left(\frac{\varepsilon\, C_{mín}}{C_C} - \frac{\varepsilon\, C_{mín}}{C_F}\right) =$$

$$= UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)\ (*)$$

$$\varepsilon = \frac{C_F\,(T_{F2} - T_{F1})}{C_{mín}\,(T_{C1} - T_{F1})} = \frac{C_C\,(T_{C1} - T_{C2})}{C_{mín}\,(T_{C1} - T_{F1})}$$

$$\frac{T_{F2} - T_{F1}}{T_{C1} - T_{F1}} = \frac{\varepsilon\, C_{mín}}{C_F}$$

$$\frac{T_{C1} - T_{C2}}{T_{C1} - T_{F1}} = \frac{\varepsilon\, C_{mín}}{C_C}$$

$\Longleftarrow$

XVIII.3.- EFICACIA, CASO FLUJOS PARALELOS EN CONTRACORRIENTE (II)

(✻✻)

$$\ln \frac{T_{C1} - T_{F2}}{T_{C2} - T_{F1}} = \left| \begin{array}{l} \varepsilon\, C_{mín} (T_{C1} - T_{F1}) = C_C (T_{C1} - T_{C2}) \rightarrow T_{C2} = T_{C1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_C} \\ \varepsilon\, C_{mín} (T_{C1} - T_{F1}) = C_F (T_{F2} - T_{F1}) \rightarrow T_{F2} = T_{F1} + (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_F} \end{array} \right|$$

$$= \ln \frac{T_{C1} - T_{F1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_F}}{T_{C1} - (T_{C1} - T_{F1}) \dfrac{\varepsilon\, C_{mín}}{C_C} - T_{F1}} = \ln \frac{(T_{C1} - T_{F1}) (1 - \dfrac{\varepsilon\, C_{mín}}{C_F})}{(T_{C1} - T_{F1}) (1 - \dfrac{\varepsilon\, C_{mín}}{C_C})} =$$

$$= \ln \frac{(1 - \dfrac{\varepsilon\, C_{mín}}{C_F})}{(1 - \dfrac{\varepsilon\, C_{mín}}{C_C})} \quad (✻✻)$$

XVIII.- INTERCAMBIADORES DE CALOR MÉTODO DE LA EFICIENCIA

XVIII.3.- EFICACIA, CASO FLUJOS PARALELOS EN CONTRACORRIENTE (III)

$$\boxed{\ln \frac{T_{C1} - T_{F2}}{T_{C2} - T_{F1}} = UA \frac{(T_{C1} - T_{C2}) - (T_{F2} - T_{F1})}{\varepsilon\, C_{mín} (T_{C1} - T_{F1})}} \quad (✻✻) = (✻)$$

$$UA \frac{(T_{C1} - T_{C2}) - (T_{F2} - T_{F1})}{\varepsilon\, C_{mín} (T_{C1} - T_{F1})} = UA \left(\frac{1}{C_C} - \frac{1}{C_F}\right) \quad (✻)$$

$$\ln \frac{T_{C1} - T_{F2}}{T_{C2} - T_{F1}} = \ln \frac{(1 - \dfrac{\varepsilon\, C_{mín}}{C_F})}{(1 - \dfrac{\varepsilon\, C_{mín}}{C_C})} \quad (✻✻)$$

$$\ln \frac{(1 - \dfrac{\varepsilon\, C_{mín}}{C_F})}{(1 - \dfrac{\varepsilon\, C_{mín}}{C_C})} = UA \left(\frac{1}{C_C} - \frac{1}{C_F}\right)$$

$$\frac{1 - \dfrac{\varepsilon\, C_{mín}}{C_F}}{1 - \dfrac{\varepsilon\, C_{mín}}{C_C}} = e^{UA \left(\frac{1}{C_C} - \frac{1}{C_F}\right)} \rightarrow 1 - \frac{\varepsilon\, C_{mín}}{C_F} = (1 - \frac{\varepsilon\, C_{mín}}{C_C})\, e^{UA \left(\frac{1}{C_C} - \frac{1}{C_F}\right)}$$

XVIII.3.- EFICACIA, CASO FLUJOS PARALELOS EN CONTRACORRIENTE (IV)

$$\rightarrow\quad 1 - \frac{\varepsilon C_{mín}}{C_F} = \left(1 - \frac{\varepsilon C_{mín}}{C_C}\right) e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}$$

$$1 - \frac{\varepsilon C_{mín}}{C_F} = e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)} - \frac{\varepsilon C_{mín}}{C_C} e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}$$

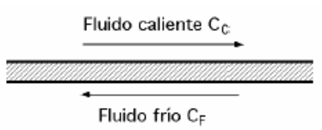
$$1 - e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)} = \frac{\varepsilon C_{mín}}{C_F} - \frac{\varepsilon C_{mín}}{C_C} e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}$$

$$1 - e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)} = \varepsilon\left(\frac{C_{mín}}{C_F} - \frac{C_{mín}}{C_C} e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}\right)$$

$$\varepsilon = \frac{1 - e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}}{C_{mín}\left\{\frac{1}{C_F} - \frac{1}{C_C} e^{UA\left(\frac{1}{C_C} - \frac{1}{C_F}\right)}\right\}}$$

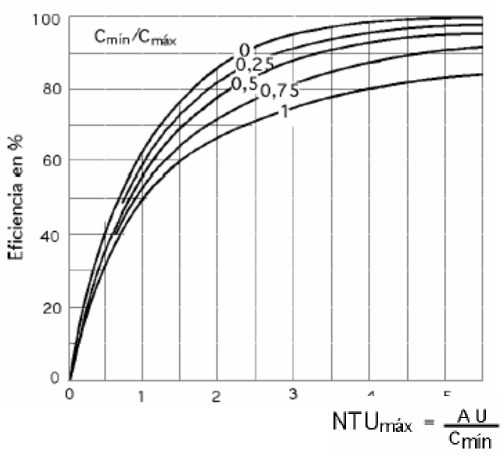
$$\boxed{\varepsilon = \frac{1 - e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}{1 - \frac{C_{mín}}{C_{máx}} e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}}$$

XVIII.3.- EFICACIA, CASO FLUJOS PARALELOS EN CONTRACORRIENTE (V)



$$\frac{UA}{C_{mín}} = NTU$$

$$\boxed{\varepsilon = \frac{1 - e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}{1 - \frac{C_{mín}}{C_{máx}} e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}}$$



$\rightarrow\quad A \rightarrow \infty \Rightarrow T_{C2} = T_{F1}$ o $T_{F2} = T_{C1} \Rightarrow \varepsilon \approx 1$

XVIII.4.- CONSIDERACIONES

Equicorriente

$$\varepsilon = \frac{1 - e^{-NTU\left(\frac{C_{mín}}{C_{máx}} + 1\right)}}{\frac{C_{mín}}{C_{máx}} + 1}$$

Contracorriente

$$\varepsilon = \frac{1 - e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}{1 - \frac{C_{mín}}{C_{máx}}\, e^{NTU\left(\frac{C_{mín}}{C_{máx}} - 1\right)}}$$

Condensación o evaporación $\Rightarrow C_{min} / C_{max} = 0$

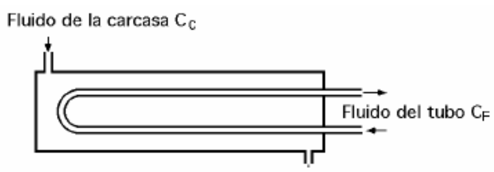
Tanto en equi como en contracorriente $\Rightarrow \quad \varepsilon = 1 - e^{-NTU}$

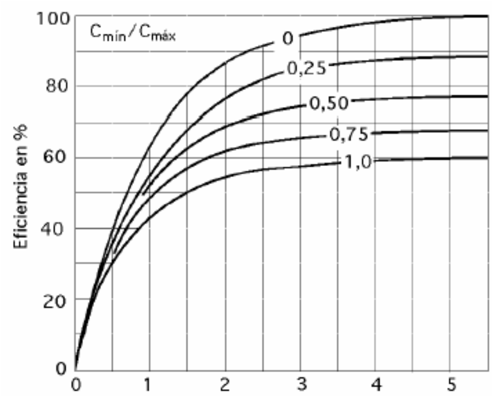
Flujo equilibrado ($C_{min} = C_{max}$)

Equicorriente $\varepsilon = \frac{1 - e^{-2\,NTU}}{2}$ **Contracorriente** $\varepsilon = \frac{NTU}{1 + NTU}$

XVIII.5.- OTRAS CONFIGURACIONES DE INTERCAMBIADORES

Un paso por carcasa y dos o múltiplo de dos pasos de tubo





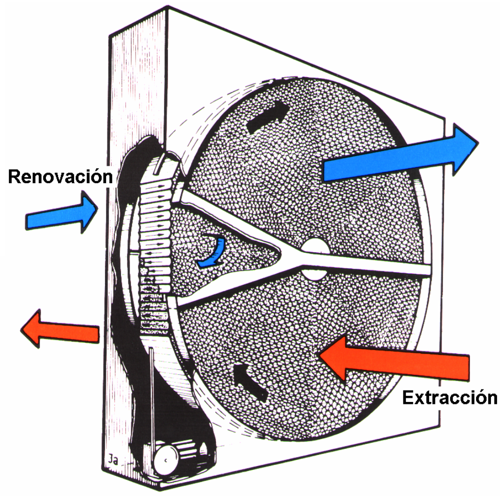
$NTU_{máx} = \frac{A\,U}{C_{mín}}$

$$NTU = -\frac{1}{\sqrt{1 + \left(\frac{C_{mín}}{C_{máx}}\right)^2}} \ln \frac{E - 1}{E + 1}$$

$$E = \frac{\frac{2}{\varepsilon} - \left(1 + \frac{C_{mín}}{C_{máx}}\right)}{\sqrt{1 + \left(\frac{C_{mín}}{C_{máx}}\right)^2}}$$

$$\varepsilon = \varepsilon_1 = 2\left\{1 + \frac{C_{mín}}{C_{máx}} + \frac{1 + e^{-NTU\sqrt{1 + \left(\frac{C_{mín}}{C_{máx}}\right)^2}}}{1 - e^{-NTU\sqrt{1 + \left(\frac{C_{mín}}{C_{máx}}\right)^2}}}\sqrt{1 + \left(\frac{C_{mín}}{C_{máx}}\right)^2}\right\}$$

XVIII.6.- INTERCAMBIADOR ROTATIVO (I)



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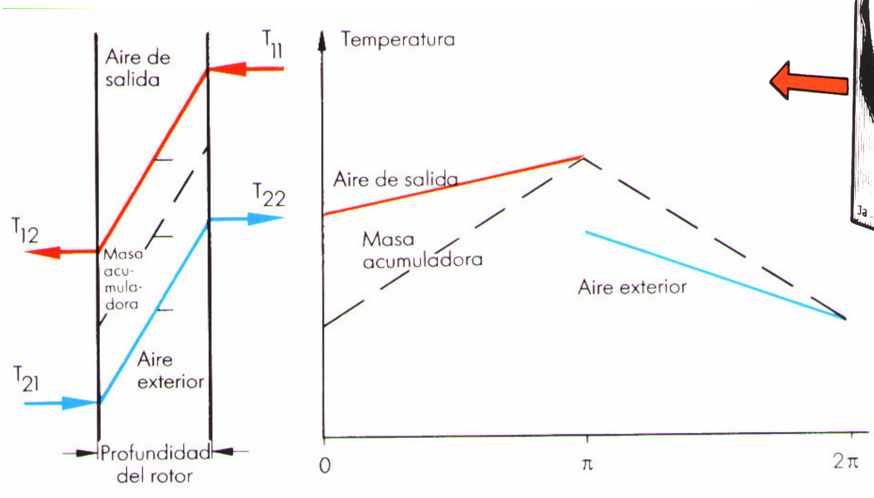


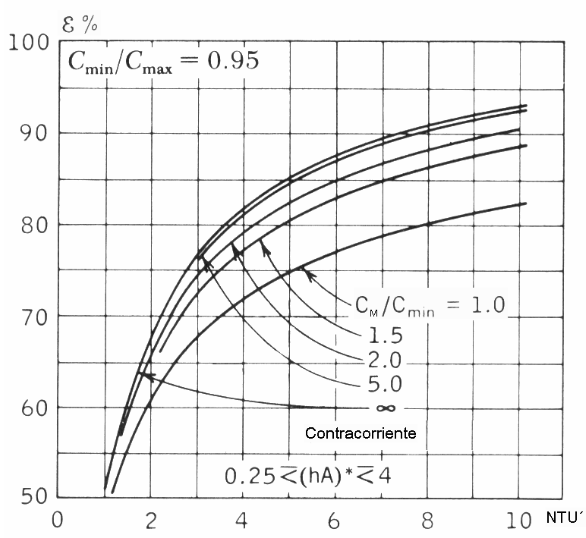
XVIII.6.- INTERCAMBIADOR ROTATIVO (II)

$$\frac{1}{U\ A} = \frac{1}{h_C\ A} + \frac{1}{h_F\ A} \Longrightarrow U\ A = \frac{h\ A}{2}$$

$C_M = N\ M_M\ c_{pM}$, siendo N el número de rpm

$$\varepsilon = \varepsilon_{CC} \left[1 - \frac{1}{9\left(C_M / C_{min}\right)^{1,93}} \right]$$

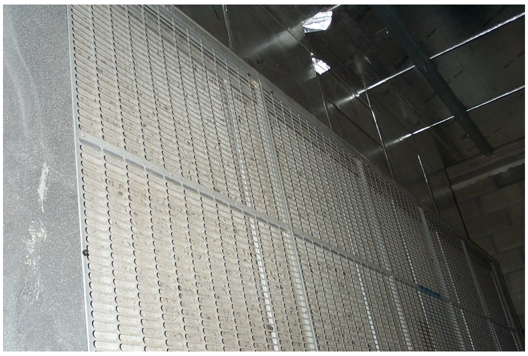
siendo ε_{CC} la eficacia de un intercambiador en contracorriente



$$hA^* = \frac{hA\ en\ C_{min}}{hA\ en\ C_{max}}\ (normalmente\ 1)$$

XVIII.7.- INTERCAMBIADORES COMPACTOS

Intercambiadores líquido-gas (con mezcla a la salida)



$$Re = \frac{G^* d_H}{\eta} \qquad d_H = 4 \frac{L A_{mín}}{A}$$

hc depende de la forma de la aleta (lisa, ondulada, …)

Se aproxima por la de la batería de tubos liso