MA3071

E3.5 HEAT EXCHANGER

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Content

1. Introduction (heat conduction and convection)
2. Heat exchanger
3. Objectives
4. Log sheet *(to be submitted)*

Heat and Mass Transfer: Fundamentals & Applications
5th Edition in SI Units
Yunus A. Çengel, Afshin J. Ghajar
McGraw-Hill, 2015

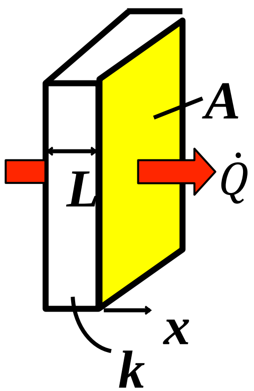
Chapter 11

Introduction

HEAT CONDUCTION

- Occurs in solids and stationary fluids (liquids and gases)
- **Fourier's law of conduction:**

$$\boxed{\dot{Q} = -kA\frac{dT}{dx}}$$



Where,

$\dot{Q}$ = heat transfer rate [W]

A = area perpendicular to the heat flow direction [m^2]

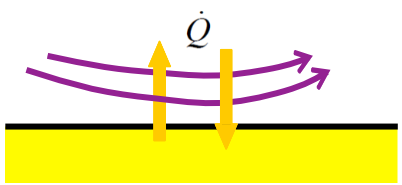
dT/dx = temperature gradient **along heat flow direction** [K/m]

k = thermal conductivity of the medium [W/m·K]

HEAT CONVECTION

- Transfer of heat through bulk motion of the fluid
- **Newton's law of cooling:**

$$\boxed{\dot{Q} = hA(T_s - T_\infty)}$$



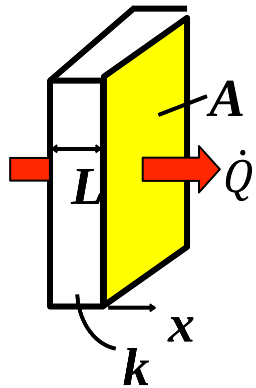
Where,

- *h* = (convective) heat transfer coefficient (W/m^2·K)
- *A* = area through which heat is transferred [m^2]
- *ΔT* = temperature difference between bulk fluid temperature and surface temperature

Introduction

HEAT CONDUCTION

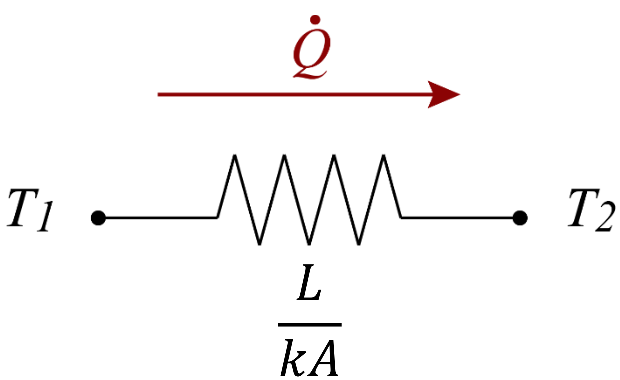
$$\boxed{\dot{Q} = -kA\frac{dT}{dx}}$$



$$\dot{Q} = \frac{\Delta T}{R}$$

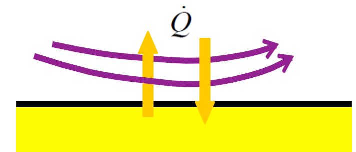
Thermal conduction resistance

$$\boxed{R = \frac{L}{kA} \quad (\mathrm{K/W})}$$



HEAT CONVECTION

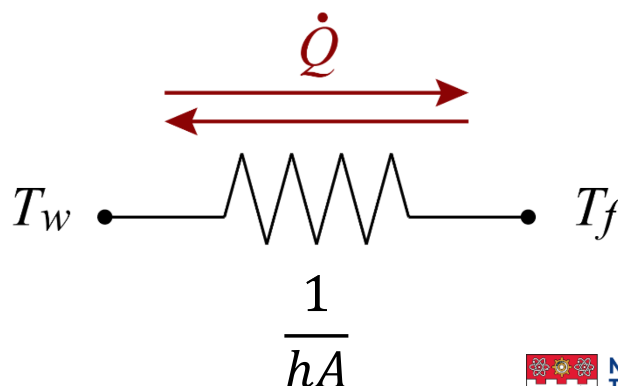
$$\boxed{\dot{Q} = hA(T_s - T_\infty)}$$



$$\dot{Q} = \frac{\Delta T}{R}$$

Thermal convective resistance

$$\boxed{R = \frac{1}{hA}}$$

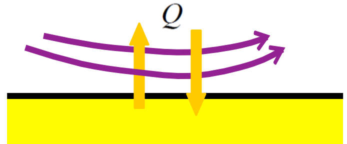


Introduction

HEAT CONVECTION

$$\boxed{\dot{Q} = hA(T_s - T_\infty)}$$

External flow

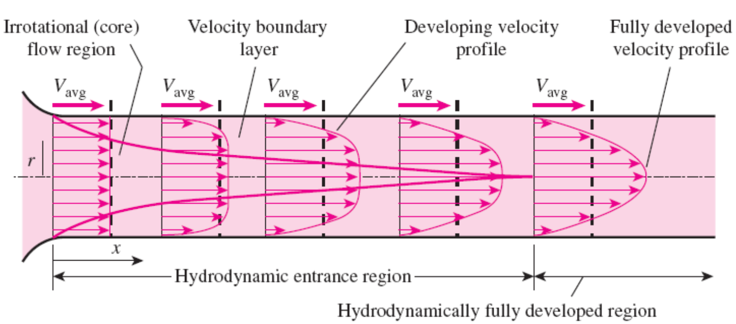


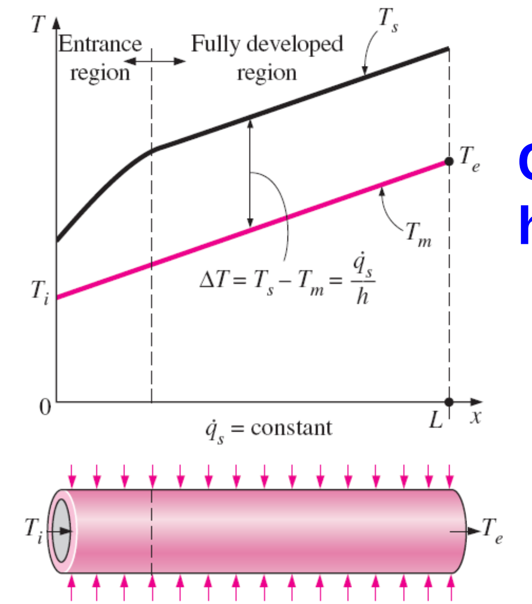
$$\boxed{\dot{q}_s = h_x(T_s - T_m)}$$

Internal flow

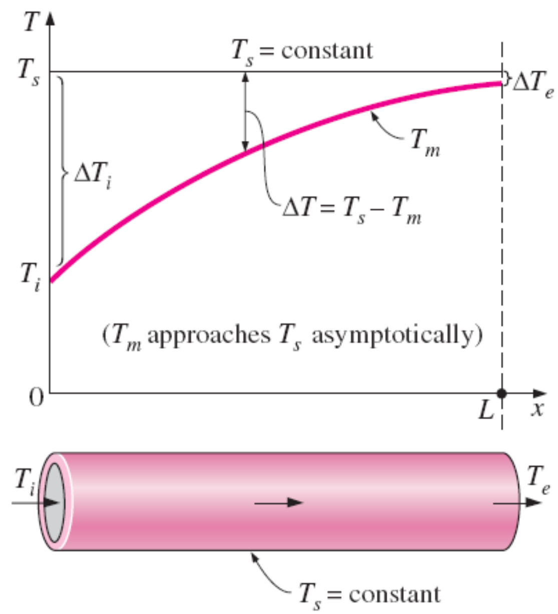
h_x the *local* heat transfer coefficient

Note that T_m of fluid flowing in a tube must change during heating/cooling.





Constant heat flux



Constant surface temperature

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Introduction

Log Mean Temperature Difference

Temperature of the fluid along the pipe varies exponentially with the length:

$$T_e = T_s - (T_s - T_i)\exp(\boxed{-hA_s/\dot{m}c_p})$$

Decays exponentially in the flow direction

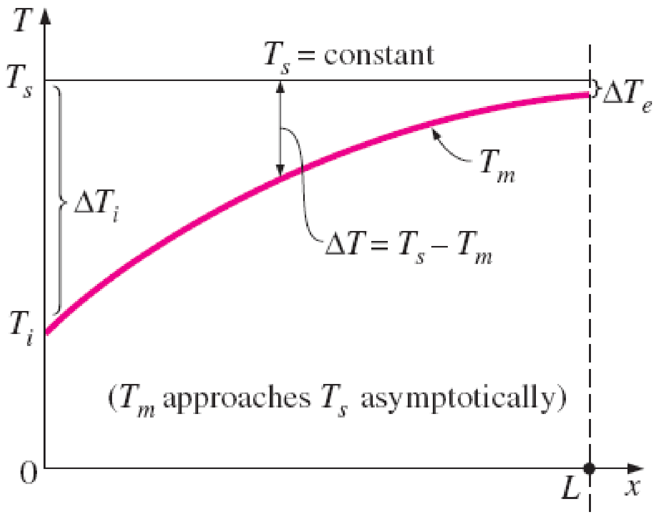
Log mean temperature difference (ΔT_{ln}) is the exact representation of the "average temperature difference" in the pipe between the fluid and surface, and used for calculating total convective heat transfer:

Where,

$$\dot{Q} = hA_s\Delta T_{\ln}$$

$$\boxed{\Delta T_{\ln} = \frac{T_i - T_e}{\ln[(T_s - T_e)/(T_s - T_i)]} = \frac{\Delta T_e - \Delta T_i}{\ln(\Delta T_e/\Delta T_i)}}$$

$$\boxed{\Delta T_{ln} = \frac{(T_s - T_e) - (T_s - T_i)}{\ln[(T_s - T_e)/(T_s - T_i)]}}$$



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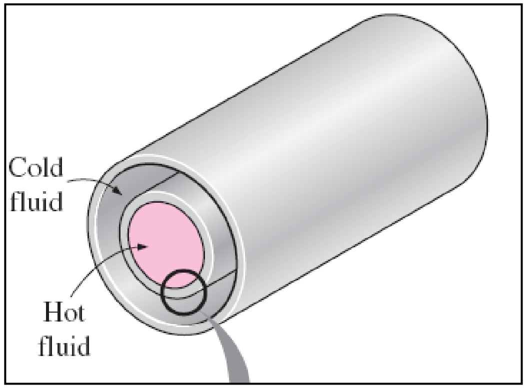
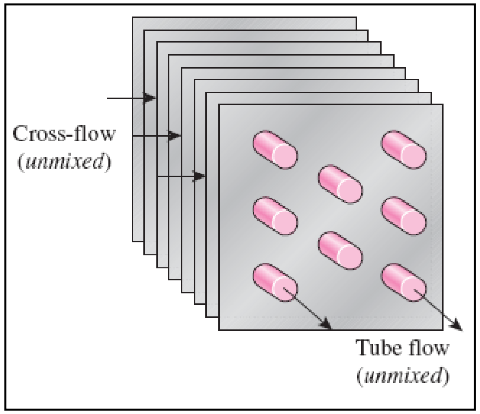
Heat exchanger

- Devices which facilitate exchange of heat between 2 fluids that are at different temperatures
- Fluids do not mix (unlike mixing chambers)
- Applications: Heater, Aircon, power plants etc.



Double-pipe heat exchanger



Cross-flow heat exchanger

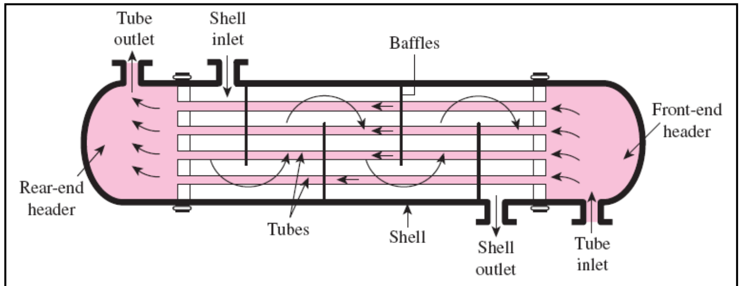
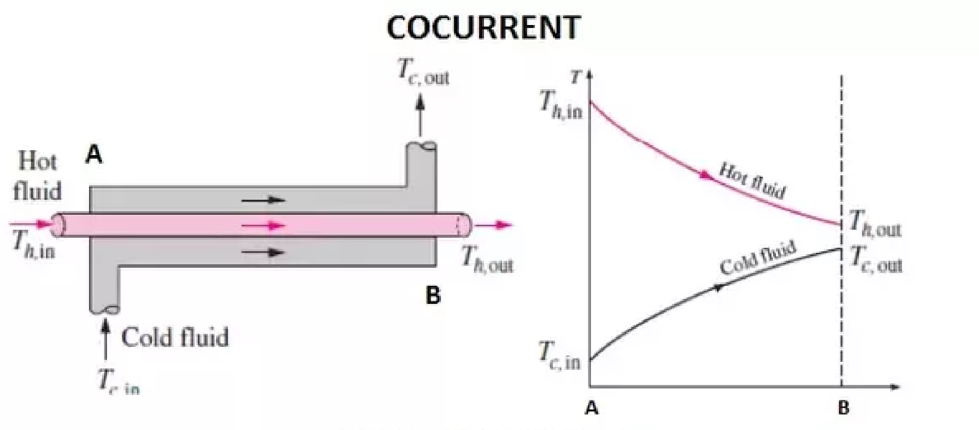


FIGURE 11–4
The schematic of a shell-and-tube heat exchanger (one-shell pass and one-tube pass).

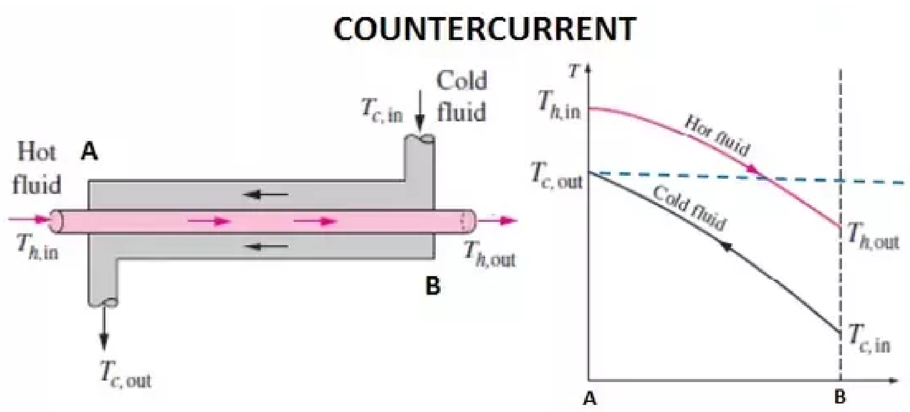
Shell-and-tube heat exchanger

Heat exchanger



-**Large** temperature differences at the ends cause large thermal stresses

-Outlet temperature of the cold fluid will never exceed the lowest temperature of the hot fluid



-**More uniform** temperature differences

- minimizes thermal stresses
- more uniform rate of heat transfer

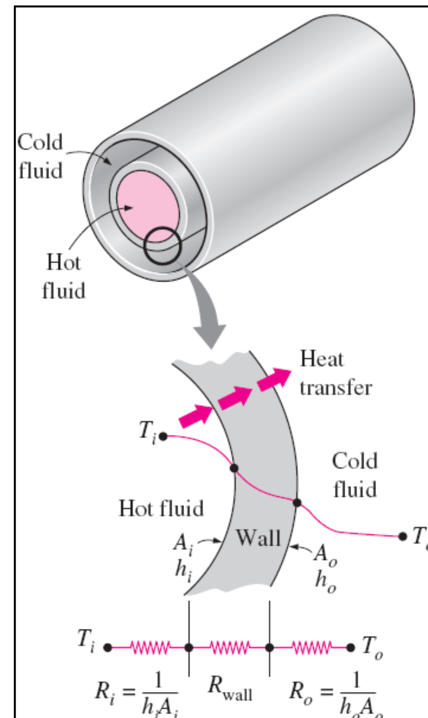
-Outlet temperature of cold fluid can approach the highest temperature of hot fluid (inlet temperature)

Heat exchanger (lab manual)

In a typical heat exchanger, heat is transferred from a hot fluid, through a separating wall, to a colder fluid. Heat is driven through three resistances in series given by

$$\sum R = R_{conv,h} + R_{cond,wall} + R_{conv,c} = \frac{1}{h_h A_h} + \frac{\Delta x}{kA} + \frac{1}{h_c A_c} \qquad (7)$$

where the subscripts h and c denote the hot and cold fluids, respectively.



The rate of heat transfer is then given by

$$\dot{Q} = \frac{T_h - T_c}{\sum R} = \frac{T_h - T_c}{\frac{1}{h_h A_h} + \frac{\Delta x}{kA} + \frac{1}{h_c A_c}} \qquad (8)$$

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Heat exchanger (lab manual)

If the tube wall of the heat exchanger is thin, we may assume that all the areas are equal such that, $A_h \approx A_c \approx A \approx A_m$. Equation (8) can then be written as

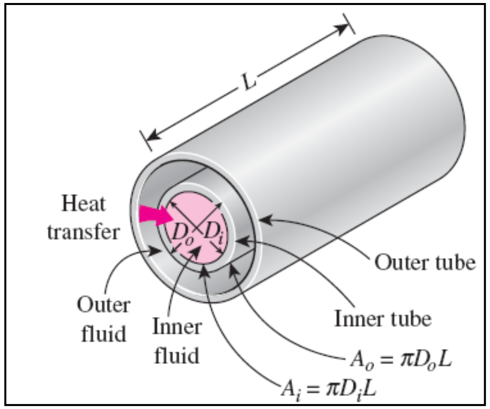
$$\dot{Q} = UA_m(T_h - T_c) \tag{9}$$

where $U = \dfrac{1}{\dfrac{1}{h_h} + \dfrac{\Delta x}{k} + \dfrac{1}{h_c}}$ is the overall heat transfer coefficient (W/m^2·K)

$A_m =$ mean heat transfer mean area (m^2)

$T_h =$ temperature of hot fluid °C

$T_c =$ temperature of cold fluid °C



The conduction thermal resistance of the tube wall is usually insignificant compared to the other two resistances and is often ignored. It can be seen that an accurate prediction of the convective heat transfer coefficients is most important when designing a heat exchanger.

Heat exchanger (lab manual)

The rate of heat transfer is then given by

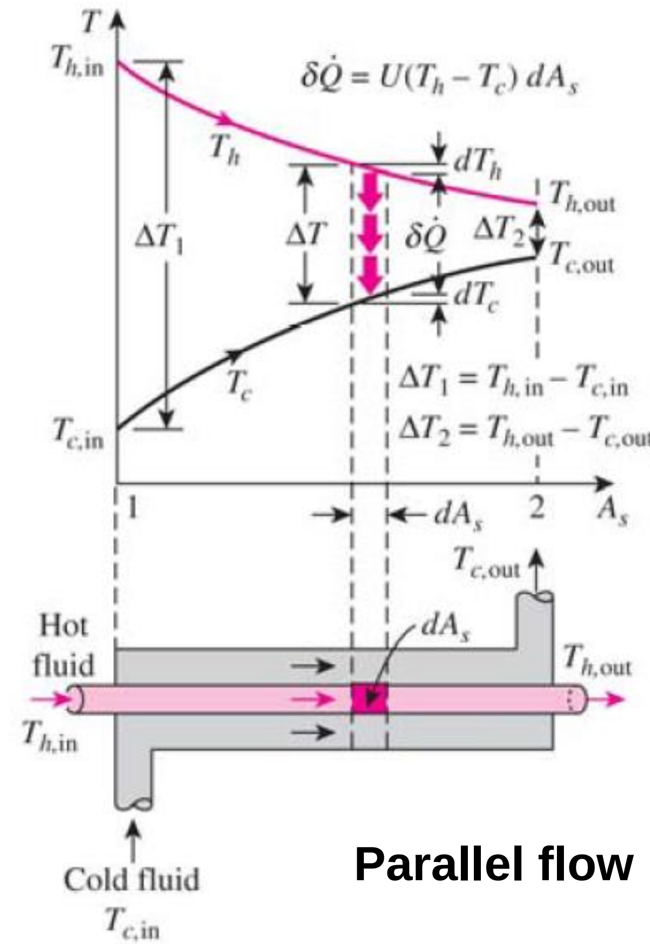
$$\dot{Q} = UA_m \Delta T_{lm}$$

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln \dfrac{\Delta T_2}{\Delta T_1}}$$

Based on the labelling of the temperatures in this equipment,

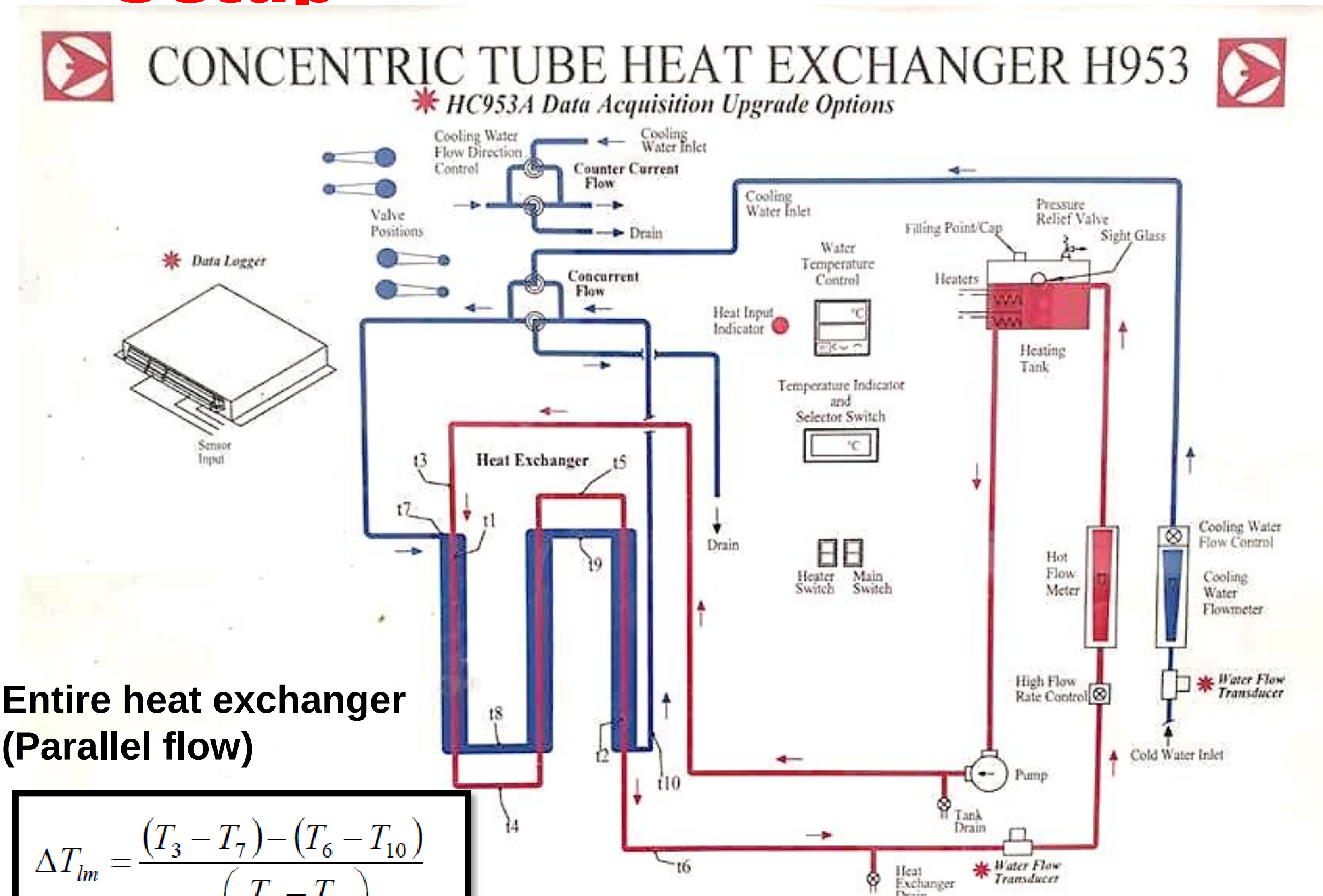
$$\Delta T_{lm} = \frac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\dfrac{T_3 - T_7}{T_6 - T_{10}}\right)}$$

where the definitions of the subscripts are given in Table 1.



Parallel flow

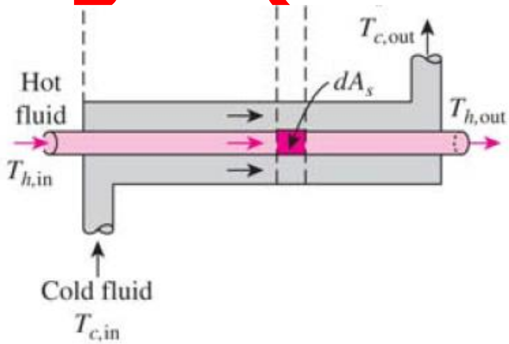
Setup



Entire heat exchanger (Parallel flow)

$$\Delta T_{lm} = \frac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\dfrac{T_3 - T_7}{T_6 - T_{10}}\right)}$$

Heat exchanger (lab manual)



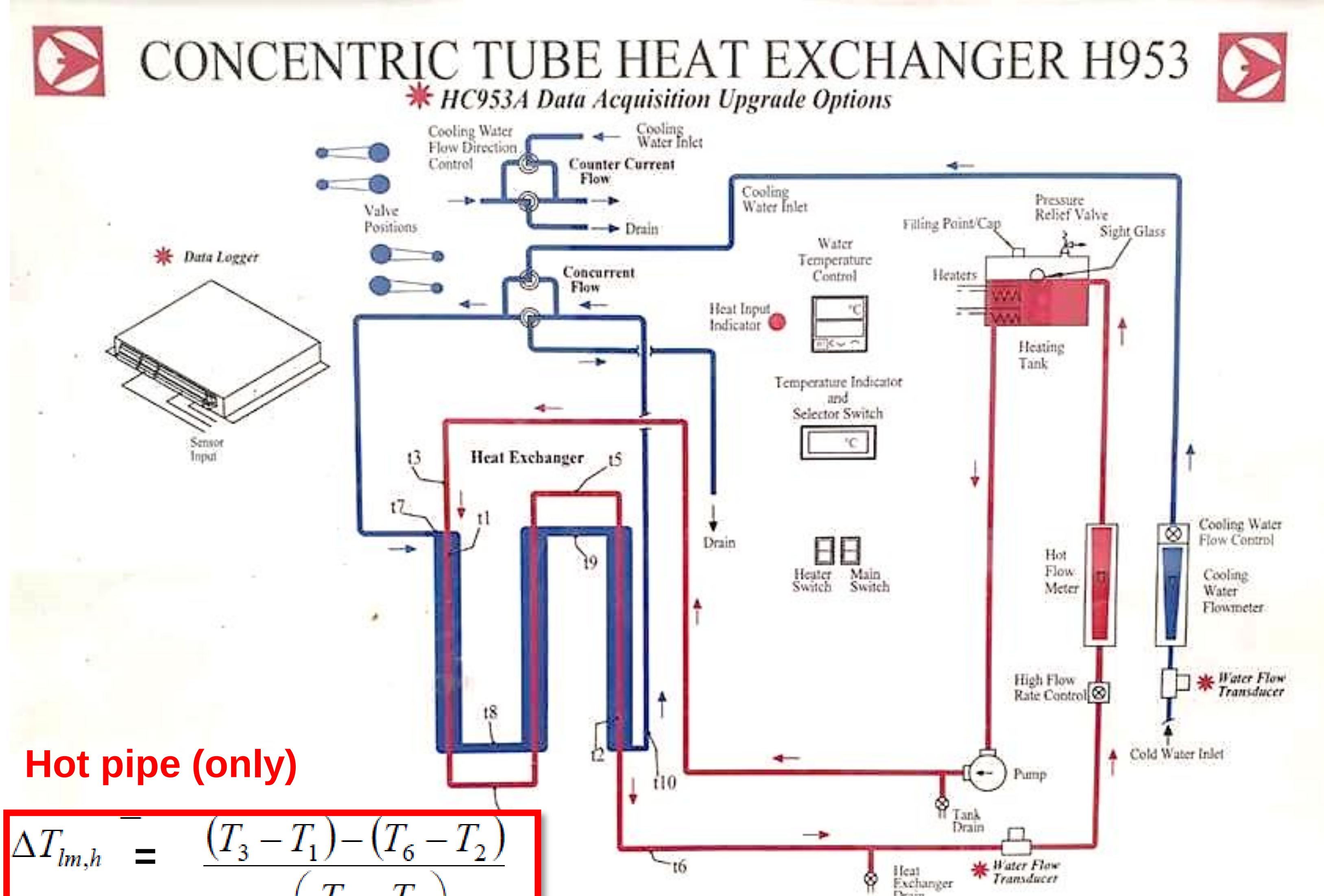
(i) Overall rate of heat transfer from the hot stream to the cold stream

$$\dot{Q}_h = \dot{m}_h c_p (T_3 - T_6) \qquad (13)$$

(iv) Average convective heat transfer coefficient between the inner surface of tube and the $\boxed{\text{hot}}$ stream

$$h_h = \frac{\dot{Q}_h}{A_h \Delta T_{lm,h}} = \frac{\dot{Q}_h}{A_h \dfrac{(T_3 - T_1) - (T_6 - T_2)}{\ln\left(\dfrac{T_3 - T_1}{T_6 - T_2}\right)}} \qquad (17)$$

Setup



Hot pipe (only)

$$\Delta T_{lm,h} = \frac{(T_3 - T_1) - (T_6 - T_2)}{\ln\left(\dfrac{T_3 - T_1}{T_6 - T_2}\right)}$$

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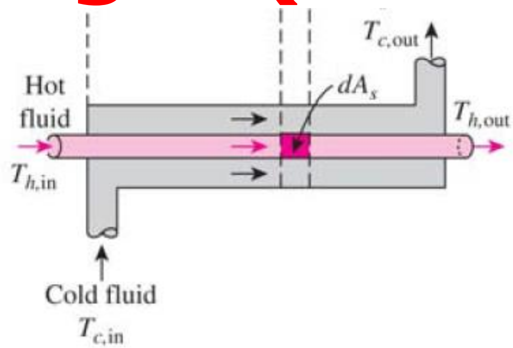
Heat exchanger (lab manual)



(ii) Overall rate of heat transfer to the cold stream from the hot stream

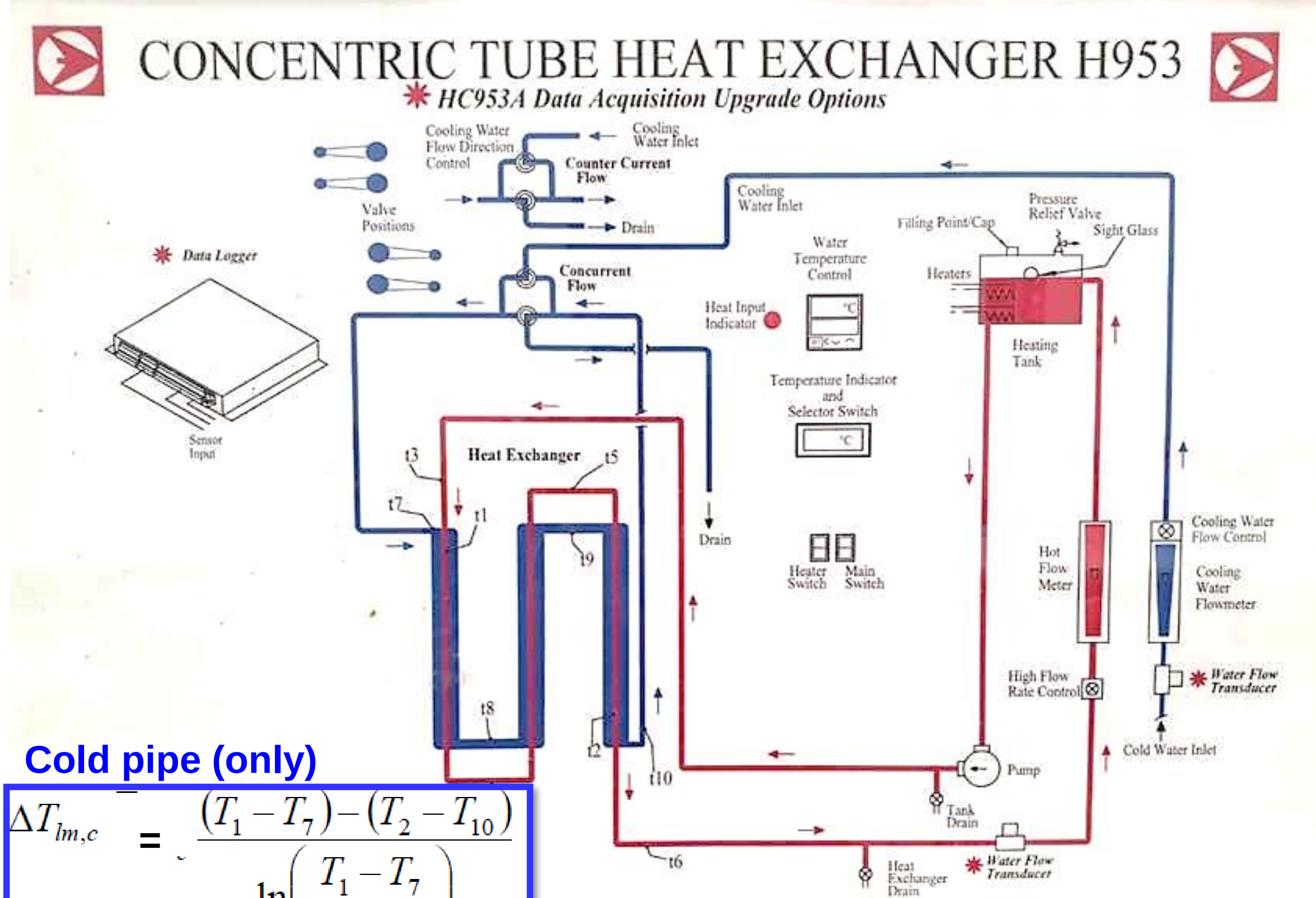
$$\dot{Q}_c = \dot{m}_c c_p (T_{10} - T_7) \qquad \text{for parallel flow} \qquad (14)$$

$$\dot{Q}_c = \dot{m}_c c_p (T_7 - T_{10}) \qquad \text{for counter flow} \qquad (15)$$

(v) Average convective heat transfer coefficient between the outer surface of tube and the $\boxed{\text{cold}}$ stream

$$h_c = \frac{\dot{Q}_c}{A_c \Delta T_{lm,c}} = \frac{\dot{Q}_c}{A_c \dfrac{(T_1 - T_7) - (T_2 - T_{10})}{\ln\left(\dfrac{T_1 - T_7}{T_2 - T_{10}}\right)}} \qquad (18)$$

Setup



Cold pipe (only)

$$\Delta T_{lm,c} = \frac{(T_1 - T_7) - (T_2 - T_{10})}{\ln\left(\frac{T_1 - T_7}{T_2 - T_{10}}\right)}$$

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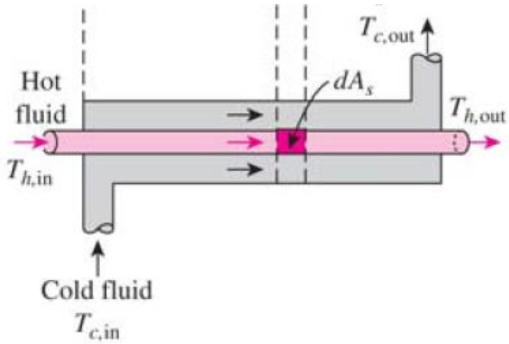
Heat exchanger (lab manual)



The rate of heat transfer is then given by

$$\dot{Q} = UA_m \Delta T_{lm}$$

(iii) Overall heat transfer coefficient

$$U = \frac{\dot{Q}_h}{A_m \Delta T_{lm}} = \frac{\dot{Q}_h}{\dfrac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\dfrac{T_3 - T_7}{T_6 - T_{10}}\right)} A_m} \qquad (16)$$

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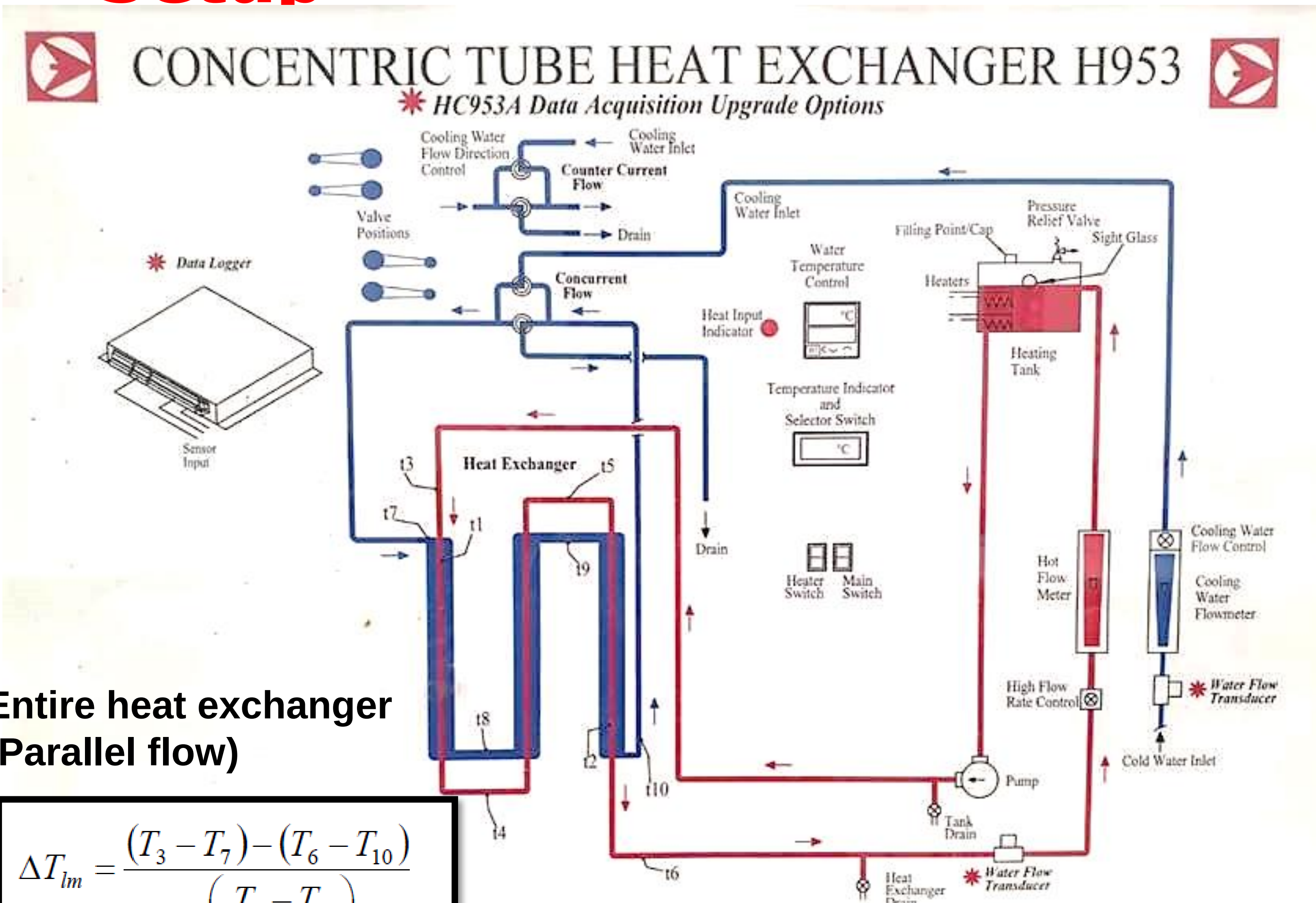
Setup



Entire heat exchanger (Parallel flow)

$$\Delta T_{lm} = \frac{(T_3 - T_7) - (T_6 - T_{10})}{\ln\left(\frac{T_3 - T_7}{T_6 - T_{10}}\right)}$$

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Objectives

- To compare the thermal performance of a concentric tube heat exchanger in **parallel** and **counter** flow.

- To determine the effect of fluid velocity on the convective heat transfer coefficients (h_h,h_c), and overall heat transfer coefficient (U) for **counter** flow.

Log sheet

Parallel and counter flow

Plot the temperature distribution of the metal wall, the hot and cold streams and discuss. Compare the heat transferred for the two flow arrangements and explain the calculated discrepancies.

Effect of fluid velocity on the convective heat transfer coefficients and the overall heat transfer coefficient

Plot, for a constant velocity in the annulus, the convective heat transfer coefficient inside and outside the tube and the overall heat transfer coefficient against the tube water velocity. Comment on the results.

Sample calculations

Show sample calculations and verify that they are the same as those generated by the spreadsheet programme in the laboratory's personal computer.

Observations

Note down in your log sheet the uncertainties associated with each measuring instrument or sensor. Record the time taken for the readings to stabilise.

Log sheet

- Sample calculations

Table 1 Parallel flow and Counter flow

Test	Parallel flow	Counter flow
Metal wall at inlet, T_1 (°C)		
Metal wall at exit, T_2 (°C)		
Hot stream at inlet, T_3 (°C)		
Hot stream 1st intermediate, T_4 (°C)		
Hot stream 2nd intermediate, T_5 (°C)		
Hot stream at exit, T_6 (°C)		
Cold stream entry/exit, T_7 (°C)		
Cold stream intermediate, T_8 (°C)		
Cold stream intermediate, T_9 (°C)		
Cold stream entry/exit, T_{10} (°C)		
Hot water flow rate, $\dot{m}_h$ (kg/s)		
Cooling water flow rate, $\dot{m}_c$ (kg/s)		
Heat transfer rate from hot water, $\dot{Q}_h$ (W)		
Heat transfer rate to cold water, $\dot{Q}_c$ (W)		

Table 2 Effect of fluid velocity on the convective heat transfer coefficients (Counter flow)

Test	1 (100%)	2 (80%)	3 (60%)	4 (40%)	5 (20%)
Metal wall at inlet, T_1 (°C)					
Metal wall at exit, T_2 (°C)					
Hot stream at inlet, T_3 (°C)					
Hot stream 1st intermediate, T_4 (°C)					
Hot stream 2nd intermediate, T_5 (°C)					
Hot stream at exit, T_6 (°C)					
Cold stream entry/exit, T_7 (°C)					
Cold stream intermediate, T_8 (°C)					
Cold stream intermediate, T_9 (°C)					
Cold stream entry/exit, T_{10} (°C)					
Hot water flow rate, $\dot{m}_h$ (kg/s)					
Cooling water flow rate, $\dot{m}_c$ (kg/s)					
Overall heat transfer coefficient, U (W/m^2·K)					
Average convective heat transfer coefficient inside the inner tube, h_h (W/m^2·K)					
Average convective heat transfer coefficient in the annulus between the tubes, h_c (W/m^2·K)					