HEAT EXCHANGER (PENUKAR KALOR)

(2)

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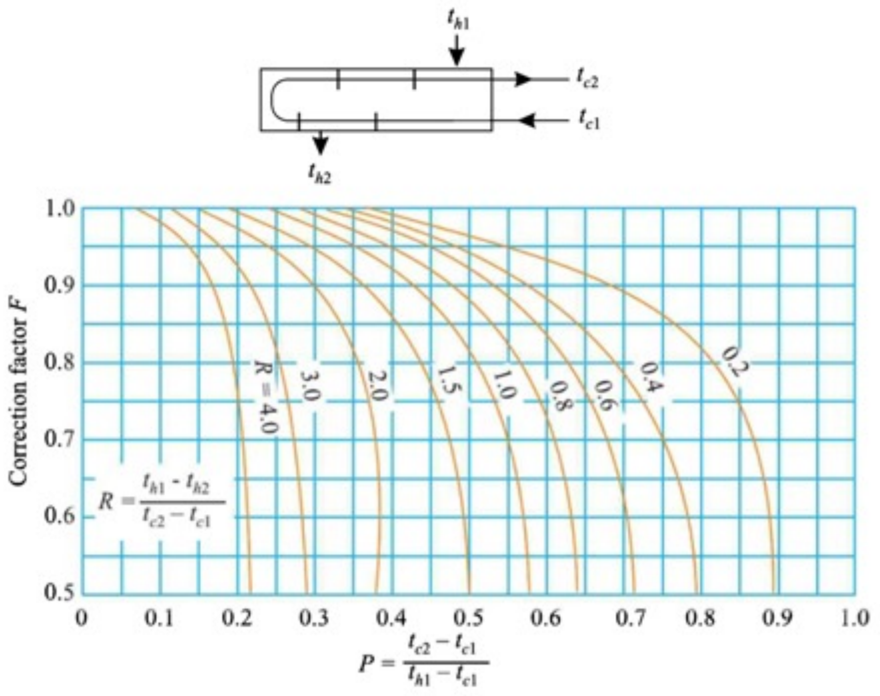
FAKTOR KOREKSI UNTUK MULTI-PASS ARRANGEMENTS

- LMTD valid terhadap single-pass heat exchanger.
- Analisa terhadap multiple pass shell and tube heat exchanger dan cross flow heat exchanger lebih sulit dari pada single pass, dimana dianalisa dengan menggunakan persamaan:

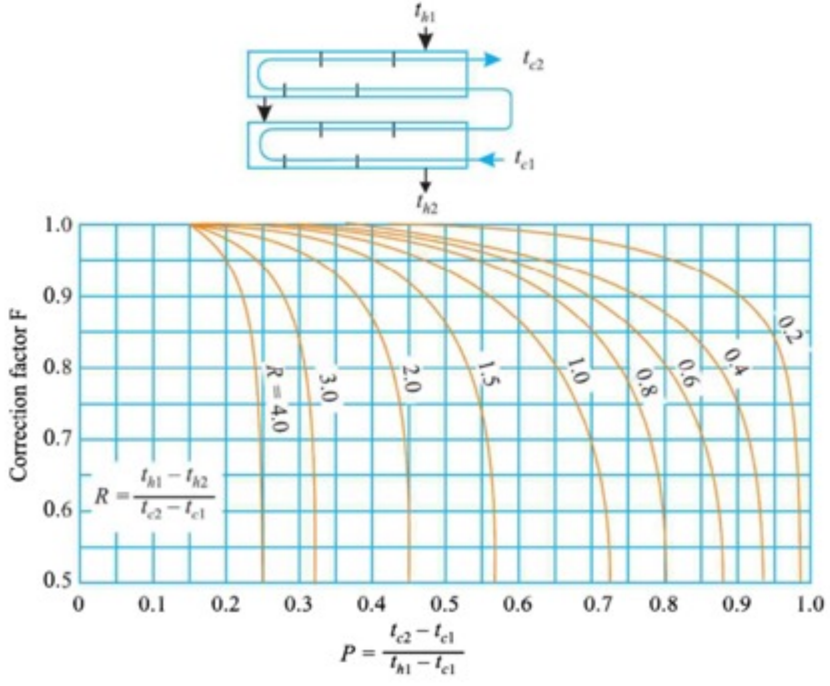
$$Q = UAF\theta m$$

dimana: F – faktor koreksi .

- Faktor koreksi untuk beberapa jenis rancangan seperti pada gambar.



Correction factor plot for heat exchanger with one shell pass and two, four or any multiple of tube passes.



Correction factor plot for heat exchanger with two shell passes and two, four, eight or any multiple of tube passes.

- Rasio temperatur, P : didefinisikan sebagai peningkatan temperatur dari fluida dingin terhadap perbedaaan dalam temperatur masuk kedua fluida.

$$P = \frac{t_{c2} - t_{c1}}{t_{h1} - t_{c1}}$$

dimana subscript h dan c menyatakan hot dan cold fluid dan subscript 1 dan 2 menyatakan kondisi masuk dan keluar.

- Rasio temperatur P menunjukkan efektivitas pendinginan atau pemanasan dan bervariasi dari 0 untuk temperatur konstan dari salah satu fluida sampai 1 untuk temperatur masuk fluida panas sama dengan temperatur keluar fluida dingin.
- Rasio kapasitas R:

$$R = \frac{\dot{m}_c \cdot c_{pc}}{\dot{m}_h \cdot c_{ph}}$$

$$\dot{m}_c \cdot c_{pc} \cdot (t_{c2} - t_{c1}) = \dot{m}_h \cdot c_{ph} \cdot (t_{h1} - t_{h2})$$

$$R = \frac{\dot{m}_c \cdot c_{pc}}{\dot{m}_h \cdot c_{ph}} = \frac{t_{h1} - t_{h2}}{t_{c2} - t_{c1}}$$

$$= \left[\frac{\text{Temperature drop of the hot fluid}}{\text{Temperature rise in the cold fluid}}\right]$$

Contoh 1:

Hitunglah kasus sebagai berikut, luas permukaan yang diperlukan untuk suatu heat exchanger dimana diperlukan untuk mendinginkan 3200 kg/h benzene (c_p = 1,74 kJ/kg°C) dari 72°C sampai 42 °C. Air pendingin (c_p = 4,18 kJ/kg°C pada 15 °C mempunyai laju massa aliran 2200 kg/h.

(i) Single pass counter flow

(ii) 1-4 exchanger (one shell pass dan four tube passes.

(iii) Cross flow single pass dengan air bercampur dan benzene tidak bercampur.

Untuk masing-masing konfigurasi, koefisien perpindahan panas keseluruhan diambil 0,28 kW/m²°C.

Solution. *Given* : $\dot{m}_h = \dfrac{3200}{3600} = 0.889$ kg/s; $c_{ph} = 1.74$ kJ/kg°C; $t_{h1} = 72°C$, $t_{h2} = 42°C$;

$\dot{m}_w = \dot{m}_c = \dfrac{2000}{3600} = 0.611$ kg/s, $c_{pc} = 4.18$ kJ/kg°C, $t_{c1} = 15°C$, $U = 280$ W/m²°C

Surface area required, *A* :

Using energy balance on both the fluids, we have

$$\dot{m}_h c_{ph} (t_{h1} - t_{h2}) = \dot{m}_c c_{pc} (t_{c2} - t_{c1})$$

$$0.889 \times 1.74 (72 - 42) = 0.611 \times 4.18 (t_{c2} - 15)$$

$$\therefore \quad t_{c2} = 33.2°C$$

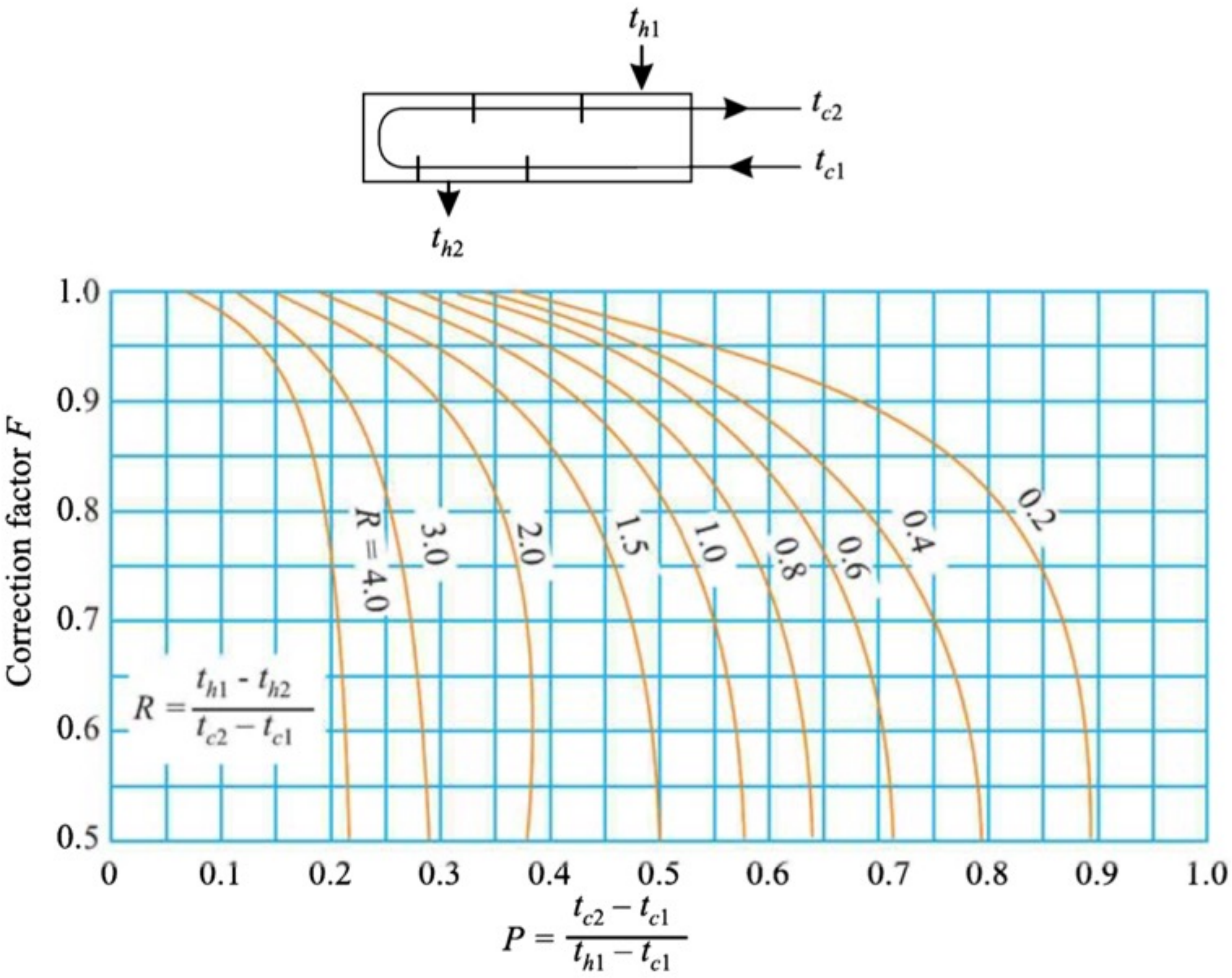


Fig. 10.40. Correction factor plot for heat exchanger with one shell pass and two, four or any multiple of tube passes.

An energy balance on the hot fluid yields the total heat transfer,

$$Q = \dot{m}_h \; c_{ph} \, (t_{h1} - t_{h2}) = 0.889 \times 1.74 \, (72 - 42) = 46.4 \text{ kW}$$

(*i*) *Single-pass counter-flow :*

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln (\theta_1/\theta_2)} = \frac{(t_{h1} - t_{c2}) - (t_{h2} - t_{c1})}{ln \, [(t_{h1} - t_{c2})/(t_{h2} - t_{c1})]}$$

$$= \frac{(72 - 33.2) - (42 - 15)}{\ln \, [(72 - 33.2)/(42 - 15)]} = \frac{38.8 - 27}{\ln \, [(38.8/27)]} = 32.5°\text{C}$$

∴ Area of the exchanger, $A = \dfrac{Q}{U \, \theta_m} = \dfrac{46.4}{0.28 \times 32.5} = \mathbf{5.1 \; m^2}$ **(Ans.)**

(*ii*) *1-4 exchanger* :

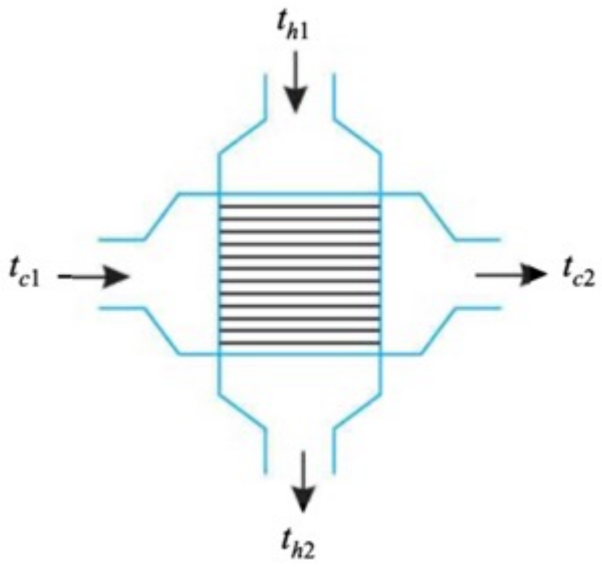
Since the number of passes is more than one hence θ_m (*LMTD*) needs correction factor, *F*. To know the correction factor we have to know first *P* (temperature ratio) and (capacity ratio) *R*.

$$P = \frac{t_{c2} - t_{c1}}{t_{h1} - t_{c1}} = \frac{(33.2 - 15)}{(72 - 15)} = 0.32$$

$$R = \frac{t_{h1} - t_{h2}}{t_{c2} - t_{c1}} = \frac{(72 - 42)}{(33.2 - 15)} = 1.65$$

Using $P = 0.32$ and $R = 1.65$ the correction factor *F* from Fig. 10.40 is read as

$$F \simeq 0.9$$



$\therefore$ Area of the exchanger, $\quad A = \dfrac{Q}{F\,U\,\theta_m} = \dfrac{46.4}{0.9 \times 0.28 \times 32.5} = \mathbf{5.66\ m^2}$ **(Ans.)**

(*iii*) *Cross-flow single-pass with water mixed and benzene unmixed :*

Using $P = 0.32$ and $R = 1.65$ the correction factor F from Fig. 10.43 is read as

$$F \simeq 0.92$$

$\therefore$ Area of the exchanger, $\quad A = \dfrac{Q}{F\,U\,\theta_m} = \dfrac{46.4}{0.92 \times 0.28 \times 32.5} = \mathbf{5.54\ m^2}$ **(Ans.)**

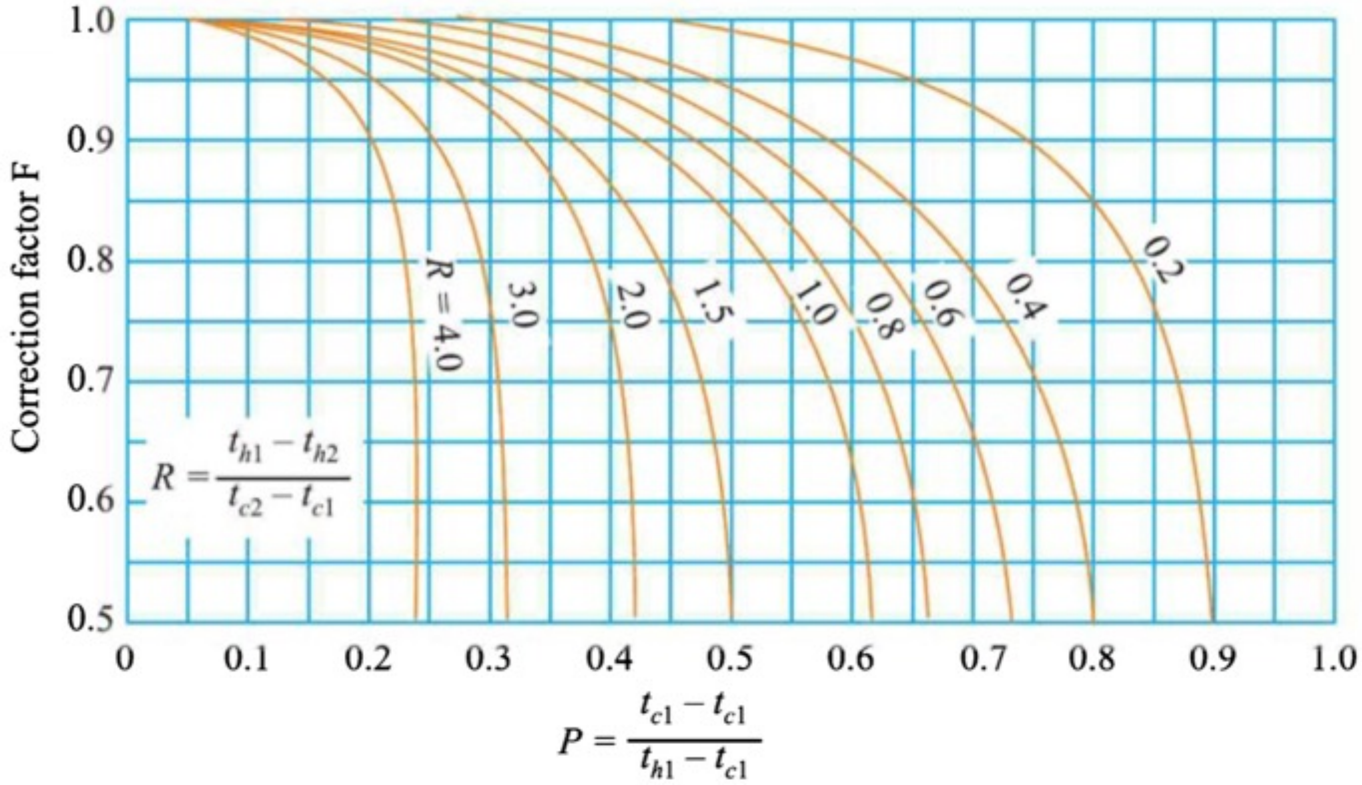


Fig. 10.43. Correction factors plot for single-pass cross-flow heat exchanger, one fluid mixed and the other unmixed.

Contoh 2: *. It is required to design a shell-and-tube heat exchanger for heating 2.4 kg/s of water from 20°C to 90°C by hot engine oil (c_p = 2.4 kJ/kg°C) flowing through the shell of the heat exchanger. The oil makes a single pass entering at 145°C and leaving at 90°C with an average heat transfer coefficient of 380 W/m²°C. The water flows through 12 thin-walled tubes of 25 mm diameter with each-tube making 8-passes through the shell. The heat transfer coefficient on the water side is 2900 W/m²°C. Calculate the length of the tube required for the heat exchanger to accomplish the required water heating.*

Solution. *Given :* $\dot{m}_w = \dot{m}_c = 2.4$ kg/s, $t_{c1} = 20°C$, $t_{c2} = 90°C$; $t_{h1} = 145°C$, $t_{h2} = 90°C$,

$c_{ph} = 2.4$ kJ/kg°C, $d = 25$mm = 0.025 m, $N = 12$; $h_i = 2900$ W/m°C, $h_0 = 380$ W/m²°C

Length of the tube L :

The overall heat transfer coefficient, neglecting thermal resistance of the tube, is given by

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_o}$$

or,

$$U = \frac{h_i \times h_o}{h_i + h_o} = \frac{2900 \times 380}{2900 + 380} = 335.97 \text{ W/m}^2\text{°C}$$

The parameters required to get the correction factors are :

$$P = \frac{t_{c2} - t_{c1}}{t_{h1} - t_{c1}} = \frac{(90 - 20)}{(145 - 20)} = 0.56$$

$$R = \frac{t_{h1} - t_{h2}}{t_{c2} - t_{c1}} = \frac{(145 - 90)}{(90 - 20)} = 0.786$$

Dari gambar 10.40: F = 0,82

For the conventional counter-flow arrangement

$$\theta_1 = t_{h1} - t_{c2} = 145 - 90 = 55°C$$

$$\theta_2 = t_{h2} - t_{c1} = 90 - 20 = 70°C$$

$$\therefore \quad \theta_m = \frac{(\theta_1 - \theta_2)}{\ln(\theta_1/\theta_2)} = \frac{55 - 70}{\ln(55/70)} = 103.6°C$$

The heat transfer rate is given by

$$Q = \dot{m}_c \, c_{pc} \, (t_{c2} - t_{c1})$$

$$= 2.4 \times 4.18 \times 10^3 \, (90 - 20) = 702240 \text{ W}$$

Also, $Q = F\, U\, A\, \theta_m$, where A = heating surface

$$\therefore \quad A = \frac{Q}{F\, U\, \theta_m} = \frac{702240}{0.82 \times 335.97 \times 103.6} = 24.6 \text{ m}^2$$

But, $A = \pi\, d\, L \times N$

$$L = \frac{A}{\pi d N} = \frac{24.6}{\pi \times 0.025 \times 12} \; 26.1 \text{ m}$$

The shell length $= \dfrac{26.1}{8} =$ **3.26 m (Ans.)**

EFEKTIVITAS HEAT EXCHANGER dan NUMBER OF TRANSFER UNIT (NTU)

- Efektivitas Heat Exchanger didefinisikan sebagai perbandingan perpindahan panas actual terhadap perpindahan panas maksimum yang mungkin terjadi.

$$\varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}} = \frac{Q}{Q_{\max}}$$

- Laju perpindahan panas aktual *Q* dapat ditentukan dengan kesetimbangan energi terhadap setiap sisi heat exchanger.

$$Q = \dot{m}_h \, c_{ph} \, (t_{h1} - t_{h2}) = \dot{m}_c \, c_{pc} \, (t_{c2} - t_{c1})$$

- Produk laju aliran massa dan panas spesifik didefinisikan sebagai kapasitas fluida *C*:

$$\dot{m}_h \, c_{ph} = C_h = \text{Hot fluid capacity rate}$$

$$\dot{m}_c \, c_{pc} = C_c = \text{Cold fluid capcity rate}$$

$$C_{min} = \text{The minimum fluid capacity rate } (C_h \text{ or } C_c)$$

$$C_{max} = \text{The maximum fluid capacity rate } (C_h \text{ or } C_c).$$

- Laju perpindahan panas maksimum untuk *parallel flow* dan *counter flow heat exchanger* akan terjadi jika temperatur keluar fluida dengan nilai C_h atau C_c yang kecil , yaitu C_{min} adalah sama dengan temperatur masuk fluida lainnya.
- Perubahan temberatur maksimum yang mungkin terjadi dapat tercapai dengan hanya satu fluida dimana tergantung kaspasitas panas.
- Perubahan maksimum tidak dapat diperoleh dengan kedua fluida kecuali kasus yang khusus dari nilai kapasitas panas yang sama.

$$Q_{max} = C_h (t_{h1} - t_{c1}) \text{ or } C_c (t_{h1} - t_{c1})$$

Q_{max} is the ***minimum*** of these two values, *i.e.*,

$$Q_{max} = C_{min} (t_{h1} - t_{c1})$$

$$\therefore \quad \varepsilon = \frac{C_h (t_{h1} - t_{h2})}{C_{min} (t_{h1} - t_{c1})} = \frac{C_c (t_{c2} - t_{c1})}{C_{min} (t_{h1} - t_{c1})} \qquad \text{........10.38}$$

- Ketika efektivitas diketahui, laju perpindahan panas dengan mudah dapat dihitung menggunakan persamaan:

$$Q = \varepsilon \, C_{min} (t_{h1} - t_{c1})$$

- Efektivitas Heat Exchanger merupakan fungsi dari beberapa variable dimana efektivitas dapat dinyatakan sebagai suatu fungsi dari parameter-parameter tidak berdimensi.
- Metode ini disebut Metode NTU dimana memfasilitasi perbandingan antara jenis-jenis heat exchanger yang digunakan untuk aplikasi tertentu.
- Efektivitas menunjukkan akiran parakek dan counter flow untuk kasus-kasus yang dijelaskan sebagai berikut.

(i) Effectiveness for the "Parallel-flow" heat exchanger :

Refer Fig. 10.8. The heat exchange dQ through an area dA of the heat exchanger is given by

$$dQ = U.dA\,(t_h - t_c) \qquad ...(i)$$

$$= -\,\dot{m}.c_{ph}\,.dt_h = \dot{m}_c\,.c_{pc}\,.dt_c$$

$$= -\,C_h.dt_h = C_c.dt_c \qquad ...(ii)$$

From expression (ii), we have

$$dt_h = \frac{-\,dQ}{C_h} \quad \text{and} \quad dt_c = \frac{dQ}{C_c}$$

$$\therefore \qquad d\,(t_h - t_c) = -\,dQ\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

Substituting the value of dQ from expression (i) and rearranging, we get

$$\frac{d\,(t_h - t_c)}{(t_h - t_c)} = -\,U\,.dA\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

Upon integration, we get

$$ln\left[\frac{(t_{h2} - t_{c2})}{(t_{h1} - t_{c1})}\right] = -\,UA\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

$$ln\left[\frac{(t_{h2} - t_{c2})}{(t_{h1} - t_{c1})}\right] = -\,\frac{UA}{C_h}\left(1 + \frac{C_h}{C_c}\right)$$

or,

$$\left(\frac{t_{h2} - t_{c2}}{t_{h1} - t_{c1}}\right) = \exp\,[-\,(UA/C_h)\,\{1 + (C_h/C_c)\}] \qquad ...(10..40)$$

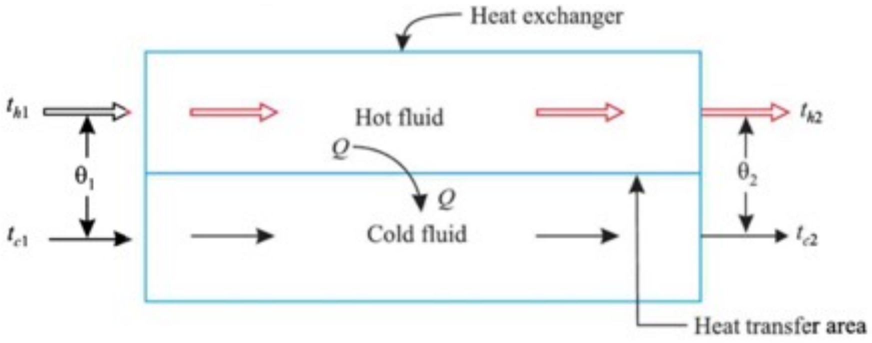


Fig.10.8

From eqn. (10.38), we have the expressions for effectiveness

$$\varepsilon = \frac{C_h\ (t_{h1} - t_{h2})}{C_{min}\ (t_{h1} - t_{c1})} = \frac{C_c\ (t_{c2} - t_{c1})}{C_{min}\ (t_{h1} - t_{c1})}$$

Hence,

$$t_{h2} = t_{h1} - \frac{\varepsilon\ C_{min}\ (t_{h1} - t_{c1})}{C_h} \qquad ...(10.41)$$

$$t_{c2} = t_{c1} + \frac{\varepsilon\ C_{min}\ (t_{h1} - t_{c1})}{C_c} \qquad ...(10.42)$$

Eliminating t_{h2} and t_{c2} from eqn. (10.40) with the help of eqns. (10.41) and (10.42), we get

$$\frac{1}{(t_{h1} - t_{c1})}\left[(t_{h1} - t_{c1}) - \varepsilon\ C_{min}\ (t_{h1} - t_{c1})\left(\frac{1}{C_h} + \frac{1}{C_c}\right)\right] = \exp\left[-\ (UA/C_h)\ \{1 + C_h/C_c)\}\right]$$

or,

$$1 - \varepsilon\ C_{min}\left(\frac{1}{C_h} + \frac{1}{C_c}\right) = \exp\left[-\ (UA/C_h)\ \{1 + C_h/C_c)\}\right]$$

or,

$$\varepsilon = \frac{1 - \exp\left[-\ (UA/C_h)\ \{1 + C_h/C_c)\}\right]}{C_{min}\left(\frac{1}{C_h} + \frac{1}{C_c}\right)} \qquad ...(10.43)$$

If $C_c > C_h$ then $C_{min} = C_h$ and $C_{max} = C_c$, hence eqn. (10.43) becomes

$$\varepsilon = \frac{1 - \exp\left[-\ (UA/C_{min})\ \{1 + C_{min}/C_{max})\}\right]}{1 + (C_{min}/C_{max})} \qquad ..(10.44)$$

If $C_c < C_h$ then $C_{min} = C_c$ and $C_{max} = C_h$, hence eqn. (10.43) becomes

$$\varepsilon = \frac{1 - \exp\left[-\ (UA/C_{max})\ \{1 + C_{max}/C_{min})\}\right]}{1 + (C_{min}/C_{max})} \qquad ...(10.45)$$

By rearranging eqns. (10.44) and (10.45), we get a common equation

$$\varepsilon = \frac{1 - \exp\,[-\,(UA/C_{min})\,\{1 + C_{min}/C_{max})\}]}{1 + (C_{min}/C_{max})}$$

where C_{min} and C_{max} represent the smaller and larger of the two heat capacities C_c and C_h.

- The grouping of the terms $(UA)/C_{min}$ is a dimensionless expression called the number of transfer units NTU; NTU is a *measure of effectiveness of the heat exchanger.*
- C_{min}/C_{max} is the second dimensionless parameter and is called the *capacity ratio R*.
- The last dimensionless parameter is the *flow arrangement*, *i.e.*, parallel flow, counter-flow, cross-flow and so on.

Thus the effectiveness of a parallel flow heat exchanger is given by

$$\varepsilon = \frac{1 - \exp\,[-\,NTU\ \{1 + (C_{min}/C_{max})\}]}{1 + (C_{min}/C_{max})} \qquad ...(10.46)$$

or,

$$\varepsilon = \frac{1 - \exp\,[-\,NTU\ (1 + R)]}{1 + R} \qquad ...[10.46\ (a)]$$

(*ii*) **"Counter-flow" heat exchanger :**

The heat exchange dQ through an area dA of the heat exchanger is given by

$$dQ = U.dA\,(t_h - t_c) \quad ...(i)$$

$$= -\dot{m}\,c_{ph}\,dt_h = -\dot{m}\,c_{pc}\,dt_c$$

$$= -C_h\,dt_h = -C_c\,dt_c \quad ...(ii)$$

From expression (*ii*), we have

$$dt_h = -\frac{dQ}{C_h} \text{ and } dt_c = -\frac{dQ}{C_c}$$

$\therefore$

$$d\,(t_h - t_c) = -dQ\left[\frac{1}{C_h} - \frac{1}{C_c}\right] = dQ\left[\frac{1}{C_c} - \frac{1}{C_h}\right]$$

Substituting the value of dQ from expression (*i*), we get,

$$\frac{d\,(t_h - t_c)}{t_h - t_c} = U\,dA\left[\frac{1}{C_c} - \frac{1}{C_h}\right]$$

Upon integration, we get

$$ln\left[\frac{t_{h2} - t_{c1}}{t_{h1} - t_{c2}}\right] = UA\left[\frac{1}{C_c} - \frac{1}{C_h}\right]$$

or,

$$ln\left[\frac{t_{h2} - t_{c1}}{t_{h1} - t_{c2}}\right] = \frac{UA}{C_c}\left[1 - \frac{C_c}{C_h}\right]$$

or,

$$\frac{t_{h2} - t_{c1}}{t_{h1} - t_{c2}} = \exp\,[(UA/C_c)\,\{1 - (C_c/C_h)\}] \quad ...(10.47)$$

we have the expressions for effectiveness,

$$\varepsilon = \frac{C_h\,(t_{h1} - t_{h2})}{C_{min}\,(t_{h1} - t_{c1})} = \frac{C_c\,(t_{c2} - t_{c1})}{C_{min}\,(t_{h1} - t_{c1})}$$

Hence,

$$t_{h2} = t_{h1} - \frac{\varepsilon\,C_{min}\,(t_{h1} - t_{c1})}{C_h} \quad ...(iii)$$

$$t_{c2} = t_{c1} + \frac{\varepsilon\,C_{min}\,(t_{h1} - t_{c1})}{C_c} \quad ...(iv)$$

Substituting these values in eqn. (10.47), we get,

$$\frac{\left[t_{h1} - \dfrac{\varepsilon\, C_{min}\,(t_{h1} - t_{c1})}{C_h}\right] - t_{c1}}{t_{h1} - \left[t_{c1} + \dfrac{\varepsilon\, C_{min}\,(t_{h1} - t_{c1})}{C_c}\right]} = \exp\,[(UA/C_c)\,\{1 - (C_c/C_h)\}]$$

$$\frac{(t_{h1} - t_{c1})\left[1 - \dfrac{\varepsilon\,.\,C_{min}}{C_h}\right]}{(t_{h1} - t_{c1})\left[1 - \dfrac{\varepsilon\,.\,C_{min}}{C_c}\right]} = \exp\,[(UA/C_c)\,\{1 - (C_c/C_h)\}]$$

or,

$$\frac{1 - \dfrac{\varepsilon\,.\,C_{min}}{C_h}}{1 - \dfrac{\varepsilon\,.\,C_{min}}{C_c}} = \exp\,[(UA/C_c)\,\{1 - (C_c/C_h)\}] \qquad \text{...(10.48)}$$

Assume $C_c < C_h$, $C_c = C_{min}$ and $C_h = C_{max}$. Substituting these values is eqn. (10.48), we get,

$$\frac{1 - \dfrac{\varepsilon\,.\,C_{min}}{C_{max}}}{1 - \dfrac{\varepsilon\,.\,C_{min}}{C_{min}}} = \exp\,[(UA/C_{min})\,\{1 - (C_{min}/C_{max})\}]$$

or,

$$\frac{1 - \dfrac{\varepsilon\,.\,C_{min}}{C_{max}}}{1 - \varepsilon} = \exp\,[(UA/C_{min})\,\{1 - (C_{min}/C_{max})\}]$$

or, $$1 - \frac{\varepsilon . C_{min}}{C_{max}} = \exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right] - \exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right]\varepsilon$$

or, $$1 - \exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right] = \varepsilon\left[\frac{C_{min}}{C_{max}} - \exp\left\{(UA/C_{min})(1 - C_{min}/C_{max})\right\}\right]$$

or, $$\varepsilon = \frac{1 - \exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right]}{\dfrac{C_{min}}{C_{max}} - \exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right]}$$

$$= \frac{\exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right] - 1}{\exp\left[(UA/C_{min})\{1 - (C_{min}/C_{max})\}\right] - \dfrac{C_{min}}{C_{max}}}$$

or, $$\varepsilon = \frac{1 - \exp\left[(-UA/C_{min})\{1 - (C_{min}/C_{max})\}\right]}{1 - \dfrac{C_{min}}{C_{max}}\exp\left[(-UA/C_{min})\{1 - (C_{min}/C_{max})\}\right]} \quad \text{...(10.49)}$$

Since $C_{min}/C_{max} = R$ and $UA/C_{min} = NTU$, therefore,

$$\varepsilon = \frac{1 - \exp\left[-NTU\,(1 - R)\right]}{1 - R\exp\left[-NTU\,(1 - R)\right]} \quad \text{...(10.50)}$$

We find that effectiveness of parallel flow and counter-flow heat exchangers is given by the following expressions :

$$(\varepsilon)_{parallel\ flow} = \frac{1 - \exp\left[-NTU\,(1 + R)\right]}{1 + R} \quad \text{...(1)}$$

$$(\varepsilon)_{counter\ flow} = \frac{1 - \exp\left[-NTU\,(1 - R)\right]}{1 - R\exp\left[-NTU\,(1 - R)\right]} \quad \text{...(2)}$$

where $R = (C_{min}/C_{max})$

Let us discuss *two limiting cases* of eqns. (1) and (2)

Case I : When $R \simeq 0$ **...Condensers and evaporators (boilers)**

By using the above case, we arrive at the following common expression for *parallel flow as well as counter-flow* heat exchangers

$$\varepsilon = 1 - exp\,(-\,NTU) \qquad ...(10.51)$$

Such cases are found in *condensers and evaporators in which one fluid remains at constant temperature throughout the exchanger*. Here $C_{max} = \infty$ and thus $R = \left(\frac{C_{\min}}{C_{\max}}\right) \simeq 0.$

Obviously, no matter how large the exchanger is or how large the overall transfer coefficient is the *maximum effectiveness for parallel flow heat exchanger is 50%. For counter-flow, this limit is 100%. For this reason, a counter flow is usually more advantageous for a gas turbine heat exchangers.*

Case II : When $R = 1$ ... **Typical regenerators**

(*i*) In case of *parallel flow* heat exchanger using $R = 1$, we get

$$\varepsilon = \frac{1 - \exp(-2NTU)}{2} \qquad \text{...(10.52)}$$

(*ii*) In case of *counter-flow* heat exchanger using $R = 1$ we get an expression for effectiveness which is indeterminate. We can find the value of ε by applying *L*, Hospital's rule :

$$\lim_{R \to 1} = \frac{1 - \exp[-NTU\ (1 - R)]}{1 - R \exp[-NTU\ (1 - R)]}$$

$$\lim_{R \to 1} = \frac{\exp[NTU\ (1 - R)] - 1}{\exp[NTU\ (1 - R)] - R}$$

Differrentiating the numerator and the denomenator with respect to R and taking the limit, we get,

$$\lim_{R \to 1} = \frac{\exp[NTU\ (1 - R)\ (-NTU)]}{\exp[NTU\ (1 - R)]\ (-NTU) - 1} = \frac{NTU}{1 + NTU} \qquad \text{...(10.53)}$$

The *NTU is a measure of the heat transfer size of the exchanger; the larger the value of NTU, the closer the heat exchanger approaches its thermodynamic limit.*

The effectiveness of various types of heat exchangers in the form of graphs (prepared by Kays and London) for values of $R \left(= \frac{C_{min}}{C_{max}}\right)$ and *NTU* are shown in Fig. 10.44 to 10.49.

PRESSURE DROP AND PUMPING POWER

Hal penting yang perlu dipertimbangkan dalam perancangan HE disamping syarat-syarat perpindahan kalor adalah *pressure drop & pumping cost.* Ukuran HE dapat diperkecil dengan memberikan gaya pada fluida pada kecepatan yang lebih tinggi sehingga meningkatkan koefisien perpindahan kalor keseluruhan *(overall heat transfer coefficient)*. Tetapi kecepatan fluida yang tinggi akan meningkatkan *pressure drop* menyebabkan *pumping cost* yang lebih besar.

Diameter pipa yang lebih kecil, untuk laju aliran yang diketahui, mungkin melibatkan biaya modal awal yang lebih sedikit tetapi *pumping cost* yang pasti lebih tinggi untuk masa pakai penukar kalor.

We know that, $\Delta p \propto \dot{m}^2$ ...(*i*)

where, Δp = Pressure drop of an incompressible fluid flowing through the pipes, and

$\dot{m}$ = Mass flow rate.

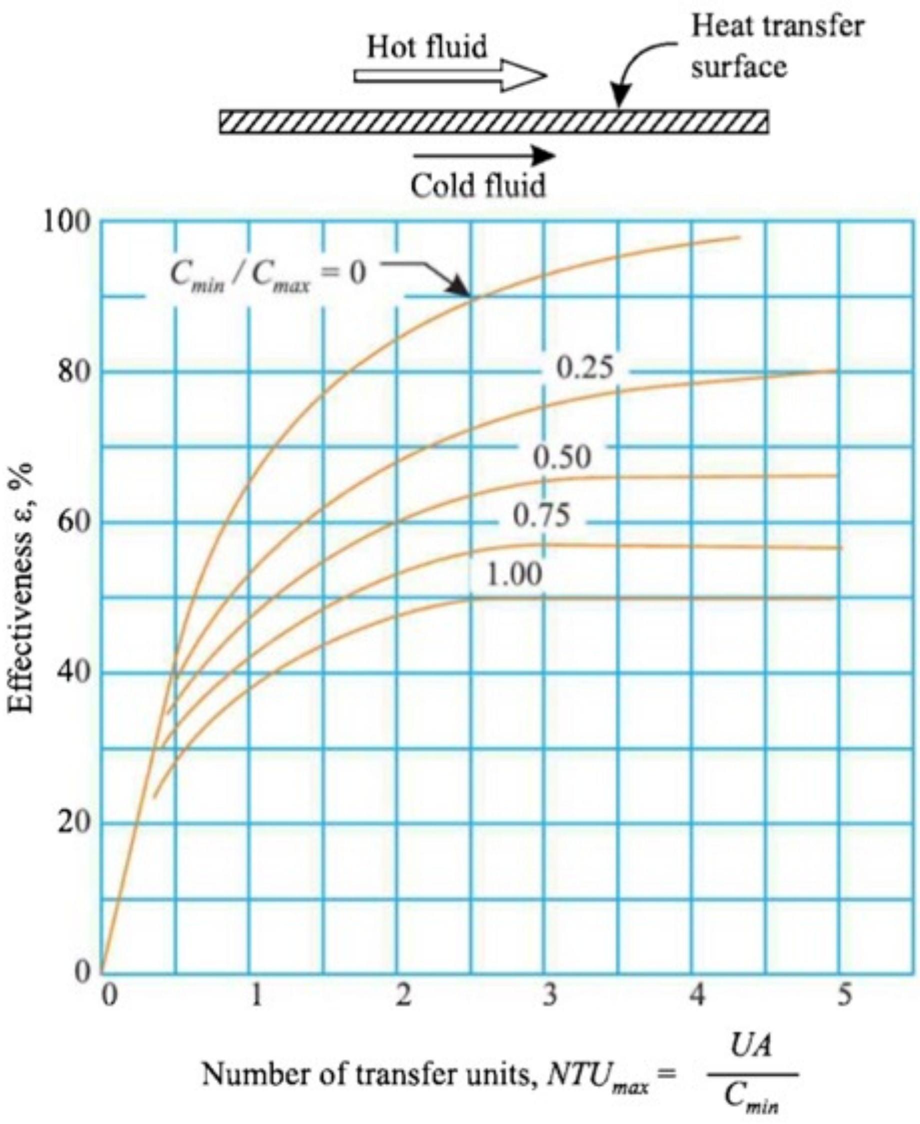


Fig. 10.44. Effectiveness for parallel flow heat exchanger.

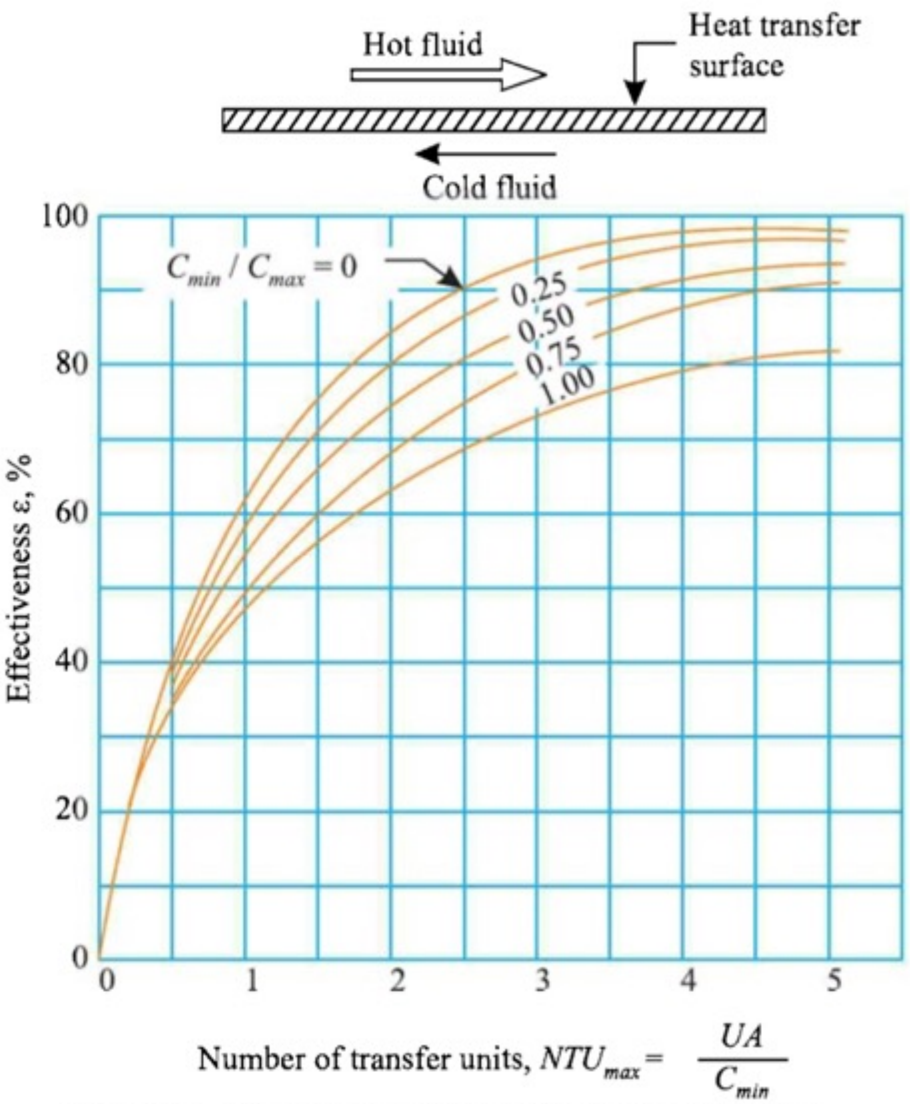


Fig. 10.45. Effectiveness for counter-flow heat exchange.

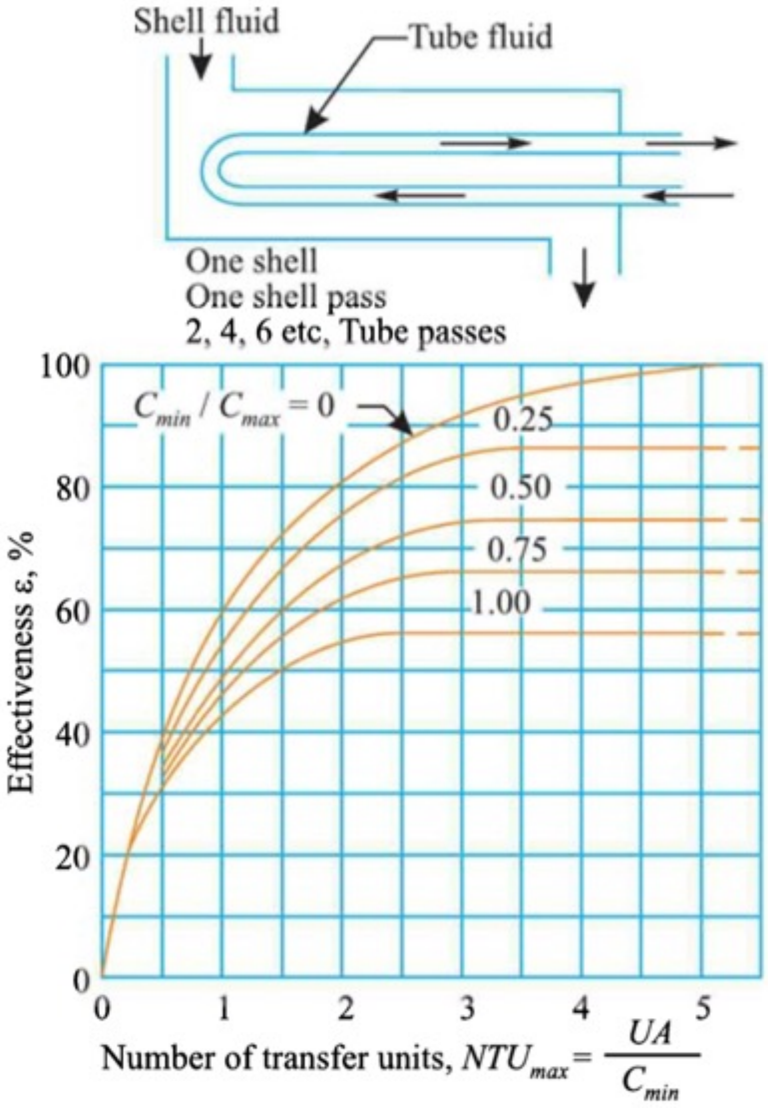


Fig. 10.46. Effectiveness for 1-2 parallel counter-flow heat exchanger.

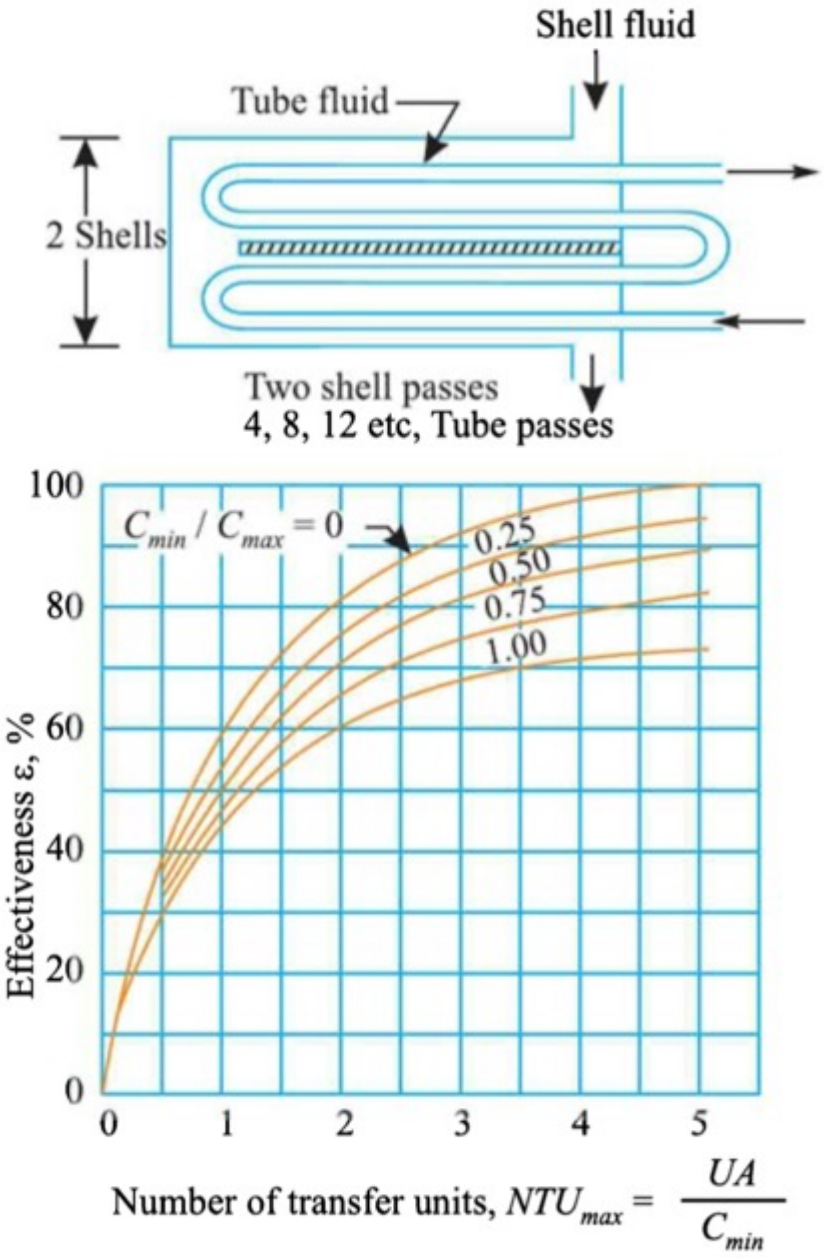


Fig. 10.47.

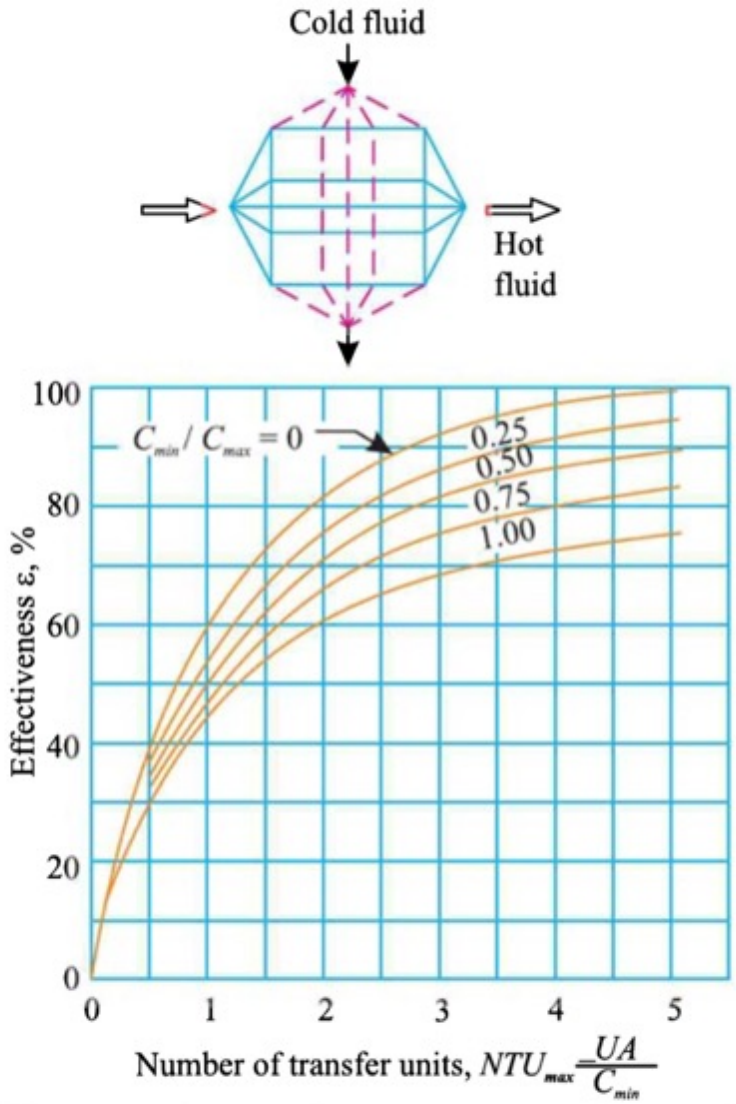


Fig. 10.48. Effectiveness for cross-flow heat exchanger with both fluids unmixed.

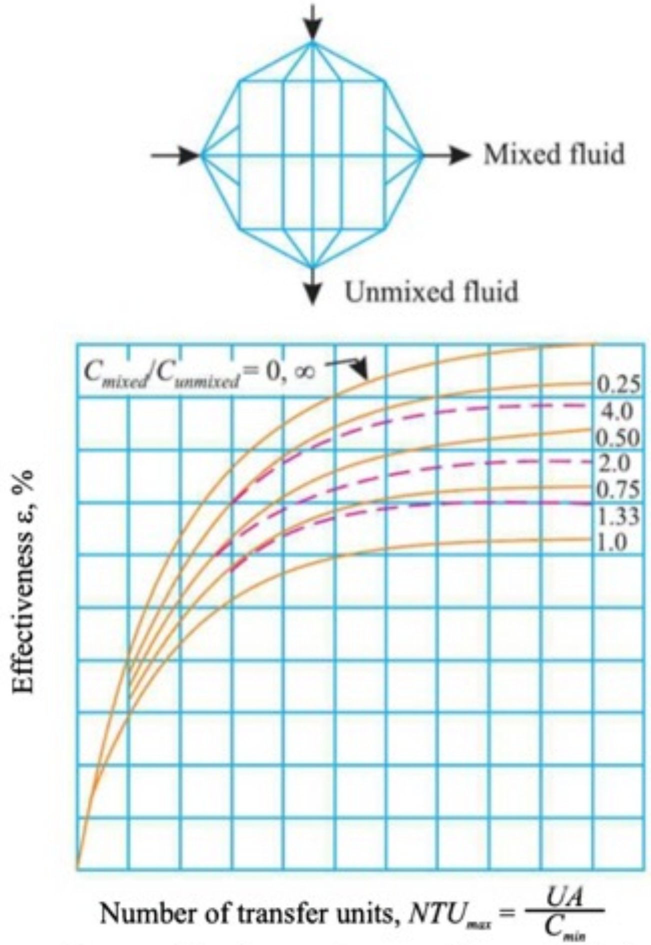


Fig. 10.49. Effectiveness for cross-flow heat exchanger with one fluid mixed and other unmixed.

In order to pump fluid in a steady state, the power requirement is given by

$$\text{Power} = \int v \, dp = \frac{\dot{m}}{\rho} \Delta p \simeq \dot{m}^3 \qquad \text{...}(ii)$$

This indicates that the *power requirement is proportional to the cube of the mass flow rate of the fluid* and it may be further increased by dividing it by the pump (fan or compressor) efficiency. Thus, we find that the *pumping cost increases greatly with higher velocities*, hence, a *compromise* will have to be made between the larger overall heat transfer coefficient and corresponding velocities.

Contoh 3: *Steam condenses at atmospheric pressure on the external surface of the tubes of a steam condenser. The tubes are 12 in number and each is 30 mm in diameter and 10 m long. The inlet and outlet temperatures of cooling water flowing inside the tubes are 25°C and 60°C respectively. If the flow rate is 1.1 kg/s, calculate the following:*

(i) The rate of condensation of steam,

(ii) The mean overall heat transfer coefficient based on the inner surface area,

(iii) The number of transfer units, and

(iv) The effectiveness of the condenser.

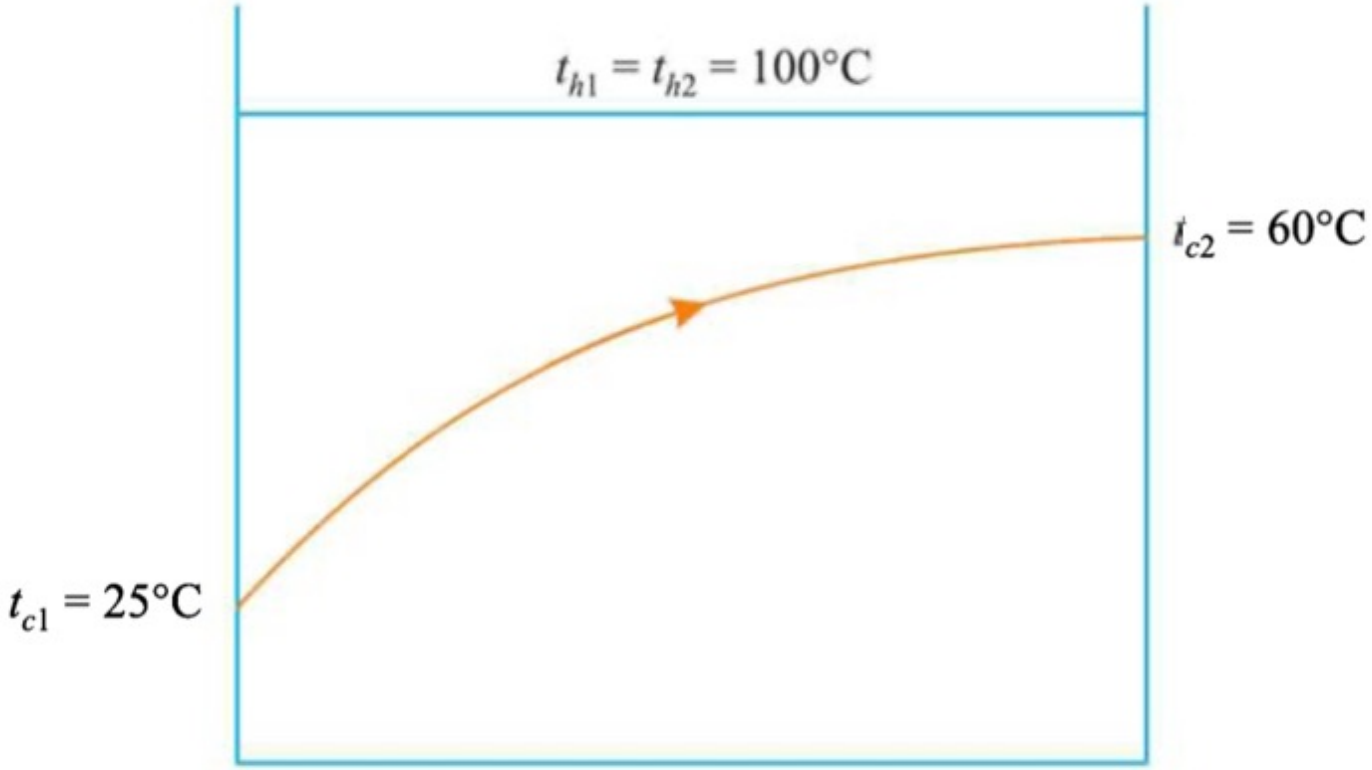


Fig. 10.50.

Solution. Refer to Fig. 10.50. *Given* : $N = 12$; $d_i = 30$ mm $= 0.03$ m; $L = 10$ m; $t_{c1} = 25°C$, $t_{c2} = 60°C$;

$t_{h1} = t_{h2} = 100°C$; $\dot{m}_w = \dot{m}_c = 1.1$ kg/s

(*i*) The rate of condensation of steam, $\dot{m}_s$ (= $\dot{m}_h$)

Heat lost by steam = Heat gained by water

$$\dot{m}_s \times h_{fg} = \dot{m}_c \times c_{pc} (t_{c2} - t_{c1})$$

where h_{fg} (latent heat of steam) at atmospheric pressure = 2257 kJ/kg. Substituting the values, we get,

$$\dot{m}_s \times 2257 = 1.1 \times 4.187 \times (60 - 25)$$

or, $$\dot{m}_s = 0.0714 \text{ kg/s} = \mathbf{257 \text{ kg/h}} \text{ (Ans.)}$$

(*ii*) The mean overall heat transfer coefficient, U :

Total heat transfer rate is given by

$$Q = \dot{m}_c \times c_{pc} \times (t_{c2} - t_{c1})$$

$$= 1.1 \times 4.187 \times 10^3 \times (60 - 25) = 161199.5 \text{ J/s}$$

Also, $$Q = U A \theta_m$$

where, $$\theta_m = \frac{\theta_1 - \theta_2}{\ln (\theta_1/\theta_2)} = \frac{(100 - 25) - (100 - 60)}{\ln [(100 - 25)/(100 - 60)]} = \frac{75 - 40}{\ln (75/40)} = 55.68°C$$

and $$A = N \times (\pi d L) = 12 \times \pi \times 0.03 \times 10 = 11.31 \text{ m}^2$$

Substituting the values in the above equation, we get

$$161199.5 = U \times 11.31 \times 55.68$$

or, $$U = \mathbf{255.9\ W/m^2°C} \qquad \textbf{(Ans.)}$$

(*iii*) The number of transfer units, *NTU* :

In a condenser, C_{max} refers to the hot fluid which remains at constant temperature. Therefore, C_{min} refers to water;

$$C_{min} = \dot{m} \times c_{pc} = 1.1 \times (4.187 \times 10^3) = 4605.7 \text{ W/°C}$$

$$\therefore \qquad NTU = \frac{UA}{C_{min}} = \frac{255.9 \times 11.31}{4605.7} = \mathbf{0.628} \qquad \textbf{(Ans.)}$$

(*iv*) The effectiveness of the condenser, ε :

$$\varepsilon = 1 - \exp(-NTU) \qquad \text{...[Eqn. (10.51)]}$$

or, $$\varepsilon = 1 - \exp(-0.628) = \mathbf{0.47} \qquad \textbf{(Ans.)}$$

Contoh 4: *Steam at atmospheric pressure enters the shell of a surface condenser in which the water flows through a bundle of tubes of diameter 25 mm at the rate of 0.05 kg/s. The inlet and outlet temperatures of water are 15°C and 70°C, respectively. The condensation of steam takes place on the outside surface of the tube. If the overall heat transfer coefficient is 230 W/m²°C, calculate the following, using NTU method :*

(i) The effectiveness of the heat exchanger,

(ii) The length of the tube, and

(iii) The rate of steam condensation.

Take the latent heat of vaporisation at 100°C = 2257 kJ/kg

Solution. *Given* :

$$d = 25 \text{ mm} = 0.025 \text{ m};\ \dot{m}_w = \dot{m}_c = 0.05 \text{ kg/s},\ t_{c1} = 15°\text{C},\ t_{c2} = 70°\text{C};$$

$$U = 230 \text{ W/m}^2°\text{C};\ t_{h1} = 100°\text{C}.$$

(*i*) The effectiveness of the heat exchanger, ε :

Throughout the condenser the hot fluid (*i.e.*, steam), remains at constant temperature. Hence C_{max} is infinity and thus C_{min} is obviously for cold fluid (*i.e.*, water). Thus $\dfrac{C_{min}}{C_{max}} \simeq 0.$

When $C_h > C_c$, then effectiveness is given by

$$\varepsilon = \frac{Q}{Q_{max}} = \frac{t_{c2} - t_{c1}}{t_{h1} - t_{c1}} = \frac{70 - 15}{100 - 15} = \mathbf{0.647} \qquad \textbf{(Ans.)}$$

(*ii*) The length of the tube, L :

$$C_{min} = \dot{m}_c\, c_{pc} = 0.05 \times 4.18 = 0.209 \text{ kJ/K}$$

For $$\frac{C_{min}}{C_{max}} (= R) \simeq 0$$

$$\varepsilon = 1 - \exp(-\text{NTU}) \qquad \text{...[Eqn (10.51)]}$$

or, $$0.647 = 1 - e^{-NTU}$$

or, $$e^{-NTU} = 1 - 0.647 = 0.353$$

or, $$-NTU = \ln(0.353) = -1.04$$

$\therefore$ $$NTU = 1.04$$

But, $$NTU = \frac{UA}{C_{min}} = \frac{U \times \pi\, d\, L}{C_{min}}$$

or, $$L = \frac{NTU \times C_{min}}{U\, \pi\, d} = \frac{1.04 \times (0.209 \times 1000)}{230 \times \pi \times 0.025} = \mathbf{12\ m} \qquad \textbf{(Ans.)}$$

(*iii*) The rate of steam condensation, $\dot{m}_h$:

Using the overall energy balance, we get

$$\dot{m}_h\, .\, h_{fg} = \dot{m}_c\, c_{pc}\, (t_{c2} - t_{c1})$$

$$= \dot{m}_h \times 2257 = 0.05 \times 4.18\, (70 - 15)$$

$$\dot{m}_h = 0.00509 \text{ kg/s or } \mathbf{18.32\ kg/h} \qquad \textbf{(Ans.)}$$

Contoh 5: *A counter-flow heat exchanger is employed to cool 0.55 kg/s (cp = 2.45 kJ/kg°C) of oil from 115°C to 40°C by the use of water. The intel and outlet temperatures of cooling water are 15°C and 75°C, respectively. The overall heat transfer coefficient is expected to be 1450 W/m²°C. Using NTU method, calculate the following :*

(i) *The mass flow rate of water;*

(ii) *The effectiveness of the heat exchanger;*

(iii) *The surface area required.*

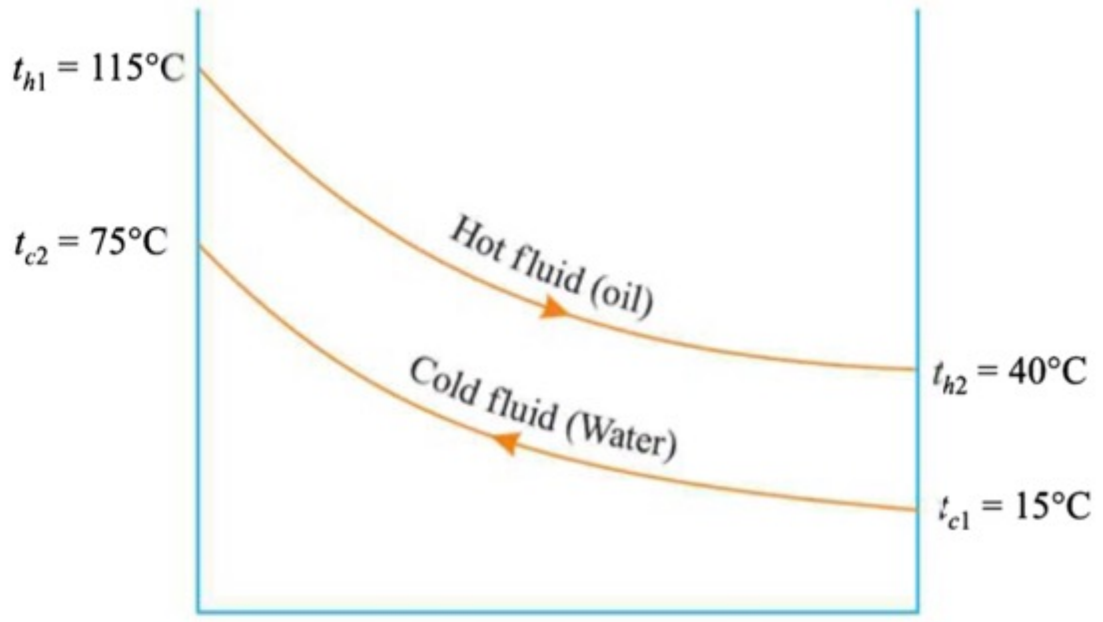


Fig. 10.51.

Solution. *Given* : $\dot{m}_{oil} = \dot{m}_h = 0.55$ kg/s; $c_{ph} = 2.45$ kJ/kg°C; $t_{h1} = 115$°C, $t_{h2} = 40$°C; $t_{c1} = 15$°C, $t_{c2} = 75$°C; $U = 1450$ W/m²°C.

(*i*) The mass flow rate of water, $\dot{m}_c$ (= $\dot{m}_w$) :

The mass flow rate of water can be found by using the overall energy balance

$$\dot{m}_h\ c_{ph}\ (t_{h1} - t_{h2}) = \dot{m}_c\ c_{pc}\ (t_{c2} - t_{c1})$$

$$0.55 \times 2.45\ (115 - 40) = \dot{m}_c \times 4.18\ (75 - 15)$$

$$\therefore \qquad \boldsymbol{\dot{m}_c = 0.4\ \text{kg/s}} \qquad \textbf{(Ans.)}$$

(*ii*) The effectiveness of the heat exchanger, ε :

The thermal capacity of cold stream (water), $C_c = \dot{m}_c\ c_{pc} = 0.4 \times 4.18 = 1.672$ kW

The thermal capacity of hot stream (oil), $C_h = \dot{m}_h\ c_{ph} = 0.55 \times 2.45 = 1.347$ kW

Since $C_c > C_h$, hence the effectiveness of the heat exchanger is given by

$$\varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum heat transfer}} = \frac{Q}{Q_{max}} = \frac{t_{h1} - t_{h2}}{t_{h1} - t_{c1}} \qquad \text{...[Eqn. (10.35)]}$$

$$\therefore \qquad \varepsilon = \frac{115 - 40}{115 - 15} = \mathbf{0.75} \qquad \textbf{(Ans.)}$$

(*iii*) The surface area required, *A* :

Here, $\quad C_{min} = C_h = 1.347$ kW; $\quad C_{max} = C_c = 1.672$ kW, hence

$$\frac{C_{min}}{C_{max}} = R = \frac{1.347}{1.672} = 0.806$$

For counter-flow heat exchanger,

$$\varepsilon = \frac{1 - \exp[-NTU\,(1-R)]}{1 - R\exp[-NTU\,(1-R)]} \quad \text{...[Eqn. (10.50)]}$$

After rearrangement, we get

$$\frac{\varepsilon - 1}{(\varepsilon R - 1)} = \exp[-NTU\,(1-R)]$$

or, $$\frac{0.75 - 1}{(0.75 \times 0.806 - 1)} = \exp[-NTU\,(1 - 0.806)]$$

or, $$0.632 = \exp[-NTU \times 0.194]$$

or, $$\ln 0.632 = -0.194\,NTU$$

or, $$NTU = 2.365$$

[This value of NTU may also be obtained from Fig. 10.45 for $R = \frac{C_{min}}{C_{max}} = 0.806$ and $\varepsilon = 0.75$]

Also, $$NTU = \frac{UA}{C_{min}}$$

or, $$2.365 = \frac{1450 \times A}{1.347 \times 1000}$$

or, $$A = \frac{2.365 \times 1.347 \times 1000}{1450} = \mathbf{2.197\ m^2\ (Ans.)}$$

Contoh 6: *. 16.5 kg/s of the product at 650°C (c_p = 3.55 kJ/kg°C), in a chemical plant, are to be used to heat 20.5 kg/s of the incoming fluid from 100°C (c_p = 4.2 kJ/kg°C). If the overall heat transfer coefficient is 0.95 kW/m²°C and the installed heat transfer surface is 44 m², calculate the fluid outlet temperatures for the counter-flow and parallel flow arrangements.*

Solution. *Given* : $\dot{m}_h$ = 16.5 kg/s, t_{h1} = 650°C; c_{ph} = 3.55 kJ/kg°C; $\dot{m}_c$ = 20.5 kg/s; t_{c1} = 100°C; c_{pc} = 4.2 kJ/kg°C; U = 1.2 kW/m²°C; A = 44 m².

Fluid outlet temperatures :

Case I. *Counter-flow arrangement :*

Thermal capacity of hot fluid, $C_h = \dot{m}_h \times c_{ph} = 16.5 \times 3.55 = 58.6$ kW/K

Thermal capacity of cold fluid, $C_c = \dot{m}_c \times c_{pc} = 20.5 \times 4.2 = 86.1$ kW/K

The cold fluid is the maximum fluid, whereas the hot fluid is the minimum fluid. Therefore,

$$\frac{C_{min}}{C_{max}} = R = \frac{58.6}{86.1} = 0.68$$

Number of transfer units, $$NTU = \frac{UA}{C_{min}} = \frac{0.95 \times 44}{58.6} = 0.71$$

The value of ε (effectiveness) for counter-flow arrangement is given by

$$\varepsilon = \frac{1 - \exp[-NTU\ (1 - R)]}{1 - R\exp[-NTU\ (1 - R)]} \qquad \text{...[Eqn. (10.50)]}$$

$$= \frac{1 - \exp[-0.71(1-0.68)]}{1 - 0.68 \times \exp[-0.71(1-0.68)]} = \frac{1 - e^{-0.2272}}{1 - 0.68 \times e^{-0.2272}}$$

$$= \frac{0.2032}{0.4582} = 0.443$$

Further, $$\varepsilon = \frac{C_h(t_{h1} - t_{h2})}{C_{\min}(t_{h1} - t_{c1})} \quad \text{...[Eqn. (10.38)]}$$

Because, the *hot fluid is minimum*, we have

$$\varepsilon = \frac{t_{h1} - t_{h2}}{t_{h1} - t_{c1}} = \frac{650 - t_{h2}}{650 - 100} = 0.443 \quad (\because C_h = C_{min})$$

or, $$\boldsymbol{t_{h2}} = 650 - 0.443(650 - 100)$$

$$\mathbf{= 406.35°C} \quad \textbf{(Ans.)}$$

Also, $$\varepsilon = \frac{C_c(t_{c2} - t_{c1})}{C_{min}(t_{h1} - t_{c1})} \quad \text{...[Eqn. (10.38)]}$$

$$0.443 = \frac{86.1(t_{c2} - 100)}{58.6(650 - 100)} = 0.002671(t_{c2} - 100)$$

$\therefore$ $$\boldsymbol{t_{c2}} \mathbf{= 265.8°C} \quad \textbf{(Ans.)}$$

Case II. *Parallel flow arrangement :*

The value of ε for parallel flow arrangement is given by

$$\varepsilon = \frac{1 - \exp\left[- NTU\ (1 + R)\right]}{1 + R} \qquad \text{...[Eqn. 10.46 (a)]}$$

$$= \frac{1 - \exp\left[- 0.71\ (1 + 0.68)\right]}{(1 + 0.68)]} = \frac{1 - e^{-1.1928}}{1.68} = 0.415$$

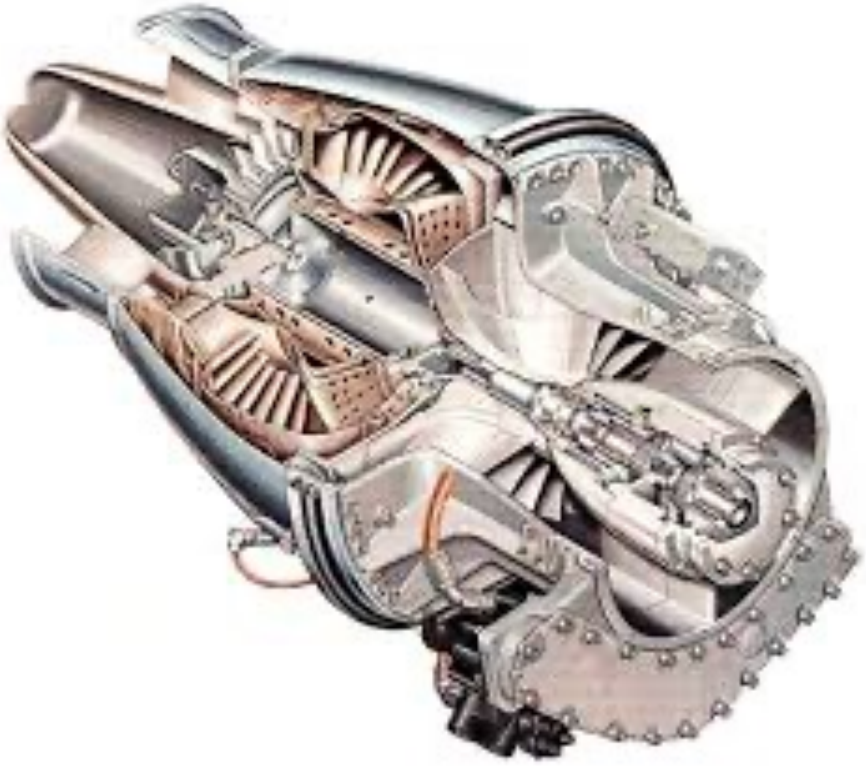
Also,

$$\varepsilon = \frac{C_c\ (t_{c2} - t_{c1})}{C_{min}\ (t_{h1} - t_{c1})} \qquad \text{...[Eqn. (10.28)]}$$

or,

$$0.415 = \frac{86.1\ (t_{c2} - 100)}{58.6\ (650 - 100)} = 0.002671\ (t_{c2} - 100)$$

or, $\boldsymbol{t_{c2} = 255.4°C}$ **(Ans.)**



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