HEAT TRANSFER

Module -IV

Contents :

OBJECTIVE TYPE QUESTIONS & ANSWERS

SHORT TYPE QUESTIONS & ANSWERS

LONG TYPE QUESTIONS & ANSWERS

Bijan Kumar Giri

Contents :

Heat Transfer

MODULE - IV

Most Important
OBJECTIVE TYPE QUESTIONS & ANSWERS

On

Chapter-1 : Boiling and Condensation
Chapter-2 : Heat Exchangers

Bijan Kumar Giri
bijankumargiri@gmail.com
MECHANICAL ENGINEERING

HEAT EXCHANGERS

4. Heat Exchanger

366. The mathematical expression of NTU in a heat exchanger is,
U = Overall heat transfer coefficient
C = Heat capacity
E = Effectiveness
A = Area of heat exchanger
(a) UA/C_{min} (b) UA/C_{max}
(c) UA/E (d) $\frac{UC_{max}}{C_{min}}$

TNPSC 2019
TNPSC AE 2013
TSPSC AEE 2015

Ans. (a) : The mathematical expression of NTU in a heat exchanger is given as $NTU = \frac{UA}{C_{min}}$

Since, number of transfer units (NTU) is directly proportional to the area. It indicates the overall size or bulkiness of H.E. usely NTU values are practically 1.115
1.2, 1.5, 2, 2.5, 4
$NTU \ngtr 18$

367. The fouling factor
(a) Increases the overall heat transfer coefficient
(b) Decreases the overall heat transfer coefficient
(c) Is equal to the overall heat transfer coefficient
(d) None of the above

UKPSC AE 2007 Paper -II

Ans. (b) : Fouling factor is dirt factor, typically denoted as (F). This is used for calculation o over all heat transfer coefficient in heat exchangers.
The fouling factor decreases the overall heat transfer coefficient. This is a measure of the thermal resistance introduce by fouling.

368. The fouling factor in case of heat exchangers is given by ____
(a) $\frac{1}{U_{dirty}} + \frac{1}{U_{clean}}$ (b) $\frac{1}{U_{dirty}} - \frac{1}{U_{clean}}$
(c) $\frac{1}{U_{dirty}}$ (d) $\frac{1}{U_{dirty}} - 1$

TSPSC AEE 2015

Ans. (b) : Fouling factor (F) in case of heat exchanger is given by,

$$F = \frac{1}{U_{dirty}} - \frac{1}{U_{clean}}$$

369. When is arithmetic mean temperature difference used instead of LMTD in heat exchange?
(a) When temperature profiles of two fluids of heat exchanger are sloping downward with curve
(b) When the temperature profiles of two fluids of heat exchanger are sloping upward with curve
(c) When the temperature profiles of two fluids of heat exchanger are straight
(d) When one of the temperature profile for the fluid is straight

APPSC AEE 2016

Ans. (c) : When the temperature profiles of two fluids of heat exchanger are sloping upward with curve then arithmetic mean temperature difference used instead of LMTD in heat exchanger.

370. For evaporators and condensers, for the given conditions, the Logarithmic Mean Temperature Difference (LMTD) for parallel flow is
(a) Equal to that for counter flow
(b) Greater than that for counter flow
(c) Less than that for counter flow
(d) Very much smaller than that for counter flow

TNPSC AE 2017

Ans. (a) : Logarithmic mean temperature difference (LMTD) → LMTD is defined as that temperature difference which is constant would give the same rate of heat transfer as actually occure at under variable condition of temperature difference.

$$\text{LMTD } \theta_m = \frac{\theta_1 - \theta_2}{ln\left(\theta_1/\theta_2\right)}$$

371. For a specified NTU and capacity ratio 'c', the effectiveness will be the highest for
(a) parallel flow heat exchanger

(b) counter flow heat exchanger
(c) cross flow heat exchanger
(d) parallel flow and cross flow heat exchanger

TNPSC AE 2018

Ans. (b) : Effectiveness for the parallel flow-

$$\varepsilon = \frac{1-\exp\left[-(1+C)NTU\right]}{1+C}$$

Effectiveness for the counter flow-

$$\varepsilon = \frac{1-\exp\left[-(1-C)NTU\right]}{1-C\exp\left[-NTU(1-C)\right]}$$

372. The Log mean Temperature Difference (LMTD) for the same inlet and outlet temperatures of hot and cold fluids, is
(a) greater for parallel flow heat exchanger than for counter flow heat exchanger
(b) greater for counter flow heat exchanger than for parallel flow heat exchanger
(c) same for both parallel and counter flow heat exchangers
(d) dependent on the heat transfer coefficient of the fluids
(e) dependent upon the thermal conductivity of material of the heat exchangers

CGPSC AE 2014 -II

Ans. (c) : The Log Mean Temperature Difference (LMTD) for the same inlet and out let temperatures of hot and cold fluids, is same for both parallel and counter flow heat exchanger.

373. In a shell and tube heat exchanger, floating head is used for
(a) less corrosion of tubes
(b) large temperature differentials
(c) high heat transfer co-efficient
(d) low pressure drop
(e) small temperature differentials

CGPSC AE 2014 -II

Ans. (b) : In a Shell and tube heat exchanger, floating head is used for large temperature differentials.

374. Consider following facts about fouling factor.
1. is a dimensionless quantity
2. accounts for additional resistance to heat flow
3. depend upon temperature
4. Its unit is m^2 K/W

Of these, which are correct
(a) 1 (b) 1 and 2
(c) 2 and 3 (d) 2, 3 and 4
(e) 1 and 4

CGPSC AE 2014 -II

Ans. (d) :
1. It is reciprocal of heat transfer coefficient (h)

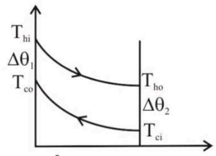
$$F \propto \frac{1}{h}$$

2. Its unit is m^2 K/W
3. Depend upon temperature
4. Accounts for additional resistance to heat flow.

375. In a counter flow heat exchanger, cold fluid enters at 30^0C and leaves at 50^0C, whereas hot fluid enters at 150^0C and leaves at 130^0C. The mean temperature difference for this case is :
(a) Indeterminate (b) 20^0C
(c) 80^0C (d) 100^0C

RPSC Vice Principal ITI 2018

Ans. (d) :



$\Delta\theta_1 = 150^0 - 50^0 = 100^0C$
$\Delta\theta_2 = 130^0 - 30^0 = 100^0 C$
$\because \Delta\theta_1 = \Delta\theta_2$
So LMTD is equal to AMTD

$$\therefore \text{ AMTD} = \frac{\Delta\theta_1 + \Delta\theta_2}{2} = \frac{100+100}{2}$$

$\boxed{LMTD = 100^0C}$

376. The equation of effectiveness $\in = 1 - e^{-NTU}$ of a heat exchanger is valid in the case of–
(a) boiler & condenser for parallel flow
(b) boiler & condenser counter flow
(c) boiler & condenser for both parallel flow and counter flow
(d) gas turbine for both parallel flow and counter flow

RPSC INSP. OF FACTORIES AND BOILER 2016

Ans : (c) We know that heat capacity ratio,

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

In phase change (Boiling and condensation both) C_{max} is very high or infinite so capacity ratio is zero.
Effectiveness of heat exchanger in both parallel and counter flow changes to

$$\boxed{\in = 1 - e^{-NTU}}$$

377. Heat is transferred by all three modes of heat transfer in–
(a) refrigeration (b) condenser
(c) electric bulb (d) boiler furnace

RPSC INSP. OF FACTORIES AND BOILER 2016

Ans : (d) There are three ways that heat is transferred. Conduction, radiation and convection and all three means occur in a boiler.
• Heat is transfer from fire side to water side by conduction mode via tube.
• Heat is transfer by convection mode to form hot water and steam and back to water to the boiler.
• Heat is transfer by radiation mode from fire side light waves are directly emitted on water tube.

378. Consider the following statements : in a shell and tube heat exchange, baffles are provided on the shell side to (a) prevent the stagnation of shell side fluid (b) improve heat transfer (c) provide support for tubes (d) prevent fouling of the above four statements the correct ones are-
(a) (b), (c) and (d) (b) (a), (b) and (c)
(c) (a), (c) and (d) (d) (a), (b) and (d)

RPSC INSP. OF FACTORIES AND BOILER 2016

Ans : (b)
a. Prevent the stagnation of shell side fluid
b. Improve heat transfer
c. Provide support for tubes

379. Heat is transferred by all there modes of transfer, viz, conduction, convection and radiation in

(a) Electric heater (b) Steam condenser
(c) Melting of ice (d) Boiler

Vizag Steel (MT) 2017

Ans. (d) : There are three modes of heat transfer in boiler conduction, convection and radiation. Heat is transfer from fire side to water side by conduction mode via tube.

380. The effectiveness relation for all heat exchangers reduces to $\varepsilon = \varepsilon_{max} = 1 - \exp(-NTU)$ when the capacity ratio (C) (NTU refers to Number of Transfer Units)

(a) C = 1 (b) C < 1
(c) C > 1 (d) C = 0

TNPSC 2019

Ans. (d) : Effectiveness for parallel H.E.

$$\varepsilon_p = \frac{1-\exp\left[-(1+C)NTU\right]}{(1+C)}$$

Effectiveness for counter flow H.E.

$$\varepsilon_p = \frac{1-\exp\left[-(1-C)NTU\right]}{1-C\exp\left[-(1-C)NTU\right]}$$

When one of the fluids in the H.E. is under going change of phase like in steam condenser or evaporator then C = 0

$$\varepsilon_p = \varepsilon_c = 1-\exp(-NTU)$$

381. A steel ball of mass 1 kg and specific heat 0.4 kJ/kg is at a temperature of 60ºC. It is dropped into 1 kg of water at 20ºC. The final steady state temp of water is,

(a) 23.5ºC (b) 30ºC
(c) 35ºC (d) 40ºC

TNPSC AE 2017

Ans. (a) : Data given,
$m_b = 1$ kg, $C_b = 0.4$ kJ/kg
$T_b = 60$ºC
$m_w = 1$ kg
$T_w = 20$ºC
We know that,
Heat loss by ball = Heat given by water

$$[mC\Delta T]_{ball} = [mC\Delta T]_{water}$$

Specific heat for water

$$C_w = 4.18 \text{ kJ/kg}$$

$$1 \times 0.4 \times [60 - T_f] = 1 \times 4.18 \times [T_f - 20]$$

$$\boxed{T_f = 23.5ºC}$$

382. In a heat exchanger, the hot liquid enters at a temperature of 180⁰C and leaves at 160ºC. The cooling fluid enters at 30oC and leaves at 110oC. The capacity ratio of the heat exchanger is

(a) 0.25 (b) 0.40
(c) 0.50 (d) 0.55

TNPSC AE 2018

Ans. (a) : We know that, Heat loss by hot liquid = heat gain by cold liquid

$$[mC\Delta T]_h = [mC\Delta T]_c$$

$$[mC]_h \times (180-160)$$

$$= (mC)_c \times (110-30)$$

It means, $(mC)_h > (mC)_c$

So, the capacity ratio of the heat exchanger

$$C = \frac{(mC)_{min}}{(mC)_{max}}$$

$$\frac{(mC)_c}{(mC)_h} = \frac{20}{80} = 0.25$$

383. In a heat exchanger, hot gasses enter with a temperature of 250°C and leave at 50°C. On the other side, air enters at a temperature of 50°C and leaves at 90°C. The effectiveness of the exchanger is to be quoted as:

(a) 0.15 (b) 0.20
(c) 0.25 (d) 0.30

JWM 2017

Ans. (*) : Effectiveness of heat exchanger

$$= \frac{\text{Actual heat transfer}}{\text{Max. possible heat transfer}}$$

$$\in = \frac{Q}{Q_{max}} = \frac{C_h(t_{h_1} - t_{h_2})}{C_{min}(t_{h_1} - t_{c_1})}$$

Where C_{min} = Minimum of c_h and C_c
C_h = and C_C = heat capacity
t_{h1} = Temperature of hot fluid at inlet
t_{h2} = Temperature of hot fluid at exit
t_{c1} = Temperature of cold fluid at inlet
t_{c2} = Temperature of cold fluid at exit.

$$\in = \frac{C_h(250-50)}{C_{min}(250-50)} = 1$$

384. The unit of fouling factor is:

(a) W/m² -K (b) m-K/W
(c) K/W (d) m²/K
(e) m²-K/W

CGPSC AE 2014- II

Ans. (e) : We know that-
unit of fouling factor

$$= \frac{1}{\text{unit of heat transfer coefficient }(h)}$$

$$= \frac{1}{\left[\frac{W}{m^2-K}\right]} = \frac{m^2-K}{W}$$

385. The equation of effectiveness $\varepsilon = 1 - e^{-NTU}$ of heat exchanger is valid (NTU) is number of transfer units) in the case of-

(a) boiler and condenser for parallel flow
(b) boiler and condenser for counter flow
(c) boiler and condenser for both parallel and counter flow
(d) gas turbine for both parallel and counter flow

RPSC AE 2018

Ans. (c) : The equation of effectiveness for parallel flow heat exchanger

$$\varepsilon_{parallel} = \frac{1-e^{-(1+C)NTU}}{1+C}$$

and

$$\varepsilon_{counter} = \frac{1-e^{-(1-C)NTU}}{1-C\times e^{-(1-C)NTU}}$$

If one of the fluid in heat exchanger is undergoing change of phase like in steam condenser or evaporator and boiler then C = 0.

So,

$$\varepsilon_{parallel} = \varepsilon_{counter} = 1 - e^{-NTU}$$

386. In a parallel flow heat exchanger, the NTU is calculated to be 2.5. The lowest possible effectiveness for this heat exchanger is

(a) 10% (b) 27%
(c) 41% (d) 50%

TNPSC AE 2014

Ans. (d) : In a parallel flow heat exchanger, NTU = 2.5. Then the lowest possible effectiveness for this heat exchanger will be 50%.

387. The correction factor of multipass counter flow heat exchanger depends on

(a) Fluid properties
(b) Geometry alone
(c) Temperature of Inlet and outlet fluid stream only
(d) Mass flow rates of hot and cold fluid streams

TNPSC AE 2014

Ans. (c) : The correction factor of multipass counter flow heat exchanger depends on temperature of Inlet and outlet fluid stream only.

388. Cold water (C_p = 4.18 kJ/kg°C) enters a heat exchanger at 15°C at a rate of 0.5kg/s, where it is heated by hot air (C_p = 1.0 kJ/kg°C) that enters the heat exchanger at 50°C at a rate of 1.8 kg/s. The maximum possible heat transfer rate in this heat exchange is

(a) 51.1 kW (b) 63.0 kW
(c) 66.8 kW (d) 73.2 kW

TNPSC AE 2014

Ans. (b) : For cold water

C_P = 4.18 kJ/kg°C
T_{iw} = 15°C
m_{cw} = 0.5 kg/s

For hot air

C_p = 1.0 kJ/kg°C
T_{iA} = 50°C
m_{HA} = 1.8 kg/s

We know that, maximum possible heat transfer rate

$$\dot{Q}_{max} = C_{min}(T_{iA} - T_{iW})$$

$$C_W = [m\,c_p]_W = 0.5\times 4.18$$

C_W = 2.09 kJ/°C
$C_{HA} = (m\,c_p)$ = 1.8 × 1 = 1.8 kJ/°C
C_{min} = 1.8 kJ/°C

$$\dot{Q}_{max} = 1.8 \times (50 - 15)$$

$$\boxed{\dot{Q}_{max} = 63\text{kW}}$$

389. Effectiveness of heat exchanger is function of:

(a) Heat capacity ratio only
(b) Surface area of heat exchanger only
(c) NTU and heat capacity ratio
(d) NTU only

UPRVUNL AE 2016

Ans. (c) : The effectiveness (ε) of a heat exchanger is defined as the ratio of the actual heat transfer to the maximum possible heat transfer.

$$\varepsilon = \frac{q}{q_{max}}$$

For heat exchanger

$$\varepsilon = f\left[NTU, \frac{C_{min}}{C_{max}}\right]$$

where the number of transfer unit, NTU

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

where,

U - overall heat transfer coefficient and A is the heat transfer area.

390. Effectiveness (ε) and NTU relation for condenser may be written as

(a) NTU = ln(1 + ε) (b) NTU = ln(1 - ε)
(c) NTU = - ln(1 - ε) (d) $\varepsilon = \frac{NTU}{1+NTU}$

RPSC LECTURER 16.01.2016

Ans. (c) : In condenser and evaporator there will be phase change of fluid so heat capacity ratio will be zero.

$$\varepsilon = 1 - e^{-NTU}$$

(same for parallel and counter flow heat exchanger)

$$NTU = -\ln(1-\varepsilon)$$

391. For a compression or heating process what is the expression for effectiveness ∈

(a) $\in = \frac{\text{increase of availability of surroundings}}{\text{loss of availability of the system}}$

(b) $\in = \frac{\text{increase of availability of the system}}{\text{loss of availability of the surroundings}}$

(c) $\in = \frac{\text{loss of availability of the surroundings}}{\text{increase of availability of the system}}$

(d) $\in = \frac{\text{loss of availability of the system}}{\text{increase of availability of the surroundings}}$

TNPSC AE 2018

Ans. (b) : $\in = \frac{\text{increase of availability of the system}}{\text{loss of availability of the surroundings}}$

392. For shell and tube heat exchanger, the corrosive liquid is normally passed through

(a) Shell side
(b) Tube side
(c) Either of (1) and (2) above
(d) None of the above

Nagaland PSC CTSE 2017 Paper-2

Ans. (b) : In a shell and tube exchanger, the corrosive liquid is normally passed through tube side.

393. The NTU of a heat exchanger is an index of its
(a) Number of tubs (b) Number of passes
(c) Mode of operation (d) Performance
Nagaland PSC CTSE 2017 Paper-2

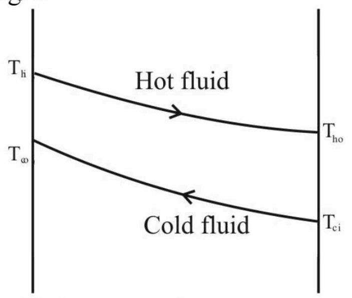
Ans. (d) : The NTU is a measure of heat transfer size of the exchanger, the larger the value of NTU the closer the heat exchanger approaches its thermodynamics limit.

394. The overall heat transfer coefficient in a fouled heat exchanger is comparison to the clean heat exchanger is
(a) Negligible (b) equal
(c) more (d) less
Nagaland PSC CTSE 2017 Paper-2

Ans. (d) : The overall heat transfer coefficient in a fouled heat exchanger in comparison to the clean heat exchanger is less, because it leaves trace/deposits on the surface of the separating wall.

395. In a double pipe counter flow heat exchanger, 10,000 kg/hr of oil [C_P = 2.09 kJ/kg-K] is cooled from 80°C to 50°C by water [C_P = 4.18 kJ/kg-K] of flow rate 8000 kg/hr entering at 25°C. What will be outlet temperature of water?
(a) 63.75°C (b) 52.55°C
(c) 48.15°C (d) 43.75°C
SJVN ET 2019

Ans. (d) : Given,
T_{hi} = 80ºC
T_{ho} = 50ºC
C_{ph} = 2.09 kJ/kg-K
m_{ph} = 10000 kg/hr
T_{ci} = 25ºC
T_{co} = ?
C_{pc} = 4.18 kJ/kgk
m_c = 8000 kg/hr



Applying heat balance equation,
$m_h C_{ph} (T_{hi} - T_{ho}) = m_c C_{pc} (T_{co} - T_{ci})$

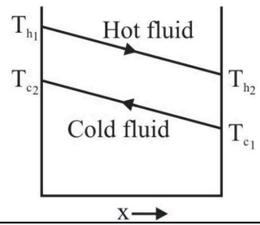
$$\frac{10000}{3600}\times 2.09\times(80-50) = \frac{8000}{3600}\times 4.18\times(T_{co}-25)$$
$$T_{co} - 25 = 18.75$$
$$T_{co} = 43.75ºC$$

396. Flat plate collectors are used to heat the water upto the temperature of
(a) 70-90ºC (b) 100-200ºC
(c) 200-300ºC (d) 300-400ºC
RPSC LECTURER 16.01.2016

Ans. (a) : Flat plate collectors—A Flat plate collector is a heat exchanger that converts the radiant solar energy from the sun into heat energy using the well known green house effect. It collects or capture, solar energy and uses that energy to heat water in the home for bathing, washing and heating etc.
A solar flate plate collector typically consists of a large heat absorbing plate, usually a large sheet of copper or aluminium as they are both good conductors of heat, which is painted or chemically etched black to absorb as much solar radiation as possible for maximum efficiency. This is used to heat the water upto the temperature of 70-90ºC.

397. In a counterflow heat exchanger, hot gases enter the system at 200ºC and leave at 80ºC. The temperature of the outside air entering the unit is 35ºC. Its temperature at the exit is 90º C. The heat exchanger has an effectiveness of
(a) 0.35 (b) 0.34
(c) 0.33 (d) 0.32
ESE 2018

Ans. (*) : Given,
T_{h_1} = 200°C
T_{h_2} = 80°C
T_{c_1} = 35°C
T_{c_2} = 90°C



From energy balance
$$C_h(T_{h_1} - T_{h_2}) = C_c(T_{c_2} - T_{c_1})$$
$$C_h(200 - 80) = C_c(90 - 35)$$
$$120\ C_h = 55\ C_c$$
$$\frac{C_h}{C_c} = \frac{55}{120}$$
$$C_h = C_{min}$$
$$C_c = C_{max}$$
$$\text{effectiveness } (\in) = \frac{C_h(T_{h_1} - T_{h_2})}{C_{min}(T_{h_1} - T_{c_1})}$$
$$= \frac{200-80}{200-35} = 0.727$$

398. Consider the following statements:
1. The efficiency of heat transfer in a condenser will improve by increase of the overall heat transfer coefficient.
2. The efficiency of heat transfer in a condenser will improve by increase of the velocity of flow of water in the tube.
3. The difference between the temperature of steam entering the condenser and the inlet water temperature should be maximum for maximum efficiency.

Which of the above statements are correct?
(a) 1 and 2 only (b) 1 and 3 only
(c) 2 and 3 only (d) 1, 2 and 3
ESE 2017

Ans. (a) : $Q = UA\,\Delta T_m$
As velocity of flow of water increases the convective heat transfer co-efficient on water side increases. As a result U value increases.

Condenses efficiency $= \dfrac{T_{wo} - T_{wi}}{T_s - T_{wi}}$

If $(T_s - T_{wi})$ is maximum denominator increases hence condenser efficiency decreases.
Where
T_{wi} = temperature of cooling water at inlet
T_{wo} = temperature of cooling water at outlet
T_s = temperature of steam corresponding to the actual absolute pressure in the condenser.

399. In a counter flow heat exchanger, hot gases enter at 250°C and leave at 100°C. Atmospheric air enters at 50° C and leaves at 80°C. The effectiveness of the heat exchanger will be
(a) 0.20 (b) 0.25
(c) 0.30 (d) 0.35

ESE 2017

Ans. (*) : Given,
$T_{h_1} = 250°C \qquad T_{c_1} = 50°C$
$T_{h_2} = 100°C \qquad T_{c_2} = 80°C$
From energy balance equation
$$\dot{m}_h c_{ph}\left(T_{h_1} - T_{h_2}\right) = \dot{m}_c c_{pc}\left(T_{c_2} - T_{c_1}\right)$$
$$\dot{m}_h c_{ph}(250 - 100) = \dot{m}_c c_{pc}(80 - 50)$$
$$\dot{m}_h c_{ph} < \dot{m}_c c_{pc}$$
Hence effectiveness of heat exchanger
$$\in = \frac{T_{h_1} - T_{h_2}}{T_{h_1} - T_{c_1}} = \frac{250 - 100}{250 - 50}$$
= 0.75 (Not in options)

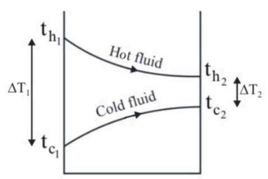
400. LMTD of a heat exchanger with ΔT_1 , and ΔT_2 being temperature differences between the hot and cold fluids at entrance and exit, respectively is:

(a) $\dfrac{\Delta T_2 - \Delta T_1}{\log\left[\dfrac{\Delta T_2}{\Delta T_1}\right]}$ (b) $\dfrac{\Delta T_2 - \Delta T_1}{\log\left[\dfrac{\Delta T_1}{\Delta T_2}\right]}$

(c) $\dfrac{\Delta T_2 - \Delta T_1}{\dfrac{\Delta T_2}{\Delta T_1}}$ (d) $\log\dfrac{\left[\Delta T_2 - \Delta T_1\right]}{\left[\dfrac{\Delta T_2}{\Delta T_1}\right]}$

OPSC AEE 2015 PAPER - II
UKPSC AE 2012 Paper–II

Ans : (a)



Parallel Heat Exchanger

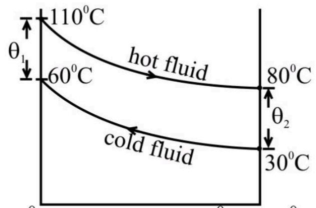
$\Delta T_1 = t_{h_1} - t_{c_1}$
$\Delta T_2 = t_{h_2} - t_{h_1}$

LMTD for Parallel flow heat exhanger
$$\text{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\log_e\left(\Delta T_2 / \Delta T_1\right)}$$

401. A counter flow heat exchanger, the hot fluid is cooled from 110°C to 80°C by a cold fluid which gets heated from 30°C to 60°C. LMTD for heat exchanger is :
(a) 80°C (b) 50°C
(c) 30°C (d) 20°C

HPPSC W.S. Poly. 2016

Ans : (b)

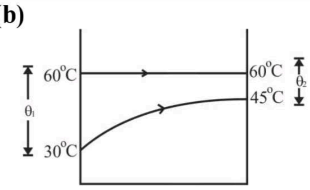


$\theta_1 = 110^0\,C - 60^0C \qquad \theta_2 = 80^0C - 30^0C$
$\theta_1 = 50°C \qquad \theta_2 = 50°C$
Hence $\boxed{\theta_1 = \theta_2 = \text{LMTD} = 50^o C}$

402. In a condenser of a power plant, the steam condenses at a temperature of 60 °C. The cooling water enters at 30 °C and leaves at 45°C. Logarithmic Mean Temperature Difference (LMTD) of the condenser
(a) 16.2 °C (b) 21.6 °C
(c) 30 °C (d) 37.5 °C

UPPSC AE 12.04.2016 Paper-II

Ans : (b)



$$\theta_1 = 60^o C - 30^o C = 30^o C$$
$$\theta_2 = 60^o C - 45^o C = 15^o C$$
Log mean temperature difference
$$\theta_m = \frac{\theta_1 - \theta_2}{\log_e\left(\dfrac{\theta_1}{\theta_2}\right)}$$
$$\theta_m = \frac{30 - 15}{\log_e\left(\dfrac{30}{15}\right)}$$
$$\theta_m = \frac{15}{0.693}$$
$$\boxed{\theta_m = 21.6°C}$$

403. In a heat exchanger, the temperature of the hot fluid decreases while temperature of the cold fluid increases. The increase and decrease following :
(a) A quadratic law (b) A linear law
(c) A cubic law (d) An exponential law

UPPSC AE 12.04.2016 Paper-II

Ans : (d) The increase and decrease following an exponential law.

404. If one of the two fluids flowing through a heat exchanger of NTU = 2 remains at constant temperature throughout the exchanger length, the effectiveness of the heat exchanger will be

(a) $1 - e^{-4}$ (b) $1 - e^{-2}$

(c) $\frac{1-e^{-2}}{2}$ (d) $\frac{1-e^{2}}{2}$

BPSC Poly. Lect. 2016

Ans : (b) It one of the two fluids flowing through a heat exchanger of NTU = 2 remains at Constant temperature throughout the exchanger length, the effectiveness of the heat exchanger will be $1\text{-}e^{-2}$

405. In a certain heat exchanger, both the fluids have identical mass flow rate and specific heat product. The hot fluid enters at 76 °C and leaves at 47 °C and cold fluid enters at 26 °C and leaves at 55 °C. The effectiveness of the heat exchanger is

(a) 0.16 (b) 0.58
(c) 0.72 (d) 1.0

UKPSC AE 2012 Paper–II

Ans. (b) : 0.58

406. During the process of boiling and condensation only a phase change takes place, and one fluid remains at constant temperature throughout the heat exchanger. In terms of number of transfer units (NTU), the effectiveness of such heat exchanger would be

(a) $\frac{NTU}{1+NTU}$

(b) 1 – exp (–NTU)

(c) $\frac{1-\exp(-2NTU)}{2}$

(d) cannot be worked out as heat capacities are unknown

UKPSC AE 2012 Paper–II

Ans. (b) : 1 – exp (–NTU)

407. For a double pipe, counter flow heat exchanger with C = 1 ($C = C_{min} / C_{max}$) the effectiveness is equal to:-

(a) $\frac{NTU}{NTU-1}$ (b) $1+1/NTU$

(c) $\frac{NTU}{NTU+1}$ (d) $\frac{NTU+1}{NTU-1}$

UKPSC AE-2013, Paper-II

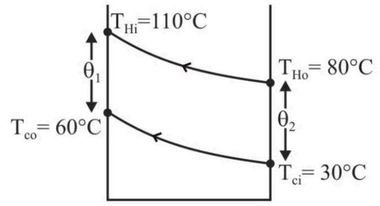
Ans. (c) :

408. In a counterflow heat exchanger, the hot fluid is cooled from 110°C to 80°C by a cold fluid which is heated from 30°C to 60°C. LMTD for the heat exchanger will be:-

(a) 80°C (b) 50°C
(c) 30°C (d) 20°C

UKPSC AE-2013, Paper-II

Ans. (b) : We know that, LMTD = $\left[\frac{\theta_1 - \theta_2}{\ln \theta_1 / \theta_2}\right]$



$\theta_1 = 50°C, \theta_2 = 50°C$

It is the case as a balanced counter-flow heat exchanger

So, LMTD = 50°C

409. Fouling factor in the design of heat exchanger is used considering the fact that:-

(a) It is used when a liquid exchanges heat with gas
(b) It is used in case of Newtonian fluids
(c) It is used as a dimensionless factor
(d) It is a factor of safety in design

UKPSC AE-2013, Paper-II

Ans. (d) :

410. A correction of L.M.T.D. is necessary in case of

(a) cross flow heat exchanger
(b) parallel flow heat exchanger
(c) counter flow heat exchanger
(d) all of the above

UKPSC AE 2007 Paper -II

Ans. (a) : Cross flow heat exchanger is a recuperater type heat exchanger in which hot fluids and cold fluid flow line intersect to each other.

* In this heat changer a correction of LMTD is necessary.

* LMTD for cross flow and multiplies heat exchanger

= Correction factor × $LMTD_{counter\ flow}$

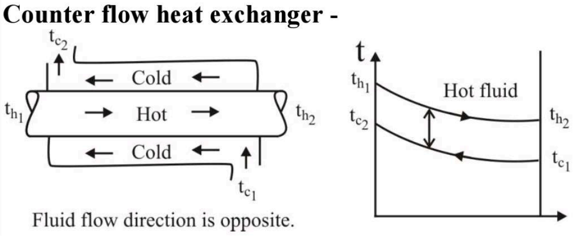
411. L.M.T.D. in case of counter flow heat exchanger as compared to parallel flow heat exchanger is

(a) higher (b) lower
(c) same (d) cannot be predicted

UKPSC AE 2007 Paper -II
UKPSC AE-2013, Paper-II
TNPSC AE 2013
Nagaland PSC CTSE 2017 Paper-2

Ans. (a) : LMTD in case of case of counter flow heat exchanger as compared to parallel flow heat exchanger is higher so counter flow heat exchanger is more effective and more useful.

Counter flow heat exchanger -



412. In case of heat exchanger, the value of logarithmic mean temperature difference should be

(a) as small as possible (b) as large as possible
(c) constant (d) none of the above

UKPSC AE 2007 Paper -II

Ans. (b) : LMTD – Logarithmic mean temperature difference. It is a performance approach of heat exchangers.

* It is defined as the temperature different which, if constant would give the same rate of heat transfer as actually occurs under variable conditions of temperature difference.

* LMTD ↑ ⇒ Performance of Heat exchanger ↑

So, in case of heat exchanger, the value of logarithmic mean temperature difference (LMTD) should be as large as possible.

413. For evaporation and condensation in a heat exchanger, the required surface area will be minimum for which type of flow?

(a) Cross (b) Counter
(c) Parallel (d) Same for all the cases

OPSC AEE 2019 PAPER - II

Ans : (d) : Same for all the cases

414. Fouling factor is used:

(a) In heat exchanger design as a safety factor
(b) In case of Newtonian fluids
(c) When a liquid exchanges heat with a gas
(d) None of these

OPSC AEE 2019 PAPER - II

Ans : (a) : Fouling factor is used in heat exchanger design as a safety factor.

415. A designer chooses the values of fluid flow rates and specific heats in such a manner that the heat capacities of the two fluids are equal. A hot fluid enters the counter flow heat exchanger at 100ºC and leaves at 60ºC. A cold fluid enters the heat exchanger at 40ºC. The mean temperature difference between the two fluids is:

(a) 30ºC (b) 20ºC
(c) 40ºC (d) 60ºC

OPSC AEE 2019 PAPER - II

Ans : (b) : Given,

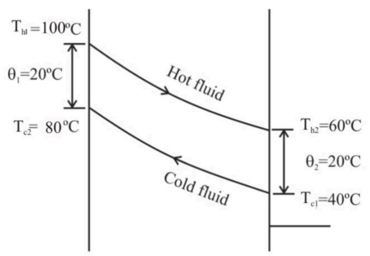
$T_{h1} = 100$ ºC
$T_{h2} = 60$ ºC
$T_{c1} = 40$ ºC
$T_{c2} = ?$

Applying heat balance equation,

$$\left(T_{h_1} - T_{h_2}\right) = \left(T_{c_2} - T_{c_1}\right)$$

$$(100 - 60) = T_{c_2} - 40$$

$$T_{c_2} = 80^\circ C$$



$\because \theta_1 = \theta_2$

$\therefore$ Log mean temperature difference (LMTD)

LMTD = $\theta_1 = \theta_2$

LMTD = 20ºC

416. In a heat exchanger, the oil is cooled from 135ºC to 15ºC with the water, if water inlet temperature is 5ºC and oil and water has the same mass flow rate $(C_p)_{oil}$ = 1.04 Joule/gram and $(C_p)_{water}$ = 4.16 Joule/gram, the water outlet temperature is:

(a) 150 (b) 135
(c) 30 (d) 35

Gujarat PSC AE 2019

Ans : (d) : Applying heat balancing equation,

$$m_h c_{P_h}\left(T_{h_1} - T_{h_2}\right) = m_c C_{P_c}\left(T_{c2} - T_{c1}\right)$$

Here, $T_{h_1} = 135^oC$
$T_{h_2} = 15^oC$
$T_{c_1} = 5^oC$
$T_{c_2} = ?$
C_{P_h} = 1.04 Joule/gram
C_{P_c} = 4.16 Joule/gram
$\dot{m}_h = \dot{m}_c$

$$1.04\ (135 - 15) = 4.16\ (T_{c_2} - 5)$$

$$\boxed{T_{c_2} = 35^oC}$$

417. An adiabatic heat exchanger is used to heat cold water at 15ºC entering at a rate of 5 kg/s by hot air at 90ºC entering also at a rate of 5 kg/s. If the exit temperature of hot air is 20ºC, the exit temperature of cold water is

(a) 27ºC (b) 32ºC
(c) 52ºC (d) 85ºC

Gujarat PSC AE 2019

Ans : (b) : Applying heat balancing equation,

$$m_h C_{P_h}\left(T_{h_1} - T_{h_2}\right) = m_c C_{P_c}\left(T_{c_2} - T_{c_1}\right)$$

Here, $T_{h_1} = 90^oC$
$T_{h_2} = 20^oC$
$T_{c_1} = 15^oC$
$T_{c_2} = ?$
m_h = 5 kg/s
m_c = 5 kg/s
$C_{P_h} = 1.008$ kJ/kgK
$C_{P_c} = 4.18$ kJ/kgK

So, $5 \times 1.0085\ (90 - 20) = 5 \times 418\ (T_{c_2} - 15)$

$$70.56 = 418.(T_{c_2} - 15)$$

$$T_{c_2} = 31.88^oC$$

$$\boxed{T_{c_2} = 32^oC}$$

418. For evaporators and condensers, for the given conditions, the logarithmic mean temperature difference (LMTD) for parallel flow is:

(a) Equal to that for counter flow
(b) Greater than that for counter flow
(c) Smaller than that for counter flow
(d) Very much smaller than that for counter flow

Gujarat PSC AE 2019

Ans : (a) : The heat exchange through evaporators and condensers does not depend on direction of flow.

419. A cross flow type air heater has an area of 50 m^2. The overall heat transfer co-efficient is 100 W/m^{2}K and heat capacity of both hot and cold stream is 1000 W/K. The value of NTU is

(a) 1000 (b) 500
(c) 5 (d) 0.2

Gujarat PSC AE 2019
UKPSC AE 2012 Paper–II

Ans : (c) :

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

$A = 50 \text{ m}^2$
$U = 100 \text{ W/m}^2\text{K}$
$C_{min} = 1000 \text{ W/K}$

$$NTU = \frac{100 \times 50}{1000}$$

$\boxed{NTU = 5}$

5. Boiling and Condensation

420. Nucleate boiling is promoted

(a) on polished surface
(b) on rough surfaces
(c) in the absence of agitation
(d) none of these

RPSC Vice Principal ITI 2018

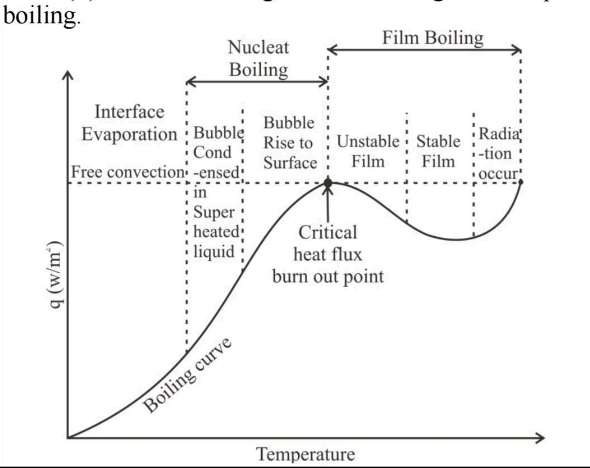
Ans. (b) : Nucleate boiling is a type of boiling that takes place when the surface temperature is hotter than the saturated fluid temperature by a certain amount. The heat transfer from surface to liquid is greater than that in film boiling.

421. Which of the following is not the regimes of pool boiling?

(a) Natural convection boiling
(b) Nucleate boiling
(c) Film boiling
(d) Flow boiling
(e) Transition boiling

CGPSC AE 2014- II
UPRVUNL AE 2016

Ans. (d) : Flow boiling is not the regimes of pool boiling.



422. Consider the following phenomena

1. Boiling
2. Free convection in air
3. Forced convection
4. Conduction in air

Their correct sequence in the increasing order of heat transfer is

(a) 4, 2,3,1 (b) 4,1,3,2
(c) 4,3,2,1 (d) 3,4,1,2
(e) 4,2,1,3

CGPSC AE 2014 -II

Ans. (a) : Current sequence in the increasing order of heat transfer is

Conduction in air < Free convection <
forced convection < Boiling

423. Which of the following is true?

(a) Heat transfer coefficient in dropwise condensation is very low in comparison to filmwise condensation
(b) Filmwise condensation is preferred over dropwise condensation on heat transfer surface
(c) Dropwise condensation required very high area of heat exchanger relative to filmwise condensation
(d) Dropwise condensation cannot be easily sustained for prolonged period of time

UPRVUNL AE 2016

Ans. (d) : Dropwise condensation cannot be easily sustained for prolonged period of time.

424. Nukiyama's Boiling curve is plotted between

(a) Boiling temperature vs excess temperature
(b) Boiling heat flux vs boiling temperature
(c) Boiling temperature vs boiling pressure
(d) Boiling heat flux vs excess temperature

RPSC LECTURER 16.01.2016

Ans. (d) : Nukiyama's Boiling curve is plotted between boiling heat flux vs excess temperature.

425. Nucleate boiling regime is formed approximately between (ΔT excess = excess temperature)

(a) $5°C \le \Delta T_{excess} \le 10°C$
(b) $50°C \le \Delta T_{excess} \le 80°C$
(c) $80°C \le \Delta T_{excess} \le 100°C$
(d) $5°C \le \Delta T_{excess} \le 50°C$

UPRVUNL AE 2016

Ans. (d) : When ΔT excess equal or greater than 5ºC and equal or less than 50ºC then Nucleate boiling regime is formed

$$5°C \le \Delta T_{excess} \le 50°C$$

426. Consider the following statements:
For the laminar condensation on a vertical plate, the Nusselt theory says that
1. Inertia force in the film is negligible compared to viscosity and weight
2. Heat flow is mainly by conduction through the liquid film, convection in liquid film as well as in vapour is neglected
3. Velocity of vapour is very high

Which of the above statements are correct?
(a) 1, 2 and 3 (b) 1 and 2 only
(c) 1 and 3 only (d) 2 and 3 only

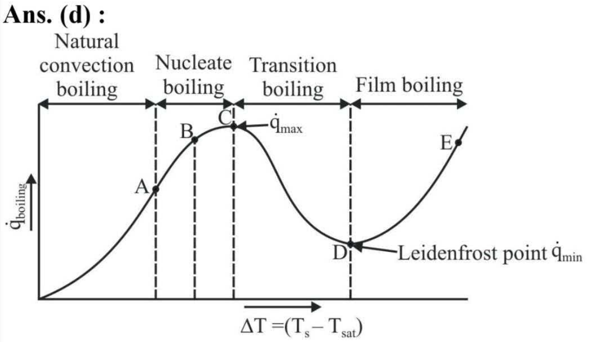
ESE 2019

Ans. (b) : Nusselt theory for the vertical plate
(i) The acceleration of condensate layer is negligible.
(ii) Heat transfer across the liquid film is by pure conduction (no convection current and in the liquid film and vapour)
(iii) The velocity of vapour is low so that it exerts no drag on the condensate (no viscous shear on the liquid vapour interface)

427. Which one of the following regimes of boiling curve can be considered as reverse of condensation?
(a) Free convection boiling regime
(b) Nucleate boiling regime
(c) Transition boiling regime
(d) Film boiling regime

ESE 2018

Ans. (d) :



(i) **Natural Convection Boiling (to point A on the boiling curve)**–We do not see any bubbles forming on the heating surface.
(ii) **Nucleate Boiling (Between Point A and C)**–The first bubbles start forming at point A of the boiling curve. The nucleate boiling regime can be separated into two distinct regions i.e. AB and BC.
(iii) **Transition Boiling (Between Point C and D)**–As the ΔT is increases past point C, the heat flux decreases.
(iv) **Film Boiling (Beyond Point D)**–In this region the heater surface is completely covered by a continuous stable vapour film.

■ Boiling take heat and condensation release heat. Boiling and condensation is opposite phenomenon. The nucleate boiling exist up to $\Delta T \simeq 40°C$ while film boiling temperature is greater than nucleate boiling.
So for film regime, condensation and boiling can be considered as reverse phenomenon.

428. Dropwise condensation occurs on the following surface:
(a) Oily (b) Smooth
(c) Glazed (d) Coated

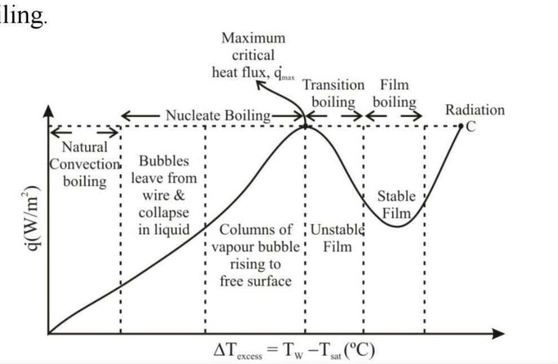
UKPSC AE 2007 Paper -II

Ans. (a) : Dropwise condensation is a surface condensation in which 90% of surface is covered by drops. It occurs on the oily surface.
* Droplet formation is superior to film formation in terms of maintaining high condensation and heat transfer rates.

429. Which of the following is not the regimes of pool boiling?
(a) Film boiling regime
(b) Nucleate boiling regime
(c) Slug flow regime
(d) Natural convection boiling regime

UPRVUNL AE 2016

Ans. (c) : Slug flow regime is not the regimes of pool boiling.



430. Large heat transfer coefficients for vapour condensation can be achieved by promoting
(a) Film condensation
(b) Dropwise condensation
(c) Cloud condensation
(d) Dew condensation

ESE 2020

Ans. (b) : Dropwise condensation.

Heat Transfer

MODULE - IV

Most Important
SHORT TYPE QUESTIONS & ANSWERS

On

Chapter-1 : Boiling and Condensation
Chapter-2 : Heat Exchangers

Bijan Kumar Giri

bijankumargiri@gmail.com

MECHANICAL ENGINEERING

1.What is meant by pool boiling?

Ans : If heat is added to a liquid from a submerged solid surface, the boiling process is referred to as pool boiling. In the case the liquid above the hot surface is essentially stagnant and its motion near the surface is due to free convection and mixing induced by bubble growth and detachment.

2. State the difference between the drop wise condensation and film wise condensation.

Ans : **Filmwise condensation:**

The liquid condensate wets the solid surface, spreads out and forms a continuous film over the entire surface is known as film wise condensation.

Drop wise condensation:

In drop wise condensation, the vapor condenses into small liquid droplets of various sizes which fall down the surface in a random fashion.

3. What is meant by LMTD ?

We know that the temperatures difference between the hot and cold fluids in the heat exchanger varies from point to point. In addition various modes of heat transfer are involved. Therefore based on concept of appropriate mean temperature difference, also called logarithmic mean temperature difference, the total heat transfer rate in the heat exchanger is expressed as

Q= UA(LMTD)

Where U = Over all heat coefficient W/ K

A = Area, m2

T- Temperature difference.

4. What is meant by Fouling factor?

We know the surface of a heat exchanger do not remain clean after it has been in use for some time. The surfaces become fouled with scaling or deposits. The effect of these deposits affecting the value of overall heat transfer coefficient. This effect is taken care of by introducing an additional thermal resistance called the fouling factor.

5. What is meant by condensation?

The change of phase from vapour to liquid state is known as condensation.

6. What is compact heat exchanger?

Answer : There are many special purpose heat exchangers called compact heat exchangers .They are generally employed when convective heat transfer coefficient associated with one of the fluids is much smaller than the associated with the other fluid.

7. Define Effectiveness.

The heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer.

Effectiveness = Actual heat transfer/ maximum possible heat transfer.

8. What is meant by parallel flow heat exchangers and counter flow heat exchanger?

Parallel flow heat exchanger:

In this type of heat exchanger, hot and cold fluids move in the same direction.

Counter flow heat exchanger:

In this type of heat exchanger,hot and cold fluids move in parallel but in opposite directions.

9. What is heat exchanger?

A heat exchanger is defined as an equipment which transfers the heat from a hot fluid to a cold fluid.

10. Give the expression for NTU.

Number of Transfer Units (NTU) = UA / C min.

11. List the various promoters used for maintaining drop wise condensation.

Oleic acid, benzyl, certain fats and waxes are effective promoters used for maintaining dropwise condensation.

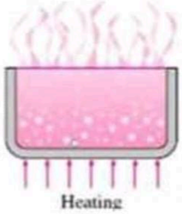
12. How are heat exchangers classified based on flow arrangement?

Parallel flow, counter flow, compact and cross flow heat exchanger.

Classification of boiling

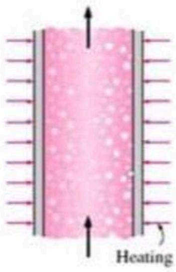
Pool Boiling

- Boiling is called **pool boiling** in the absence of bulk fluid flow.
- Any motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy.



Flow Boiling

- Boiling is called **flow boiling** in the presence of bulk fluid flow.
- In flow boiling, the fluid is forced to move in a heated pipe or over a surface by external means such as a pump.



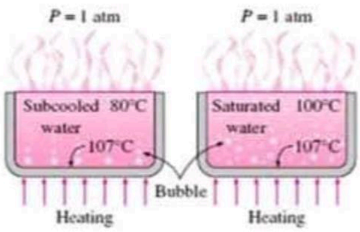
Classification of boiling

Subcooled Boiling

- When the temperature of the main body of the liquid is below the saturation temperature.

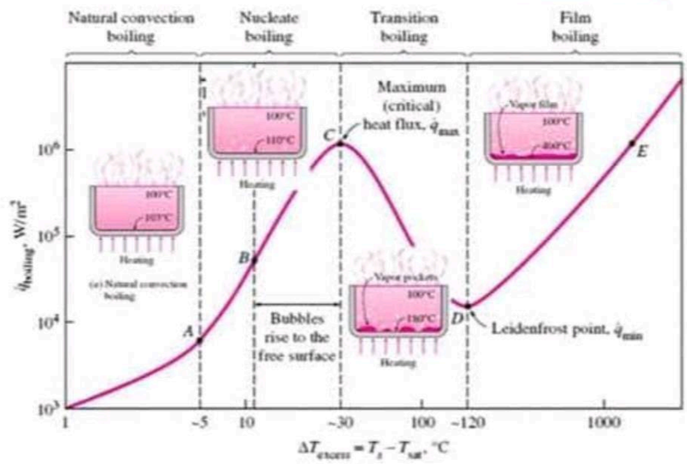
Saturated Boiling

- When the temperature of the liquid is equal to the saturation temperature.



Draw the boiling regime curve.

Boiling takes different forms, depending on the $DT_{excess}=T_s-T_{sat}$



LONG TYPE QUESTIONS & ANSWERS

BIJAN KUMAR GIRI

Example 10.1. *For what value of end temperature differences ratio $\frac{\theta_1}{\theta_2}$, is the arithmatic mean temperature difference 5 per cent higher than the log-mean temperature difference?*

Solution. The arithmetic mean temperature difference $(\bar{\theta})$ and log-mean temperature difference (θ_m) ratio may be written as

$$\frac{\bar{\theta}}{\theta_m} = \frac{\left(\frac{\theta_1 + \theta_2}{2}\right)}{\left[\frac{\theta_1 - \theta_2}{ln\,(\theta_1/\theta_2)}\right]} = \frac{(\theta_1 + \theta_2)}{2\,(\theta_1 - \theta_2)} \times ln\,(\theta_1/\theta_2)$$

It is given that $\bar{\theta}$ is to be 5 percent higher than θ_m

$$\therefore \qquad \frac{\bar{\theta}}{\theta_m} = 1.05 = \frac{(\theta_1/\theta_2) + 1}{2\,[(\theta_1/\theta_2) - 1]}\,ln\,(\theta_1/\theta_2)$$

or, $$\frac{(\theta_1/\theta_2) + 1}{(\theta_1/\theta_2) - 1}\,ln\,(\theta_1/\theta_2) = 2 \times 1.05 = 2.1$$

By hit and trial method, we get

$$\frac{\theta_1}{\theta_2} = \mathbf{2.2} \text{ (Ans.)}$$

Thus the simple arithmetic mean temperature difference gives results to within 5 percent when end temperature differences vary by *no more than a factor of 2.2.*

Example 10.2. (*a*) *Derive an expression for the effectiveness of a parallel flow heat exchanger in terms of the number of transfer units, NTU, and the capacity ratio C_{min}/C_{max}.*

(*b*) *In a parallel flow double-pipe heat exchanger water flows through the inner pipe and is heated from 20°C to 70°C. Oil flowing through the annulus is cooled from 200°C to 100°C. It is desired to cool the oil to a lower exit temperature by increasing the length of the heat exchanger. Determine the minimum temperature to which the oil may be cooled.* **(U.P.S.C., 1995)**

Solution. (*a*) : Refer Classnote

(*b*) Using subscripts *h* and *c* for oil and water respectively, we have

$t_{h1} = 200°C;\ t_{h2} = 100°C;$

$t_{c1} = 20°C;\ t_{c2} = 70°C$ ...(Given)

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

or, $\dot{m}_h c_{ph}\,(200 - 100) = \dot{m}_c c_{pc}\,(70 - 20)$

or, $$\frac{\dot{m}_c c_{pc}}{\dot{m}_h c_{ph}} = \frac{100}{50} = 2$$

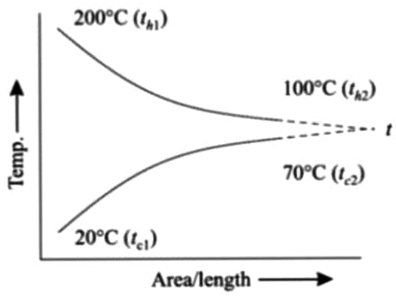


Fig. 10.13.

Let '*t*' be the lowest temperature to which oil may be cooled and this will be the highest temperature of water too (Refer Fig. 10.13).

Hence, $\dot{m}_h c_{ph}\,(200 - t) = \dot{m}_c c_{pc}\,(t - 20)$

or, $$(200 - t) = \frac{\dot{m}_c c_{pc}}{\dot{m}_h c_{ph}}\,(t - 20) = 2\,(t - 20)$$

or, $200 - t = 2t - 40$

or, $t = \mathbf{80°C}$ **(Ans.)**

Eample 10.3. *The flow rates of hot and cold water streams running through a parallel flow heat exchanger are 0.2 kg/s and 0.5 kg/s respectively. The inlet temperatures on the hot and cold sides are 75°C and 20°C respectively. The exit temperature of hot water is 45°C. If the individual heat transfer coefficients on both sides are 650 W/m²°C, calculate the area of the heat exchanger.*

Solution. *Given* : $\dot{m}_h = 0.2$ kg/s; $\dot{m}_c = 0.5$ kg/s; $t_{h1} = 75°$ C; $t_{h2} = 45°$C; $t_{c1} = 20°$C; $h_i = h_o = 650$ W/m²°C.

The area of heat exchanger, *A* :

The heat exchanger is shown diagrammatically in Fig. 10.14.

The heat transfer rate, $Q = \dot{m}_h \times c_{ph} \times (t_{h1} - t_{h2})$

$= 0.2 \times 4.187 \times (75 - 45) = 25.122$ kJ/s

Heat lost by hot water = Heat gained by cold water

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

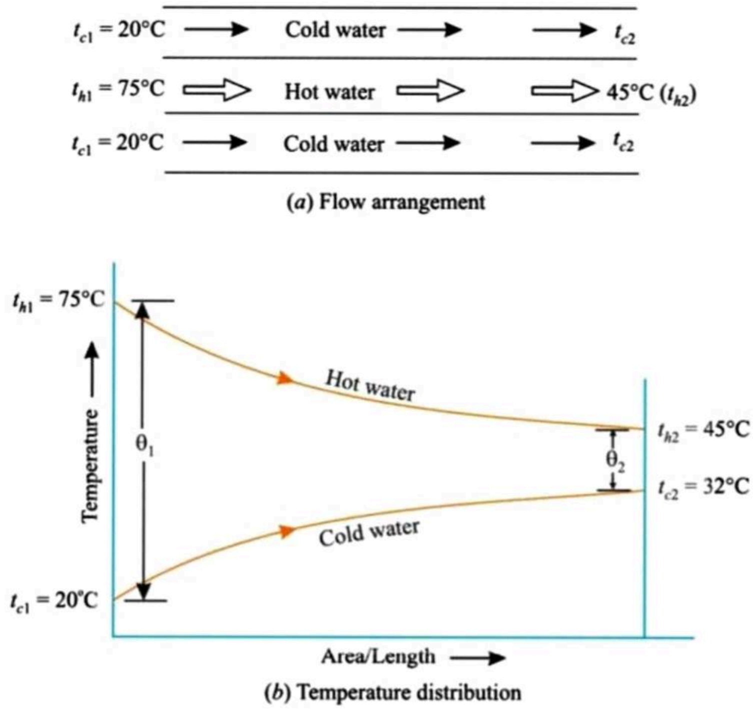
$$0.2 \times 4.187 \times (75 - 45) = 0.5 \times 4.187 \times (t_{c2} - 20)$$

$$\therefore \qquad t_{c2} = 32°C$$

Logarithmic mean temperature difference (*LMTD*) is given by

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln\,(\theta_1/\theta_2)} \qquad \text{...[Eqn. (10.9)]}$$

or, $$\theta_m = \frac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln\,[(t_{h1} - t_{c1})/(t_{h2} - t_{c2})]} = \frac{(75 - 20) - (45 - 32)}{\ln\,[(75 - 20)/(45 - 32)]} = \frac{55 - 13}{\ln\,(55/13)} = 29.12°C$$



(a) Flow arrangement

(b) Temperature distribution

Fig. 10.14. Parallel flow heat exchanger.

Overall heat transfer coefficient U is calculated from the relation,

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

$$= \frac{1}{650} + \frac{1}{650} = \frac{1}{325}$$

∴ $U = 325 \text{ W/m}^2\text{°C}$

Also, $Q = U A \theta_m$

or, $A = \dfrac{Q}{U\theta_m} = \dfrac{25.122 \times 1000}{325 \times 29.12} = \mathbf{2.66 \ m^2}$ **(Ans.)**

Example 10.5. *A hot fluid at 200°C enters a heat exchanger at a mass flow rate of 10^4 kg/h. Its specific heat is 2000 J/kg K. It is to be cooled by another fluid entering at 25°C with a mass flow rate 2500 kg/h and specific heat 400 J/kg K. The overall heat transfer coefficient based on outside area of 20 m² is 250 W/m² K. Find the exit temperature of the hot fluid when the fluids are in parallel flow.*

(GATE, 1998)

Solution. *Given* : $t_{h1} = 200°\text{C}$; $\dot{m}_h = \dfrac{10000}{3600} = 2.78$ kg/s; $c_{ph} = 2000$ J/kg K; $t_{c1} = 25°\text{C}$;

$$\dot{m}_c = \frac{2500}{3600} = 0.694 \text{ kg/s}; \ c_{pc} = 400 \text{ J/kg K}; \ U = 250 \text{ W/m}^2\text{ K}.$$

Exit temperature of the hot fluid, t_{h2} :

Heat lost by the hot fluid, $Q = \dot{m}_h c_{ph} (t_{h1} - t_{h2})$

$= 2.78 \times 2000 \times (200 - t_{h2}) = 5560 (200 - t_{h2})$ ...(*i*)

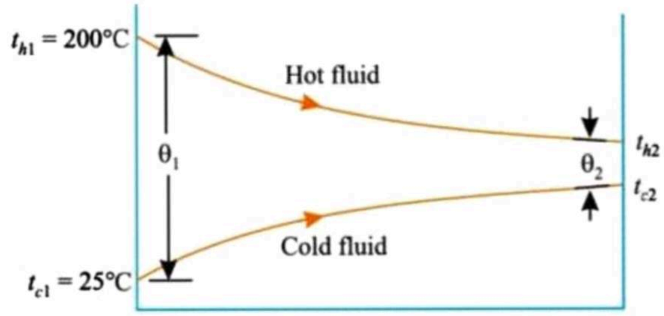


Fig. 10.15.

Heat gained by the cold fluid, $Q = 0.694 \times 400 \ (t_{c2} - 25)$

$= 277.6 \ (t_{c2} - 25)$ ...(*ii*)

Equating (*i*) and (*ii*), we have

$$5560 \ (200 - t_{h2}) = 277.6 \ (t_{c2} - 25)$$

or, $$t_{c2} = \frac{5560}{277.6}(200 - t_{h2}) + 25 = 4025 - 20\,t_{h2} \quad \text{...(iii)}$$

Also, heat transferred is given by,

$$Q = UA\theta_m$$

where, $$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)}$$

Here $\theta_1 = t_{h1} - t_{c1} = 200 - 25 = 175°C$; and $\theta_2 = t_{h2} - t_{c2}$

$$\therefore \quad \theta_m = \frac{175 - (t_{h2} - t_{c2})}{\ln\left[\dfrac{175}{t_{h2} - t_{c2}}\right]}$$

Substituting the values in the above equation, we get

$$Q = 250 \times 20 \left[\frac{175 - (t_{h2} - t_{c2})}{\ln\left(\dfrac{175}{t_{h2} - t_{c2}}\right)}\right] \quad \text{...(iv)}$$

Substituting the values of t_{c2} from (*iii*) in (*iv*), we get

$$Q = 250 \times 20 \left[\frac{175 - \{t_{h2} - (4025 - 20\,t_{h2})\}}{\ln\left\{\dfrac{175}{t_{h2} - (4025 - 20\,t_{h2})}\right\}}\right]$$

$$= 5000\left[\frac{175 - (t_{h2} - 4025 + 20\,t_{h2})}{\ln \dfrac{175}{(t_{h2} - 4025 + 20\,t_{h2})}}\right] = 5000\left[\frac{175 - (21\,t_{h2} - 4025)}{\ln\left\{\dfrac{175}{21\,t_{h2} - 4025}\right\}}\right] \quad \text{...(v)}$$

Equating (*i*) and (*v*), we get

$$5560\,(200 - t_{h2}) = 5000\left[\frac{175 - (21\,t_{h2} - 4025)}{\ln\left\{\dfrac{175}{21\,t_{h2} - 4025}\right\}}\right]$$

Using hit and trial method, the value of t_{h2} may be found out.

Example 10.6. *In a certain double pipe heat exchanger hot water flows at a rate of 5000 kg/h and gets cooled from 95°C to 65°C. At the same time 50000 kg/h of cooling water at 30°C enters the heat exchanger. The flow conditions are such that overall heat transfer coefficient remains constant at 2270 W/m² K. Determine the heat transfer area required and the effectiveness, assuming two streams are in parallel flow. Assume for the both the streams* $c_p = 4.2$ *kJ/kg K.* **(GATE, 1997)**

Solution. *Given :* $\dot{m}_h = \dfrac{50000}{3600} = 13.89$ kg/s; $t_{h1} = 95°C$; $t_{h2} = 65°C$;

$\dot{m}_c = \dfrac{50000}{3600} = 13.89$ kg/s; $t_{c1} = 30°C$; $U = 2270$ W/m² K;

$c_{ph} = c_{pc} = 4.2$ kJ/kg or 4200 J/kg K.

Q = Heat lost by hot water = Heat gained by cold water.

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

or, $13.89 \times 4200 \times (95 - 65) = 13.89 \times 4200 \times (t_{c2} - 30)$

$$\therefore \quad t_{c2} = 60°C$$

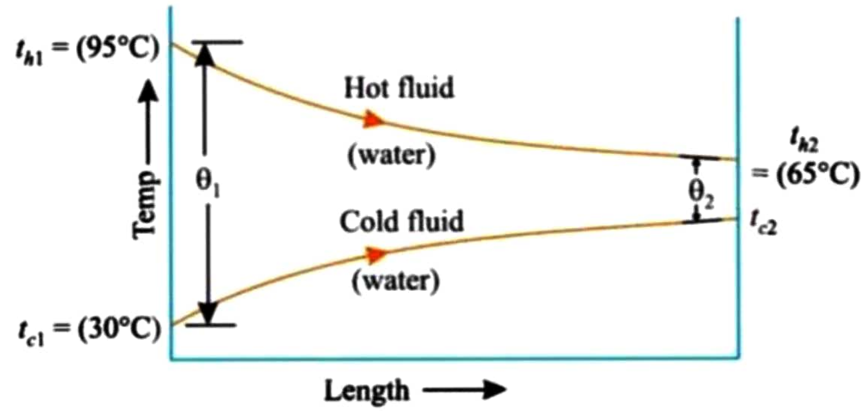


Fig. 10.16. Parallel-flow heat-exchanger.

Log mean temperature difference,

$$LMTD,\ \theta_m = \frac{(\theta_1 - \theta_2)}{\ln(\theta_1/\theta_2)}$$

$$= \frac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln\left(\frac{t_{h1} - t_{c1}}{t_{h2} - t_{c2}}\right)}$$

$$= \frac{(95 - 30) - (65 - 60)}{\ln\left(\frac{95 - 30}{65 - 60}\right)} = \frac{60}{0.583} = 23.4°C$$

Also, $Q = UA\theta_m$

or, $13.89 \times 4200 \times (95 - 65) = 2270 \times A \times 23.4$

Heat transfer area, A = **32.95 m² (Ans.)**

Also, $Q_{actual} = \dot{m}_h c_{ph} (t_{h1} - t_{h2})$ and $Q_{max} = \dot{m}_c c_{pc} (t_{h1} - t_{c1})$

∴ Effectiveness of the heat exchanger,

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} = \frac{\dot{m}_h c_{ph} (t_{h1} - t_{h2})}{\dot{m}_h c_{ph} (t_{h1} - t_{c1})} = \frac{95 - 65}{95 - 30} = \mathbf{0.461} \quad \textbf{(Ans.)}$$

Example 10.8. *In a counter-flow double pipe heat exchanger, water is heated from 25°C to 65°C by an oil with a specific heat of 1.45 kJ/kg K and mass flow rate of 0.9 kg/s. The oil is cooled from 230°C to 160°C. If the overall heat transfer coefficient is 420 W/m²°C, calculate the following :*

(*i*) *The rate of heat transfer,*

(*ii*) *The mass flow rate of water, and*

(*iii*) *The surface area of the hat exchanger.*

Solution. *Given :* t_{c1} = 25°C; t_{c2} = 65°C, c_{ph} = 1.45 kJ/kg K; $\dot{m}_h$ = 0.9 kg/s;

t_{h1} = 230°C; t_{h2} = 160°C, U = 420 W/m²°C.

(i) The rate of heat transfer, Q :

$$Q = \dot{m}_h \times c_{ph} \times (t_{h1} - t_{h2})$$

or, $$Q = 0.9 \times (1.45) \times (230 - 160) = \mathbf{91.35\ kJ/s} \qquad \textbf{(Ans.)}$$

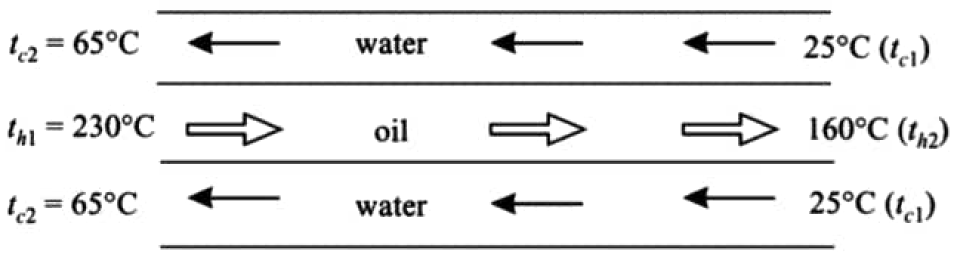
(ii) The mass flow rate of water, $\dot{m}_c$:

Heat lost by oil (hot fluid) = Heat gained by water (cold fluid)

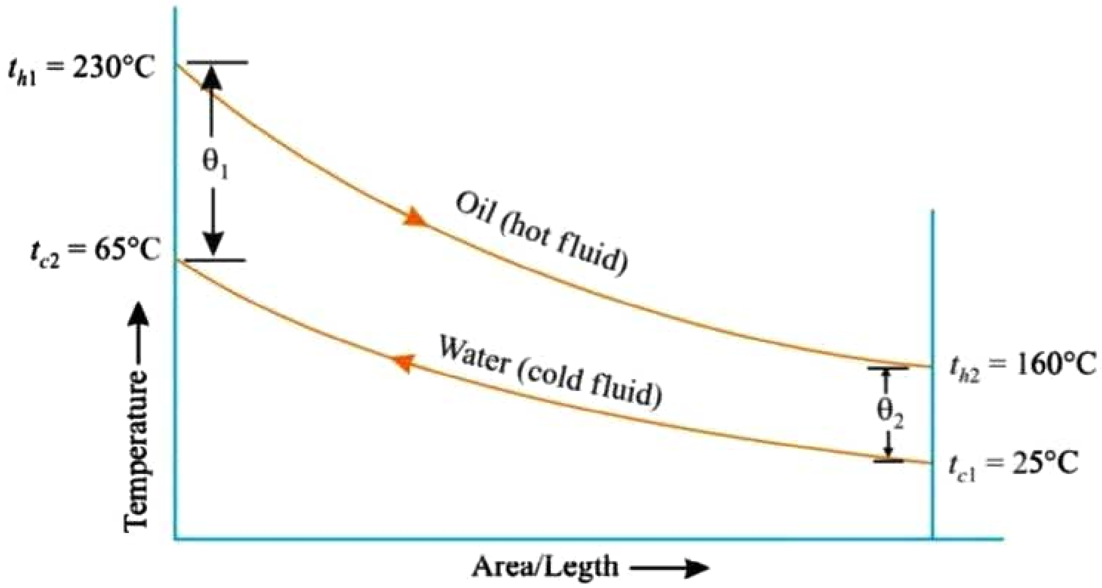
$$\dot{m}_h \times c_{ph} \times (t_{h1} - t_{h2}) = \dot{m}_c \times c_{pc} \times (t_{c2} - t_{c1})$$

$$91.35 = \dot{m}_c \times 4.187\,(65 - 25)$$

$\therefore$ $$\dot{m}_c = \frac{91.35}{4.187 \times (65 - 25)} = \mathbf{0.545\ kg/s\ (Ans.)}$$



(*a*) Flow arrangement



(*b*) Temperature distribution

Fig. 10.17. Counter-flow heat exchnager.

(iii) The surface area of heat exchanger, A :

Logarithmic mean temperature difference (LMTD) is given by

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)}$$

$$= \frac{(t_{h1} - t_{c2}) - (t_{h2} - t_{c1})}{\ln[(t_{h1} - t_{c2})/(t_{h2} - t_{c1})]} = \frac{(230 - 65) - (160 - 25)}{\ln[(230 - 65)/(160 - 25)]}$$

or, $$\theta_m = \frac{165 - 135}{\ln[(165/135)]} = 149.5°\text{C}$$

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

or, $$A = \frac{Q}{U\theta_m} = \frac{91.35 \times 10^3}{420 \times 149.5} = \mathbf{1.45\ m^2} \quad \textbf{(Ans.)}$$

Example 10.9. *An oil cooler for a lubrication system has to cool 1000 kg/h of oil (c_p =2.09 kJ/kg°C) from 80°C to 40°C by using a cooling water flow of 1000 kg/h at 30°C. Give your choice for a parallel flow or counter-flow heat exchanger, with reasons. Calculate the surface area of the heat exchanger, if the overall heat transfer coefficient is 24 W/m²°C.*

Take c_p of water = 4.18 kJ/kg°C.

Solution. *Given :* $\dot{m}_h = \frac{1000}{3600}$ kg/s; c_{ph} = 2.09 kJ/kg°C; c_{pc} = 4.18 kJ/kg°C; $\dot{m}_c = \frac{1000}{3600}$ kg/s; t_{h1} = 80°C, t_{c1} = 30°C; t_{h2} = 40°C; U = 24 W/m²°C.

Surface area of heat exchanger, *A* :

Let subscripts *h* and *c* stand for hot and cold fluids respectively.

Rate of heat transfer is given by

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

or,
$$\frac{1000}{3600} \times 2.09 (80 - 40) = \frac{1000}{3600} \times 4.18 (t_{c2} - 30)$$

or,
$$t_{c2} = 50°C$$

Since $t_{c2} > t_{h2}$, *counter-flow arrangement must be used.*

Again,
$$\theta_m = \frac{\theta_1 - \theta_2}{\ln (\theta_1/\theta_2)}$$
$$= \frac{(t_{h1} - t_{c2}) - (t_{h2} - t_{c1})}{\ln [(t_{h1} - t_{c2})/(t_{h2} - t_{c1})]} = \frac{(80 - 50) - (40 - 30)}{\ln [(80 - 50)/(40 - 30)]}$$

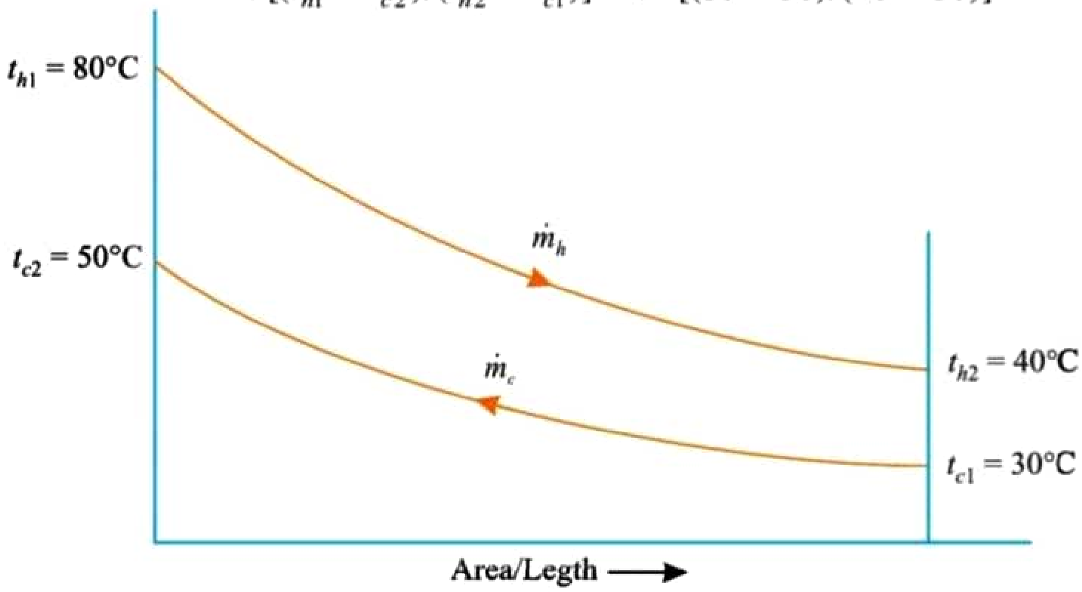


Fig. 10.18.

$$= \frac{30 - 10}{\ln (30/10)} = 18.2°C$$

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

$$\frac{1000}{3600} (2.09 \times 10^3) (80 - 40) = 24 \times A \times 18.2$$

or,
$$A = \frac{1000 \times (2.09 \times 10^3) \times (80 - 40)}{3600 \times 24 \times 18.2} = \mathbf{53.16\ m^2}\ \textbf{(Ans.)}$$

Example 10.10. *Show that in a double-pipe counter flow heat exchanger if $\dot{m}_h c_h = \dot{m}_c c_c$ the temperature profiles of the two fluids along its length are parallel straight lines.* **(GATE, 1996)**

Solution. For heat exchanger, $dQ = -\ \dot{m}_h c_h dt_h = \dot{m}_c c_c dt_c$

$$= - C_h dt_h = C_c dt_c$$

where, $\dot{m}_h$ = Mass flow rate of hot fluid,
and,

$\dot{m}_c$ = Mass flow rate of cold fluid.

Due to heat exchanger, temperature of hot fluid decreases by dt_h and that of cold fluid increases by dt_c

Also, C_c = Heat capacity of cold fluid,
and,

C_h = Heat capacity of hot fluid.

$$\dot{m}_h c_h = \dot{m}_c c_c \quad \text{...(Given)}$$

or, $C_h = C_c$

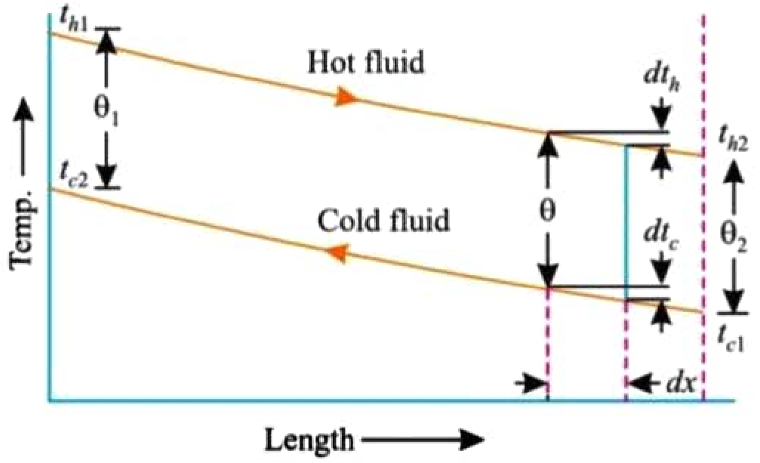


Fig. 10.19.

In counter-flow system, temperature of both the fluids decrease in the direction of heat exchanger length, therefore

$$dQ = -C_h\,dt_h = -C_c\,dt_c$$

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

$$\text{or,} \quad dt_h - dt_c = d\theta = -dQ\left[\frac{1}{C_h} - \frac{1}{C_c}\right]$$

Since constant $C_h = C_c$, $\therefore$ $d\theta = 0$ or θ = constant.

Thus, both the straight lines showing the variation of temperatures along the length are *parallel lines.* **...Proved**

Example 10.11. *A counter-flow double pipe heat exchanger using superheated steam is used to hot water at the rate of 10500 kg/h. The steam enters the heat exchanger at 180°C and leaves at 130°C. The inlet and exit temperatures of water are 30°C and 80°C respectively. If overall heat transfer coefficient from steam to water is 814 W/m²°C, calculate the heat transfer area. What would be the increase in area if the fluid flows were parallel?*

Solution. *Given* : $\dot{m}_w\ (= \dot{m}_c) = \frac{10500}{3600} = 2.917$ kg/s; $t_{h1} = 180°C$; $t_{h2} = 130°C$; $t_{c1} = 30°C$; $t_{c2} = 80°C$; $U = 814\ W/m^2°C$.

(*i*) *When the flow is counter* :

$$\theta_m = \frac{\theta_1 - \theta_2}{ln\,(\theta_1/\theta_2)}$$

In this $\quad \theta_m = \theta_1 = \theta_2 = 100°C$

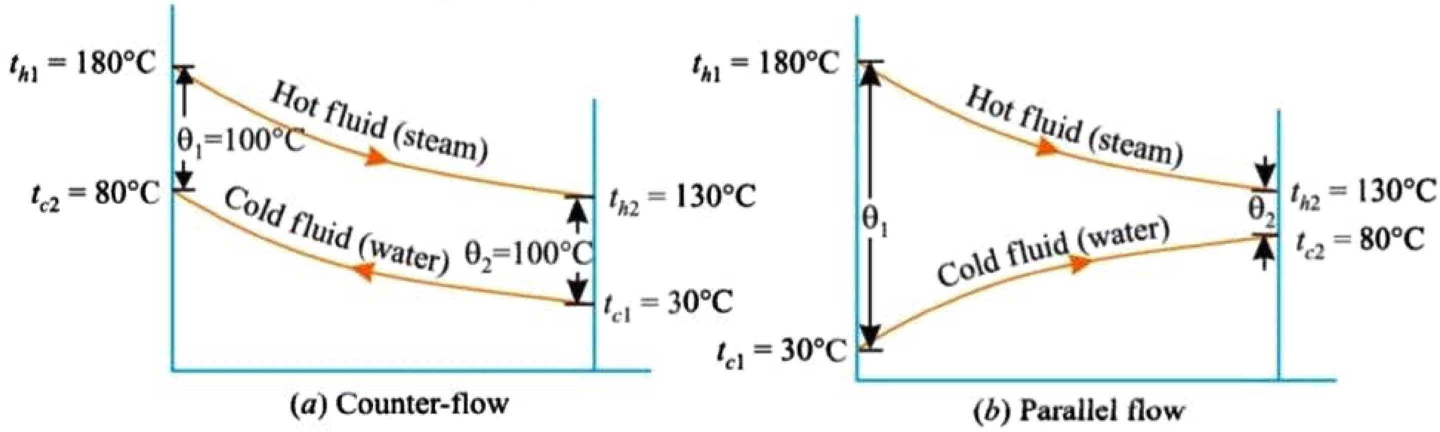


Fig. 10.20.

The heat transfer rate is given by

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

or, $$\dot{m}_c \times c_{pc} \times (t_{c2} - t_{c1}) = U A \theta_m$$

or, $$2.917 \times 4.187 \times 10^3 \times (80 - 30) = 814 \times A \times 100$$

or, $$A = \frac{2.917 \times 4.187 \times 10^3\ (80 - 30)}{814 \times 100} = \mathbf{7.5\ m^2} \quad \textbf{(Ans.)}$$

(*ii*) *When the flow is parallel* :

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

$$= \frac{(180 - 30) - (130 - 80)}{\ln [(180 - 30)/(130 - 80)]} = \frac{150 - 50}{\ln (150/50)} = 91°C$$

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

or, $$2.917 \times (4.187 \times 10^3) \times (80 - 30) = 814 \times A \times 91$$

$$A = \frac{2.917 \times (4.187 \times 10^3) \times (80 - 30)}{814 \times 91} = 8.24\ m^2$$

∴ Increase in area $$= \frac{8.24 - 7.5}{7.5} = 0.0987 \text{ or } \mathbf{9.87\%} \quad \textbf{(Ans.)}$$

Example 10.13. *Steam enters a counter-flow heat exchanger, dry saturated at 10 bar and leaves at 350°C. The mass flow of steam is 800 kg/min. The gas enters the heat exchanger at 650°C and mass flow rate is 1350 kg/min. If the tubes are 30 mm diameter and 3 m long, determine the number of tubes required. Neglect the resistance offered by metallic tubes. Use the following data :*

For steam : $t_{sat} = 180°C$ *(at 10 bar);* $c_{ps} = 2.71$ *kJ/kg°C;* $h_s = 600$ *W/m²°C*

For gas : $c_{pg} = 1$ *kJ/kg°C;* $h_g = 250$ *W/m²°C.* **(P.U.)**

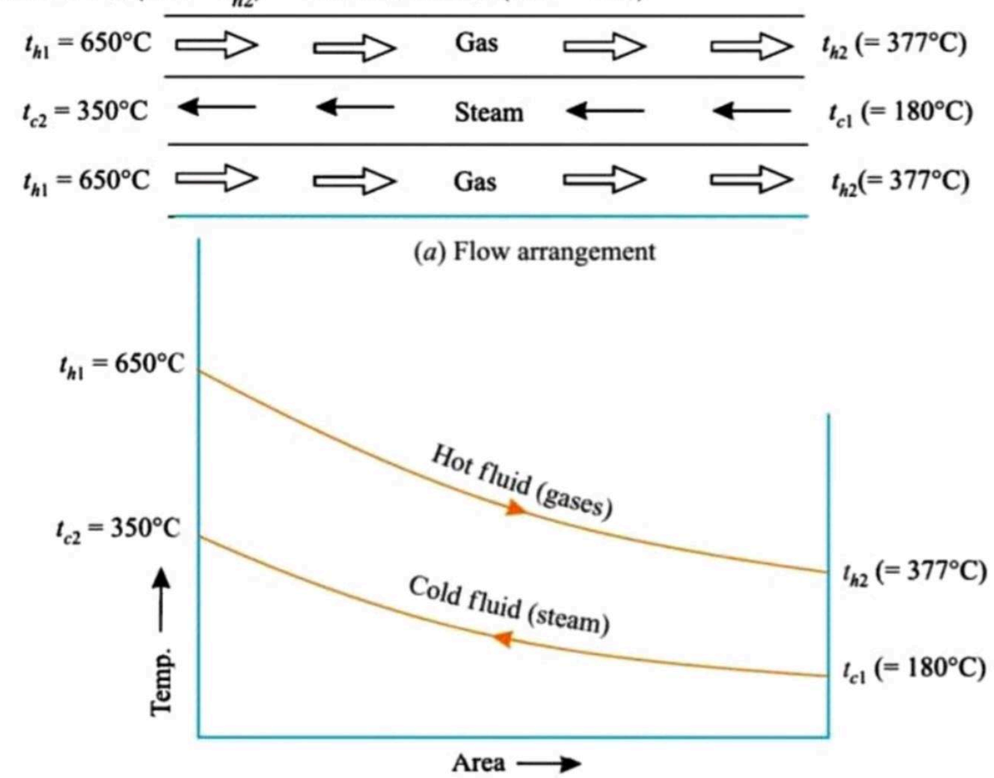
Solution. *Given* : $\dot{m}_s = \dot{m}_c = \frac{800}{60} = 13.33$ kg/s; $\dot{m}_g = \dot{m}_h = \frac{1350}{60} = 22.5$ kg/s; $t_{h1} = 650°C$; $t_{c1}\ (= t_{sat}) = 180°C$; $t_{c2} = 350°C$; $d = 30$ mm $= 0.03$ m; $L = 3$ m.

Number of tubes required, *N*:

Heat lost by gases = Heat gained by steam

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

$$22.5 \times 1 \times (650 - t_{h2}) = 13.33 \times 2.71 \times (350 - 180)$$



(*a*) Flow arrangement

(*b*) Temperature distribution

Fig. 10.21. Counter-flow heat exchanger.

$\therefore \qquad t_{h2} = 377°C$

Overall heat transfer coefficient is given by

$$\frac{1}{U} = \frac{1}{h_g} + \frac{d_o}{d_i}\frac{1}{h_s} = \frac{1}{h_g} + \frac{1}{h_s} \qquad \text{as } d_i \approx d_o \qquad \text{...(given)}$$

or,
$$U = \frac{h_g \times h_s}{h_g + h_s} = \frac{250 \times 600}{250 + 600} = 176.5 \text{ W/m}^2 °\text{C}$$

Total heat transfer rate is given by

$$Q = U A \theta_m \qquad \text{...}(i)$$

where,
$$A = N \times (\pi d L) = N \times \pi \times 0.03 \times 3 = 0.2827 \text{ N m}^2$$

$$Q = 22.5 \times (1 \times 10^3) \times (650 - 377) = 6142.5 \times 10^3 \text{ W}$$

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

$$= \frac{(650 - 350) - (377 - 180)}{\ln[(650 - 300)/(377 - 180)]} = \frac{300 - 197}{\ln(300/197)} = 244.9°\text{C}$$

Substituting the values in eqn. (i), we get

$$6142.5 \times 10^3 = 176.5 \times 0.2827 \text{ N} \times 244.9$$

or,
$$N = \frac{6142.5 \times 10^3}{176.5 \times 0.2827 \times 244.9} = \textbf{503 tubes} \quad \textbf{(Ans.)}$$

Example 10.19. *Saturated steam at 100°C is condensing on the shell side of a shell-and-tube heat exchanger. The cooling water enters the tube at 30°C and leaves at 70°C. Calculate the mean temperature difference if arrangement is (i) parallel flow, (ii) counter flow.* **(AMIE, Winter, 1997)**

Solution. The mean temperature difference will be the *same* for parallel flow or counter flow arrangements as is evident from the diagrams (Fig. 10.27) of temperature variations in both the arrangements. The mean temperature difference may be logarithmic mean (*LMTD*), or arithmetic mean temperature difference (*AMTD*).

(*i*) $$LMTD = \frac{(100-30)-(100-70)}{\ln\left[\frac{(100-30)}{100-70)}\right]} = \frac{40}{\ln\left(\frac{70}{30}\right)} = \mathbf{47.21°C} \quad \textbf{(Ans.)}$$

(*ii*) $$AMTD = \frac{(100-30)+(100-70)}{2} = \frac{70+30}{2} = \mathbf{50°C} \quad \textbf{(Ans.)}$$

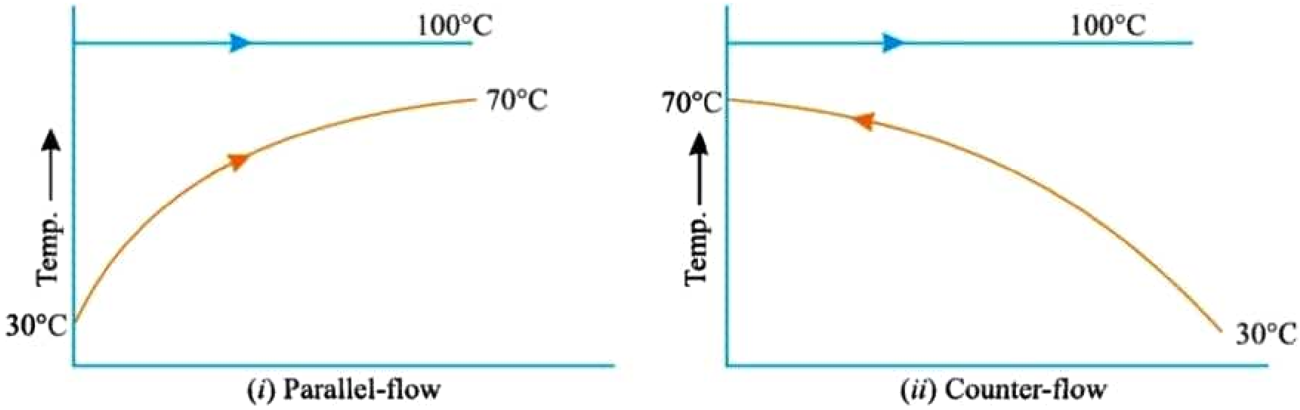


Fig. 10.27.

Example 10.20. *The amount of F_{12} used in compression refrigeration system is 4 tonnes/hour. The brine, flowing at 850 kg/min. with inlet temperature of 12°C, is cooled in the evaporator. Assuming F_{12} entering and leaving the evaporator as saturated liquid and saturated vapour respectively, determine the area of evaporator required. Take the following properties :*

For F_{12} : Saturation temperature : – 23°C; c_p = 1.17 kJ/kg°C; h_{fg} = 167.4 kJ/kg

c_p (brine) = 6.3 kJ/kg°C; U = 8368 kJ/m²h°C. **(AMIE Summer, 2000)**

Solution. Making energy balance, we have

$$-\dot{m}_h c_{ph} (t_{h2} - t_{h1}) = \dot{m}_c h_{fg}$$

or, $$\dot{m}_h c_{ph} (t_{h1} - t_{h2}) = \dot{m}_c h_{fg}$$

or, $$850 \times 6.3\,(12 - t_{h2}) = \frac{4 \times 1000 \times 167.4}{60} = 11160 \text{ kJ/min}$$

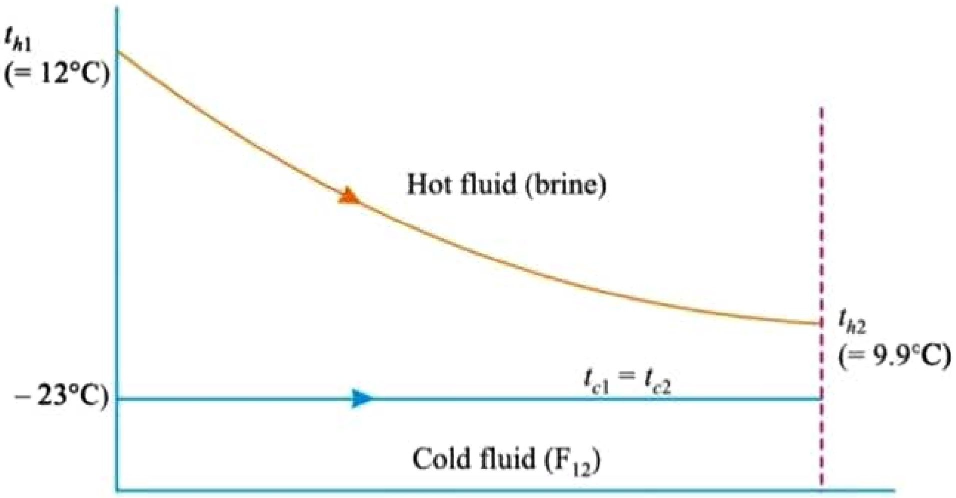


Fig. 10.28.

$\therefore$ Exit temperature of brine, $t_{h2} = 12 - \dfrac{11160}{850 \times 6.3} = 9.9°C$

Log mean temperature, $$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)} = \frac{(t_{h1} - t_{c1}) - (t_{h2} - t_{c2})}{\ln\left[\dfrac{t_{h1} - t_{c1}}{t_{h2} - t_{c2}}\right]}$$

$$= \frac{[12 - (-23)] - [9.9 - (-23)]}{\ln\left[\dfrac{12 - (-23)}{9.9 - (-23)}\right]} = \frac{35 - 32.9}{\ln\left(\dfrac{35}{32.9}\right)} = 33.94°C$$

Now, $Q = UA\theta_m$ (where A = area of evaporator)

$$11160 \times 60 = 8368 \times 33.94$$

$\therefore$ $$A = \frac{11160 \times 60}{8368 \times 33.94} = \mathbf{2.357\ m^2}$$ **(Ans.)**

Example 10.21. *A heat exchanger is to be designed to condense an organic vapour at a rate of 500 kg/min which is available at its saturation temperature 355 K. Cooling water at 286 K is available at a flow rate of 60 kg/s. The overall heat transfer coefficient is 475 W/m²°C. Latent heat of condensation of the organic vapour is 600 kJ/kg. Calculate :*

(*i*) *The number of tubes required, if 25 mm outer diameter, 2mm thick and 4.87 m long tubes are available, and*

(*ii*) *The number of tube passes, if the cooling water velocity (tube side) should not exceed 2 m/s.*

(M.U.)

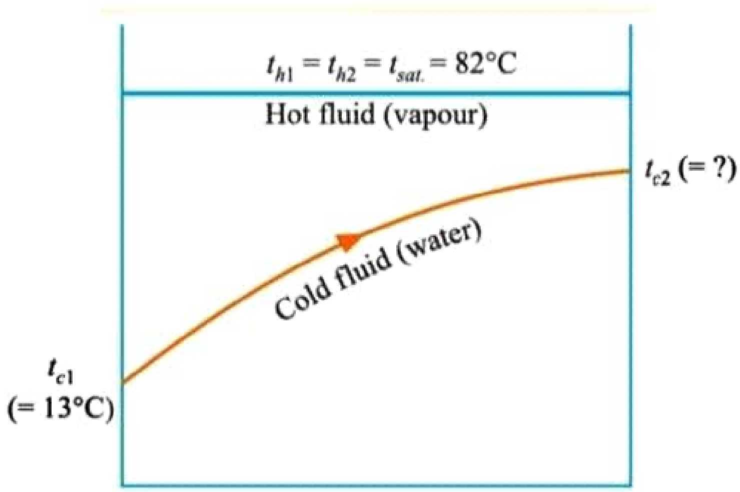


Fig. 10.29.

Solution. *Given* : d_o = 25 mm = 0.025 m; d_i = 25 – 2 × 2 = 21 mm = 0.021 m; L = 4.87m; V = 2 m/s; t_{c1} = 286 – 273 = 13°C, $t_{h1} = t_{h2} = t_{sat}$ = 355 – 273 = 82°C; U = 475 W/m°C, h_{fg} (organic vapour) = 600 kJ/kg, $\dot{m}_v = \dot{m}_h = \dfrac{500}{60}$ = 8.33 kg/s; $\dot{m}_v = \dot{m}_c$ = 60 kg/s.

(i) The number of tubes required, N :

Heat lost by vapour = Heat gained by water

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

$$8.33 \times 600 = 60 \times 4.18 \times (t_{c2} - 13)$$

$$\therefore \quad t_{c2} = \frac{8.33 \times 600}{60 \times 4.18} + 13 = 32.9°\text{C}$$

Logarithmic mean temperature difference (*LMTD*) is given by,

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln(\theta_1/\theta_2)} = \frac{(82 - 13) - (82 - 32.9)}{\ln[(82 - 13)/(32.9 - 13)]}$$

$$= \frac{69 - 49.1}{\ln(69/49.1)} = 58.5°\text{C}$$

Heat transfer rate is given by,

$$Q = \dot{m}_h \times h_{fg} = U A \theta_m = U(\pi d_o L N) \times \theta_m$$

$$8.33 \times 600 \times 10^3 = 475 \times (\pi \times 0.025 \times 4.87 \times N) \times 58.5$$

$\therefore$ $\quad N =$ **470 tubes** **(Ans.)**

(ii) The number of tube passes, p :

The cold water flow mass passing through each pass (assume p are number of passes) is given by,

$$\dot{m}_c = \left(\frac{\pi}{4} d_i^2 \times V \times \rho\right) \times N_p$$

where, $\quad N_p$ = Number of tubes in each pass ($N = p \times N_p$)

$$60 = \frac{\pi}{4} \times (0.021)^2 \times 2 \times 1000 \times N_p$$

$$\therefore \quad N_p = \frac{60 \times 4}{\pi \times (0.021)^2 \times 2 \times 1000} = 95.5$$

Number of passes, $p = \frac{N}{N_p} = \frac{470}{95.5} = 4.91 =$ **5** **(Ans.)**

Example 10.22. (*a*) *A steam condenser consists of 3000 brass tubes of 20 mm diameter. Cooling water enters the tubes at 20°C with a mean flow rate of 3000 kg/s. The heat transfer coefficient on the inner surface is 11270 W/m²°C and that for condensation on the outer surface is 15500 W/m²°C. The steam condenses at 50°C, and the condenser load is 230 MW. The latent heat of steam is 2380 kJ/kg. Assuming counter flow arrangement, calculate the tube length per pass if two tube passes are used.*

(*b*) *Explain why in steam condensers the LMTD is independent of flow arrangement ?*

(AMIE Summer, 2001)

Solution. (*a*) *Given* : N_p = 3000 per pass; d = 20 mm = 0.02 m; t_{c1} = 20°C; $\dot{m}_c$ = 3000 kg/s; h_i = 11270 W/m²°C; h_o = 15500 W/m²°C, $t_{h1} = t_{h2}$ = 50°C; condenser load = 230 MW (or 230×10^3 kW); h_{fg} = 2380 kJ/kg; number of passes = 2.

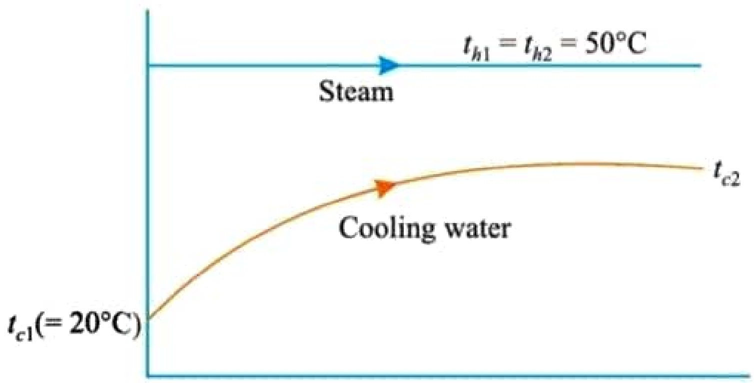


Fig. 10.30.

Tube length per pass, L :

Assuming the tubes to be thin, the overall heat transfer coefficient :

$$U_o = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} = \frac{1}{\frac{1}{11270} + \frac{1}{15500}}$$

$$= 6525.4 \text{ W/m}^2{}^\circ\text{C}$$

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

i.e., $230 \times 10^3 = 3000 \times 4.187 \, (t_{c2} - 20)$

$\therefore$ Water outlet temperature, $t_{c2} = 38.31°\text{C}$

Log-mean temperature difference,

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

$$= \frac{(50 - 20) - (50 - 38.31)}{\ln\left[\frac{50 - 20}{50 - 83.31}\right]} = \frac{18.31}{0.9425} = 19.43°\text{C}$$

Now, $Q = U_o A \, \theta_m$

$$230 \times 10^6 = 6525.4 \times (\pi \, dL) \times (2N_p) \times 19.43$$

$$= 6525.4 \times (\pi \times 0.02 \times L) \times (2 \times 3000) \times 19.43$$

$\therefore$ $$L = \frac{230 \times 10^6}{6525.4 \times \pi \times 0.02 \times (2 \times 3000) \times 19.43} = \mathbf{4.812 \text{ m}}$$ **(Ans.)**

(*b*) In steam condensers, the temperature of hot fluid (steam) is the *same at inlet and exit.* Hence the terminal temperature difference *would not depend upon the arrangement.* The effectiveness of heat exchanger for all the arrangements in this case (the heat capacity ratio for condensation being *zero*) would be

$$\varepsilon = 1 - e^{-NTU}$$

The temperature variations for parallel-flow and counter-flow are as shown in Fig. 10.31 and Fig. 10.32 respectively.

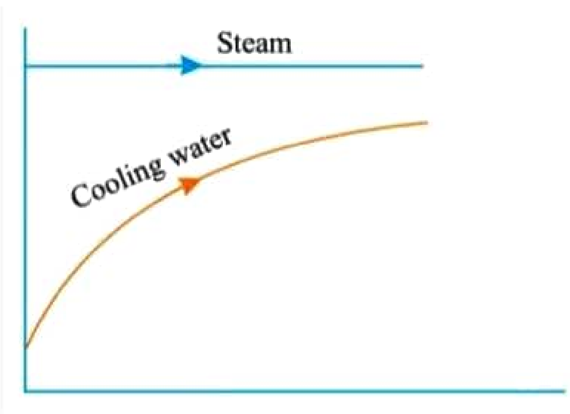


Fig. 10.31. Parallel-flow.

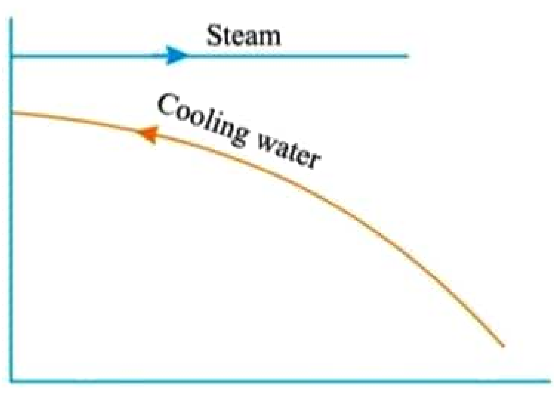


Fig. 10.32. Counter-flow.

Example 10.33. *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.

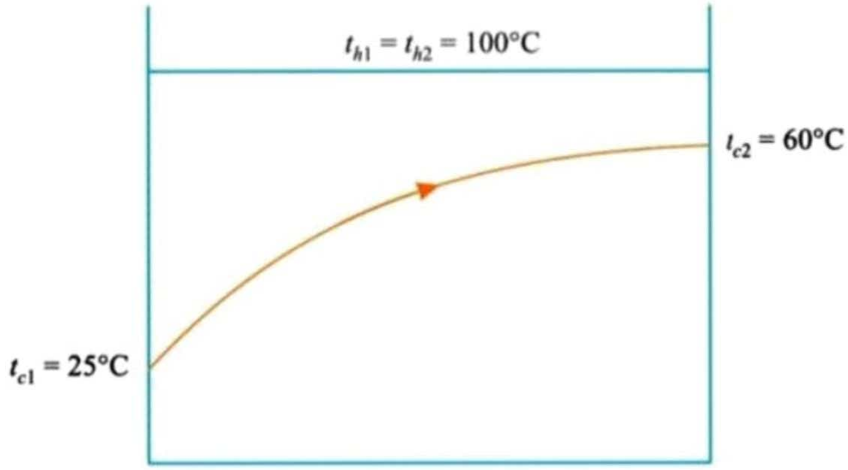


Fig. 10.50.

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

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

(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;

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

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

(iv) The effectiveness of the condenser, ε :

$$\varepsilon = 1 - \exp(-NTU)$$

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

Example 10.34. *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 :* $d = 25\text{ mm} = 0.025\text{ m};\ \dot{m}_w = \dot{m}_c = 0.05\text{ kg/s},\ t_{c1} = 15°C,\ t_{c2} = 70°C;$

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

(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 $\frac{C_{min}}{C_{max}} \simeq 0$.

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

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

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

$$\varepsilon = 1 - \exp(-\text{NTU})$$

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

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

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

∴ $NTU = 1.04$

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

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

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

Using the overall energy balance, we get

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

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

or, $\dot{m}_h = 0.00509$ kg/s or **18.32 kg/h** **(Ans.)**

Example 10.35. *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.

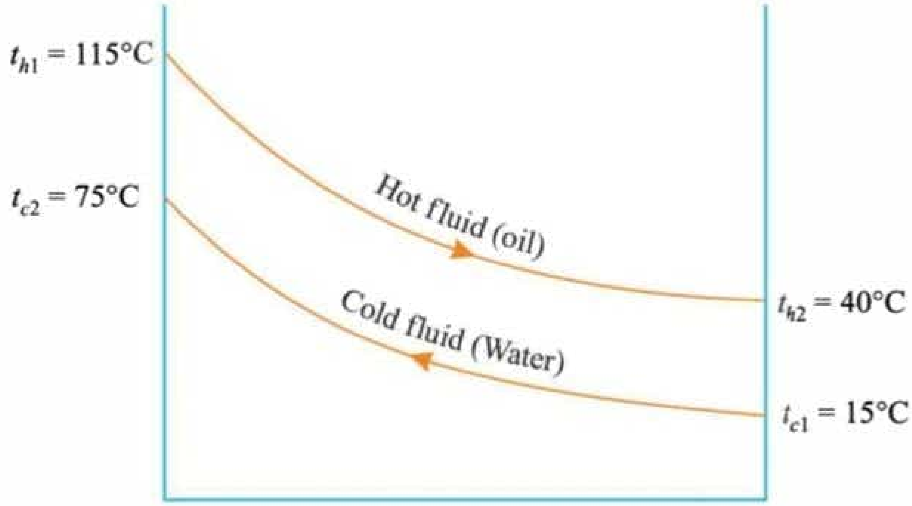


Fig. 10.51.

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

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

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

$\therefore$ $\dot{m}_c = 0.4$ **kg/s** **(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

$$\varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum heat transfer}} = \frac{Q}{Q_{max}} = \frac{t_{h1} - t_{h2}}{t_{h1} - t_{c1}}$$

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

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

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

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

For counter-flow heat exchanger,

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

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

Example 10.36. *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

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

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

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

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

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

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

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

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

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

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

∴ $$t_{c2} = \mathbf{265.8°C} \qquad \textbf{(Ans.)}$$

Case II. *Parallel flow arrangement :*

The value of ε for parallel flow arrangement is given by

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

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

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

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

or, $$t_{c2} = \mathbf{255.4°C} \qquad \textbf{(Ans.)}$$

Example 10.37. *Oil (c_p = 3.6 kJ/kg°C) at 100°C flows at the rate of 30000 kg/h and enters into a parallel flow heat exchanger. Cooling water (c_p = 4.2 kJ/kg°C) enters the heat exchanger at 10°C at the rate of 50000 kg/h. The heat transfer area is 10 m² and U = 1000 W/m²°C. Calculate the following :*

(i) The outlet temperatures of oil, and water;

(ii) The maximum possible outlet temperature of water. **(P.U.)**

Solution. *Given :* $\dot{m}_{oil} = \dot{m}_h = \frac{30000}{3600} = 8.333$ kg/s; c_{ph} = 3.6 kJ/kg°C; t_{h1} = 100°C; $\dot{m}_{water} = \dot{m}_c = \frac{50000}{3600} = 13.89$ kg/s, c_{pc} = 4.2 kJ/kg°C, t_{c1} = 10°C; U = 1000 W/m²°C; A = 10 m².

(i) The outlet temperature of oil and water, t_{h2}, t_{c2} :

$$C_h = \dot{m}_h c_{ph} = 8.333 \times (3.6 \times 1000) = 30 \times 10^3 = C_{min}$$

$$C_c = \dot{m}_c c_{pc} = 13.89 \times (4.2 \times 1000) = 58.34 \times 10^3 = C_{max}$$

$$\frac{C_{min}}{C_{max}} = \frac{30 \times 10^3}{58.34 \times 10^3} = 0.514$$

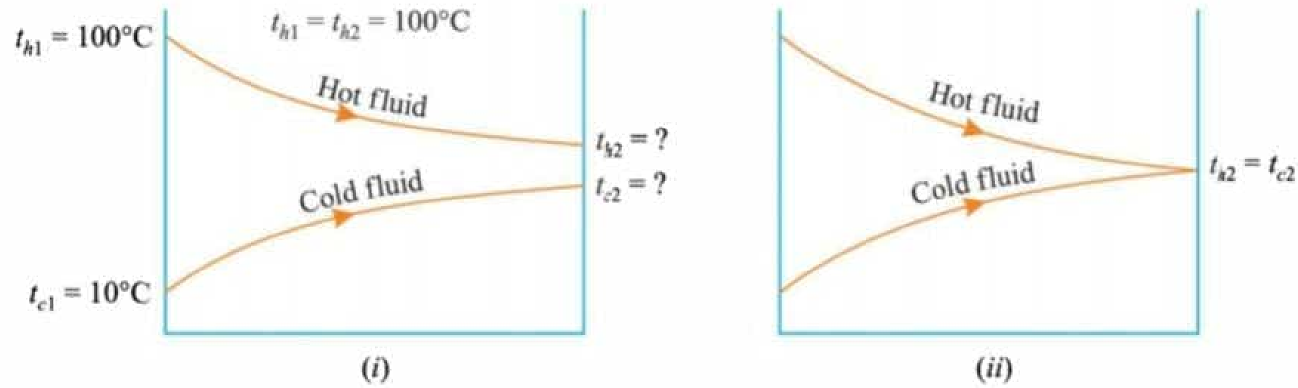


Fig. 10.52.

$$NTU = \frac{UA}{C_{min}} = \frac{1000 \times 10}{30 \times 10^3} = 0.33$$

For the calculated values of $\frac{C_{min}}{C_{max}} = 0.514$ and $NTU = 0.33$, from the Fig. 10.44, we get

$$\varepsilon = 0.32$$

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

or, $$0.32 = \frac{30 \times 10^3\ (100 - t_{h2})}{30 \times 10^3\ (100 - 10)} = \frac{58.34 \times 10^3\ (t_{c2} - 10)}{30 \times 10^3\ (100 - 10)}$$

or, $$0.32 = \left(\frac{100 - t_{h2}}{100 - 10}\right) = 1.945\left(\frac{t_{c2} - 10}{100 - 10}\right)$$

∴ $$\boldsymbol{t_{h2}} = 100 - 0.32\ (100 - 10) = \mathbf{71.2°C} \quad \textbf{(Ans.)}$$

and, $$\boldsymbol{t_{c2}} = \frac{0.32\ (100 - 10)}{1.945} + 10 = \mathbf{24.8°C} \quad \textbf{(Ans.)}$$

(ii) The maximum possible outlet temperature of water, t_{c2} :

When *maximum possible outlet temperature* of water exists then,

$t_{h2} = t_{c2}$ and under this case

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

or, $$30 \times 10^3\ (100 - t_{c2}) = 58.34 \times 10^3\ (t_{c2} - 10)$$

or, $$100 - t_{c2} = 1.945\ (t_{c2} - 10) = 1.945\ t_{c2} - 19.45$$

$$\boldsymbol{t_{c2}} = \mathbf{40.5°C} \qquad \textbf{(Ans.)}$$

Example 10.38. *The following data is given for counter-flow heat exchanger :*

$\dot{m}_h$ = *1 kg/s*; $\dot{m}_c$ = *0.25 kg/s*

c_{ph} = *1.045 kJ/kg°C*; c_{pc} = *4.18 kJ/kg°C*

t_{h1} = *1000°C* ; t_{c2} = *850°C; U = 88.5 W/m²°C; A = 10 m²*

Calculate t_{h2} *and* t_{c1}. **(P.U.)**

Solution. $C_h = \dot{m}_h\, c_{ph} = 1 \times (1.045 \times 10^3) = 1045$

$C_c = \dot{m}_c\, c_{pc} = 0.25 \times (4.18 \times 10^3) = 1045$

∴ $C_{min} = C_{max} = C_h = C_c = 1045$

The effectiveness ε is given by the relation :

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

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

or, $$\varepsilon = \frac{(t_{h1} - t_{h2})}{(t_{h1} - t_{c1})} = \frac{(t_{c2} - t_{c1})}{(t_{h1} - t_{c1})} \quad ...(i)$$

$$NTU = \frac{UA}{C_{min}} = \frac{88.5 \times 10}{1045} = 0.85$$

$$\frac{C_{min}}{C_{max}} = 1$$

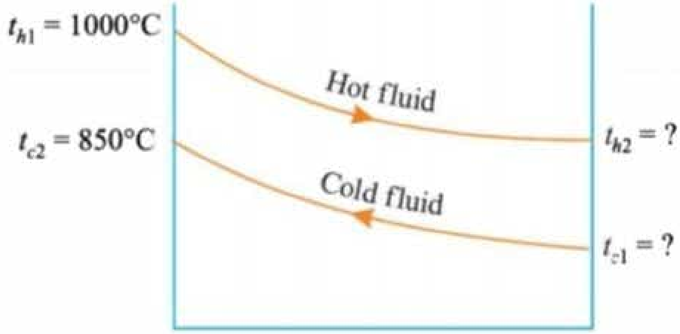


Fig. 10.53.

For the known values of C_{min}/C_{max} and NTU for the counter-flow, we get from Fig. 10.45,

$$\varepsilon = 0.47$$

Substituting this value in eqn. (*i*), we get

$$0.47 = \frac{1000 - t_{h2}}{1000 - t_{c1}} = \frac{850 - t_{c1}}{1000 - t_{c1}}$$

or, $$0.47 = \frac{850 - t_{c1}}{1000 - t_{c1}}$$

$$0.47\ (1000 - t_{c1}) = 850 - t_{c1} \quad \text{or} \quad 470 - 0.47\ t_{c1} = 850 - t_{c1}$$

$$t_{c1} - 0.47\ t_{c1} = 850 - 470$$

$$\mathbf{t_{c1}} = \frac{(850 - 470)}{0.53} = \mathbf{717°C} \quad \textbf{(Ans.)}$$

or, $$0.47 = \frac{1000 - t_{h2}}{1000 - 717}$$

or, $$\mathbf{t_{h2}} = 1000 - 0.47\ (1000 - 717) \simeq \mathbf{867°C} \quad \textbf{(Ans.)}$$

Example 10.39. *Water (c_{pc} = 4200 J/kg°C) enters a counter-flow double pipe heat exhanger at 38°C flowing at 0.076 kg/s. It is heated by oil (c_p = 1880 J/kg°C) flowing at the rate of 0.152 kg/s from an inlet temperature of 116°C. For an area of 1m² and U = 340 W/m²°C, determine the total heat transfer rate.*

Solution. *Given :* $\dot{m}_w = \dot{m}_c = 0.076$ kg/s, c_{pc} = 4200 J/kg°C; t_{c1} = 38°C; $\dot{m}_{oil} = \dot{m}_h = 0.152$ kg/s, c_{ph} = 1880 J/kg°C; t_{h1} = 116°C; U = 340 W/m²°C; A = 1 m².

The total heat transfer rate, *Q* :

As *outlet temperatures of both fluids are not known, we have to use NTU method for solving the problem.*

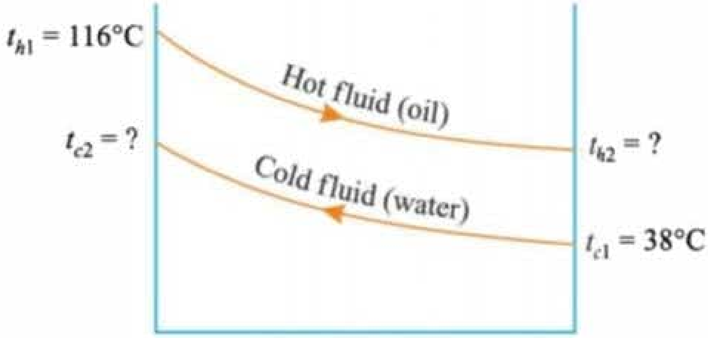


Fig. 10.54. Counter-flow heat exchanger.

The effectiveness ε of heat exchanger is given by

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

$$C_h = \dot{m}_h\, c_{ph} = 0.152 \times 1880 = 258.8 = C_{min}$$

$$C_c = \dot{m}_c\, c_{pc} = 0.076 \times 4200 = 319.2 = C_{max}$$

$$\frac{C_{\min}}{C_{\max}} = \frac{285.8}{391.2} = 0.895$$

$$\text{NTU} = \frac{UA}{C_{\min}} = \frac{340 \times 1}{285.8} = 1.19$$

For the calculated values of $\frac{C_{\min}}{C_{\max}} = 0.895$ and $NTU = 1.19$, from the Fig. 10.45, we get

$$\varepsilon \simeq 0.53$$

Substituting the values in eqn (*i*), we get

$$0.53 = \frac{285.8\,(116 - t_{h2})}{285.8\,(116 - 38)} = \frac{319.2\,(t_{c2} - 38)}{285.8\,(116 - 38)}$$

or,
$$0.53 = \frac{(116 - t_{h2})}{(116 - 38)} = 1.117\left(\frac{t_{c2} - 38}{116 - 38}\right)$$

∴
$$t_{h2} = 116 - 0.53\,(116 - 38) = 74.66°\text{C} \simeq 75°\text{C}$$

and,
$$t_{c2} = \frac{0.53\,(116 - 38)}{1.117} + 38 = 75°\text{C}$$

The total rate of heat transfer is given by

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

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

$$= \frac{(116 - 75) - (75 - 38)}{\ln[(116 - 75)/(75 - 38)]} = \frac{41 - 37}{\ln(41/37)} \simeq 39°\text{C}$$

∴
$$Q = 340 \times 1 \times 39 = 13260\ \text{W} = \mathbf{13.26\ kW} \qquad \textbf{(Ans.)}$$

Example 10.40. *The overall temperature rise of the cold fluid in a cross-flow heat exchanger is 20°C and overall temperature drop of hot-fluid is 30°C. The effectiveness of heat exchanger is 0.6. The heat exchanger area is 1m² and overall heat transfer coefficient is 60 W/m²°C. Find out the rate of heat transfer. Assume both fluids are unmixed.*

Solution. *Given* : $t_{c2} - t_{c1} = 20°$C; $t_{h1} - t_{h2} = 30°$C; $\varepsilon = 0.6$; $A = 1\text{m}^2$; $U = 60\ \text{W/m}^2°\text{C}$.

Rate of heat transfer, Q :

Heat lost by hot fluid = Heat gained by water

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

∴
$$\frac{t_{h1} - t_{h2}}{t_{c2} - t_{c1}} = \frac{\dot{m}_c\, c_{pc}}{\dot{m}_h\, c_{ph}} = \frac{30}{20} = 1.5$$

∴
$$\dot{m}_c\, c_{pc} = C_{max} \quad \text{and} \quad \dot{m}_h\, c_{ph} = C_{min}$$

$$\frac{C_{min}}{C_{max}} = \frac{1}{1.5} = 0.67$$

Now from the graph, for the given values of

$$\varepsilon = 0.6 \quad \text{and } C_{min}/C_{max} = 0.67, \text{ we get}$$

$$NTU = 1.4$$

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

$\therefore$ $$C_{min} = \frac{UA}{NTU} = \frac{60 \times 1}{1.4} = 42.86 = C_h;$$

$$C_{max} = \frac{C_{min}}{0.67} = \frac{42.86}{0.67} = 63.97 = C_c$$

$\therefore$ $$Q = \dot{m}_h\, c_{ph}\,(t_{h1} - t_{h2}) = C_h\,(t_{h1} - t_{h2})$$
$$= 42.86 \times 30 = \mathbf{1285.8\ W}\ \textbf{(Ans.)}$$

Example 10.41. *Define the terms NTU and effectiveness. Derive an expression for effectiveness of a counter-flow heat exchanger in terms of NTU and capacity ratio.* **(U.P.S.C., 1996)**

Solution. Refer Article 10.7.

Example 10.42. *Two fluids, A and B exchange heat in a counter-current heat exchanger. Fluid A enters at 420°C and has a mass flow rate of 1 kg/s. Fluid B enters at 20°C and has a mass flow rate of 1 kg/s. Effectiveness of heat exchanger is 75%.*

Determine : (i) The heat transfer rate;

(ii) The exit temperature of fluid B.

Specific heat of fluid A is 1 kJ/kg K and that of fluid B is 4 kJ/kg K. **(GATE, 1999)**

Solution. *Given* : $t_{A1} = t_{h1} = 420°C$; $\dot{m}_h = 1$ kg/s; $\dot{m}_c = 1$ kg/s;

$t_{B1} = t_{c1} = 20°C$; $\varepsilon = 0.75$; $c_{pA} = c_{ph} = 1$ kJ/kg K;

$c_{pB} = c_{pc} = 4$ kJ/kg K.

(*i*) The heat transfer rate, *Q* :

Effectiveness, $$\varepsilon = \frac{C_h\,(t_{h1} - t_{h2})}{C_{min}\,(t_{h1} - t_{c1})} = \frac{t_{h1} - t_{h2}}{t_{h1} - t_{c1}} \qquad (\because C_h = \dot{m}_h\, c_{ph} = 1 \times 1 = 1 = C_{min})$$

or, $$0.75 = \frac{420 - t_{h2}}{420 - 20}$$

or, $$t_{h2} = 420 - 0.75\,(420 - 20) = 120°C$$

Now, $$Q = \varepsilon\, C_{min}\,(t_{h1} - t_{c1})$$
$$= 0.75 \times \dot{m}_h\, c_{ph} \times (t_{h1} - t_{c1})$$
$$= 0.75 \times 1 \times 1 \times (420 - 20) = \mathbf{300\ kJ}\ \textbf{(Ans.)}$$

(*ii*) The exit temperature of fluid B, t_{c2} :

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

or, $$300 = 1 \times 4\,(t_{c2} - 20)$$

$\therefore$ $$t_{c2} = \frac{300}{4} + 20 = \mathbf{95°C}\ \textbf{(Ans.)}$$