Τ.Ε.Ι. ΑΘΗΝΑΣ / Σ.ΤΕ.Φ.

ΤΜΗΜΑ ΕΝΕΡΓΕΙΑΚΗΣ ΤΕΧΝΟΛΟΓΙΑΣ

ΕΡΓΑΣΤΗΡΙΟ ΜΕΤΑΔΟΣΗΣ ΘΕΡΜΟΤΗΤΟΣ

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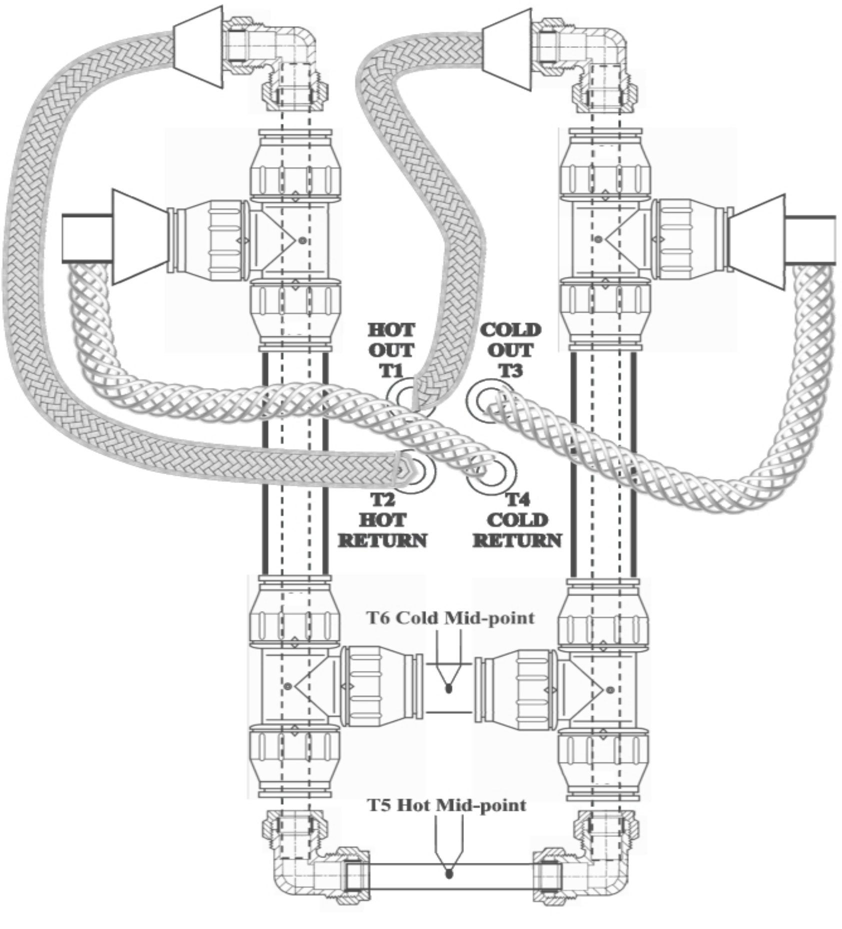
Η ΜΕΛΕΤΗ ΤΟΥ ΘΕΡΜΙΚΟΥ ΙΣΟΖΥΓΙΟΥ ΕΝΑΛΛΑΚΤΗ ΘΕΡΜΟΤΗΤΑΣ ΜΕ ΔΙΑΤΑΞΗ ΡΕΥΜΑΤΩΝ ΟΜΟΡΡΟΗΣ ¨Η ΑΝΤΙΡΡΟΗΣ ΣΕ ΣΥΝΘΗΚΕΣ ΜΟΝΙΜΗΣ ΚΑΤΑΣΤΑΣΗΣ

Σκοπός : Η εργαστηριακή άσκηση έχει σαν σκοπό την διεξαγωγή μετρήσεων για τον υπολογισμό της ισχύος του εναλλάκτη θερμότητας και την επιβεβαίωση του θερμικού ισοζυγίου για συνθήκες μόνιμης κατάστασης σε περίπτωση διάταξης ρευμάτων σε ομορροή ή αντιρροή.

H101A Concentric Tube Heat Exchanger (Co-Current Flow)



T_{hi}=T1 **Θερμοκρασία εισόδου ζεστού νερού στον εναλλακτη**

T_{ho}=T2 **Θερμοκρασία εξόδου ζεστού νερού από τον εναλλακτη**

T_{ci}=T3 **Θερμοκρασία εισόδου ψυχρού νερού στον εναλλακτη**

T_{co}=T4 **Θερμοκρασία εξόδου ψυχρού νερού απο τον εναλλακτη**

T_{hm}=T5 **Μέση θερμοκρασία ζεστού νερού**

T_{cm}=T6 **Μέση θερμοκρασία ψυχρού νερού**

USEFUL DATA

CONCENTRIC TUBE HEAT EXCHANGER H101A

Inner Tube

Material	Stainless steel
Outside Diameter	0.012m
Wall Thickness	0.001m

Outer Tube

Material	Clear Acrylic
Inside Diameter	0.022m
Wall Thickness	0.003m

Active Heat Transfer Section

Length	2 x 0.3180m
Area	0.02198 m^2

Παραδείγματα θερμοκρασιακής κατανομής σε **ομορροή – αντιρροή**

Thermocouple Stations

Co-current and Counter current flow

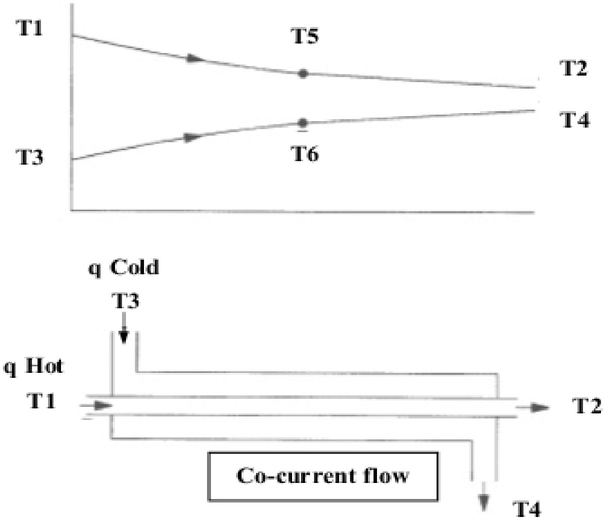
Thermocouples sense the stream temperatures at the four fixed stations: -

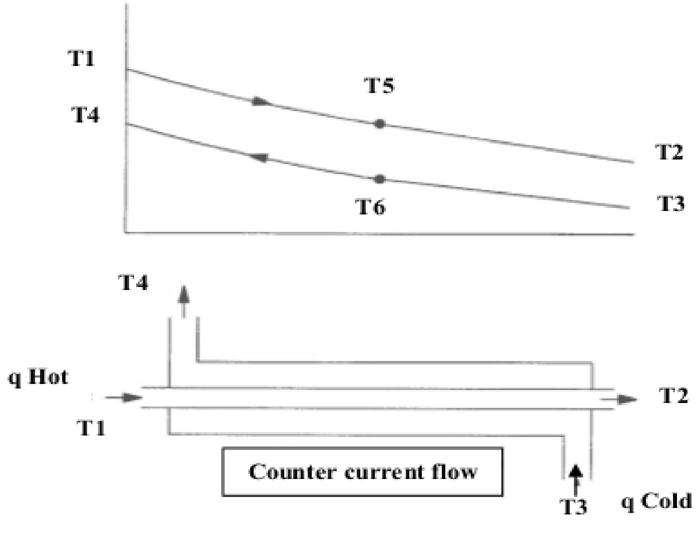
T1 – Hot Water INLET to Heat Exchanger
T2 – Hot Water RETURN from Heat Exchanger
T3 – Cooling Water INLET to Heat Exchanger
T4 – Cooling Water RETURN from Heat Exchanger

In addition, two plug-in stations: -

T5 – Hot Mid-position (for Concentric Tube)
T6 – Cold Mid-position (for Concentric Tube)

All thermocouples are duplex sensors, the spare sensor is utilised when HC101A Data Acquisition upgrade is fitted.

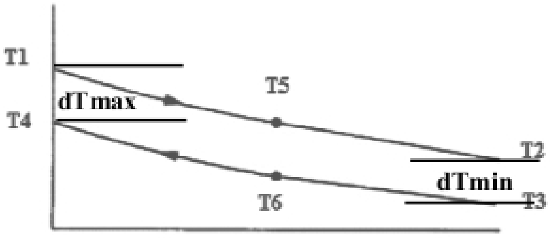




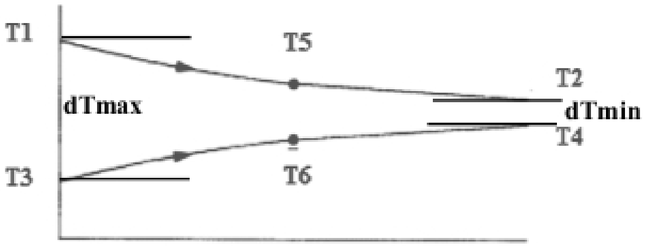
Καθώς οι θερμοκρασιακές διαφορές μεταξύ του ζεστού και ψυχρού ρεύματος μεταβάλονται κατά μήκος του εναλλάκτη θερμότητας, είναι αναγκαίο να ορισθεί μια μέση θερμοκρασιακή διαφορά ωστε να χρησιμοποιηθεί στον ενεργειακούς υπολογισμούς.

Λογαριθμική μέση θερμοκρασιακή διαφοράς

$$ΛΜΘΔ = \overline{ΔT} = \frac{ΔT_1 - ΔT_2}{\ln \frac{ΔT_1}{ΔT_2}} = \frac{dT_{max} - dT_{min}}{\ln \frac{dT_{max}}{dT_{min}}}$$



Counter current flow



Co-current flow

Για την περίπτωση **αντιρροής**: $ΔT_1 = T_{hi} - T_{co}$ $ΔT_2 = T_{ho} - T_{ci}$

Για την περίπτωση **ομορροής**: $ΔT_1 = T_{hi} - T_{ci}$ $ΔT_2 = T_{ho} - T_{co}$

Παράδειγμα 1:

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T5	T2	T3	T6	T4	V_{cold}	V_{hot}
----	°C	°C	°C	°C	°C	°C	G/sec	G/sec
1	59.2	56.6	53.0	15.4	25.1	30.9	17	50
2								
3								
4								
5								

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}$ e	$\dot{Q}$ a	$\eta_{Thermal}$
---	K	K	W	W	%
	6.2	15.5	1277	1099	86.1

CALCULATIONS

For the example the calculations are as follows.

It is necessary to correct mass flow rates using the conversion factors in tables 1 and 2 on pages A7 and A8. The water density ρ (kg litre^{-1}) and specific heat capacity Cp (kJ kg^{-1} K^{-1}) is dependant upon the temperature and the mid point temperature T5 and T6 is a good approximation of the mean temperature for the hot and cold streams.

For the Hot stream:

From table 1 and 2 at T5 = 56.6 °C $\quad \rho_{hot} = 0.9852$ kg litre^{-1}

$Cp_{Hot} = 4.183$ kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}$ e

$$\begin{aligned}\dot{Q}e &= V_{hot}\,\rho_{hot}\,Cp_{Hot}\left(T1-T3\right) \quad \text{Watts}\\ &= 50\times 0.9852\times 4.183\times\left(59.2-53.0\right)\\ &= 1277 \quad \text{Watts}\end{aligned}$$

For the cold stream:

From table 1 and 2 at T6 = 25.1 °C $\quad \rho_{Cold} = 0.9970$ kg litre^{-1}

$Cp_{Cold} = 4.185$ kJ kg^{-1} k^{-1}

The power absorbed by the cold stream $\dot{Q}$ a

$$\begin{aligned}\dot{Q}a &= V_{cold}\,\rho_{cold}\,Cp_{Cold}\left(T4-T3\right) \quad \text{Watts}\\ &= 17\times 0.997\times 4.186\times\left(30.9-15.4\right)\\ &= 1099 \text{ Watts}\end{aligned}$$

The overall thermal efficiency

$$\eta_{\text{ Thermal}} = \frac{\dot{Q}a}{\dot{Q}e}\times 100(\%)$$

Hence

$$\begin{aligned}\eta_{\text{ Thermal}} &= \frac{1099}{1277}\times\ 100(\%)\\ &= 86.1\%\end{aligned}$$

Note that in this procedure the cold water circulates through the outer annulus and is not insulated from the outside environment. Therefore if the ambient temperature is below the cold stream temperature further heat will be lost from the system. If the ambient is above the outer stream temperature then heat can be gained from the atmosphere. In extreme cases, this can result in an *apparent* thermal efficiency greater than 100%.

Table 1 Specific Heat capacity Cp of Water in kJ kg $^{-1}$ K^{-1}

°C	0	1	2	3	4	5	6	7	8	9
0	4.1274	4.2138	4.2104	4.2074	4.2054	4.2019	4.1996	4.1974	4.1954	4.1936
10	4.1919	4.1904	4.189	4.1877	4.1866	4.1855	4.1864	4.1837	4.1829	4.1822
20	4.1816	4.181	4.1805	4.1801	4.1797	4.1793	4.1790	4.1787	4.1785	4.1783
30	4.1782	4.1781	4.1780	4.1780	4.1779	4.1779	4.1780	4.1780	4.1781	4.1782
40	4.1783	4.1784	4.1786	4.1788	4.1789	**4.1792**	4.1794	4.1796	4.1799	4.180
50	4.1804	4.1807	4.1811	4.1814	4.1817	4.1821	4.1825	4.1829	4.1833	4.1837
60	4.1841	4.1846	4.1850	4.1855	4.1860	4.1865	4.1871	4.1876	4.1882	4.1887
70	4.1893	4.1899	4.1905	4.1912	4.1918	4.1925	4.1932	4.1939	4.1964	4.1954

To use the table the vertical columns denote whole degrees and the Horizontal rows denote tens of degrees. For example the bold value 4.1792 kJ kg-1 is at 40 + 5 = 45 °C.

Alternatively the equation $\mathbf{Cp = 6x10^{-9}\,t^4 - 1.0x10^{-6}\,t^3 + 7.0487x10^{-5}\,t^2 - 2.4403x10^{-3}\,t + 4.2113}$ may be used if the data is to be calculated using a spreadsheet.

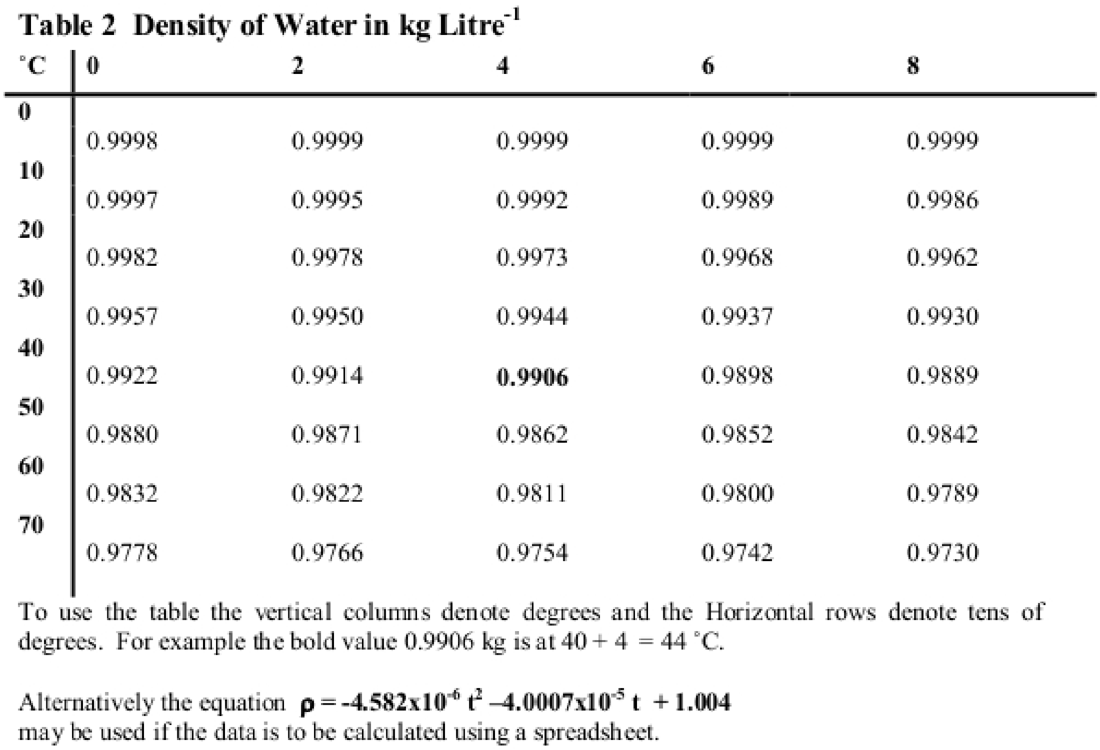


Table 2 Density of Water in kg Litre^{-1}

°C	0	2	4	6	8
0	0.9998	0.9999	0.9999	0.9999	0.9999
10	0.9997	0.9995	0.9992	0.9989	0.9986
20	0.9982	0.9978	0.9973	0.9968	0.9962
30	0.9957	0.9950	0.9944	0.9937	0.9930
40	0.9922	0.9914	**0.9906**	0.9898	0.9889
50	0.9880	0.9871	0.9862	0.9852	0.9842
60	0.9832	0.9822	0.9811	0.9800	0.9789
70	0.9778	0.9766	0.9754	0.9742	0.9730

To use the table the vertical columns denote degrees and the Horizontal rows denote tens of degrees. For example the bold value 0.9906 kg is at 40 + 4 = 44 °C.

Alternatively the equation $\boldsymbol{\rho = -4.582\mathrm{x}10^{-6}\, t^2 - 4.0007\mathrm{x}10^{-5}\, t + 1.004}$ may be used if the data is to be calculated using a spreadsheet.

<u>Ορισμός της Λογαραθμικής Μέσης Θερμοκρασιακής Διαφοράς (LMTD)</u>

The **logarithmic mean temperature difference** (also known as **log mean temperature difference** or simply by its initialism **LMTD**) is used to determine the temperature driving force for heat transfer in flow systems, most notably in heat exchangers. The LMTD is a logarithmic average of the temperature difference between the hot and cold feeds at each end of the double pipe exchanger (A,B). **The larger the LMTD, the more heat is transferred**. The use of the LMTD arises straightforwardly from the analysis of a heat exchanger with constant flow rate and fluid thermal properties..

ΔT_A = Θερμοκρασιακή διαφορά των δύο ρευμάτων στο άκρο A
ΔT_B = Θερμοκρασιακή διαφορά των δύο ρευμάτων στο άκρο B

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{\Delta T_A - \Delta T_B}{\ln \Delta T_A - \ln \Delta T_B} \qquad \textbf{(1)}$$

$$Q = U \times Ar \times LMTD \qquad \textbf{(2)}$$

Where Q is the exchanged heat duty (in watts), U is the heat transfer coefficient (in watts per kelvin per square meter) and Ar is the exchange area (eq.2)

Παράδειγμα υπολογισμού του συντελεστή μετάδοσης θερμότητας στον εναλλάκτη H101A με διάταξη αντιρροής σε συνθήκες μόνιμης κατάστασης

OBSERVATIONS

Flow Direction: Counter-Current

Sample No.	T1	T5	T2	T3	T6	T4	V_{hot}	V_{cold}
----	°C	°C	°C	°C	°C	°C	G/sec	G/sec
1	37.9	36.5	34.5	15.5	18.9	21.3	35	17
2	49.1	46.7	43.7	14.4	20.9	24.8	35	17
3	58.9	55.7	51.6	14.5	22.9	28.1	35	17
4	68.1	64.5	59.0	14.3	25.0	31.7	35	17
5	73.2	69.4	63.2	14	26.4	34.4	35	17

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}$ e	$\dot{Q}$ a	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%
1	3.4	5.8	459	403	25.9	15.2	20.6
2	5.4	10.4	741	723	30.0	15.6	22.8
3	7.3	13.6	1003	955	30.6	16.4	23.5
4	9.1	17.4	1246	1222	32.3	16.9	24.6
5	10.0	20.4	1367	1360	34.5	16.9	25.7

Sample No.	LMTD	U
---	K	$W\,m^2K^{-1}$
1	17.77	1291
2	26.7	1503
3	33.9	1606
4	40.4	1671
5	43.8	1692

Similar observations may be obtained for the Co-current configuration. The calculation procedures are shown below.

CALCULATIONS

For the example No. 1 the calculations are as follows.

For the Hot stream:

From table 1 and 2 at T5 = 36.5 °C ρ_{hot} = 0.993 kg $litre^{-1}$

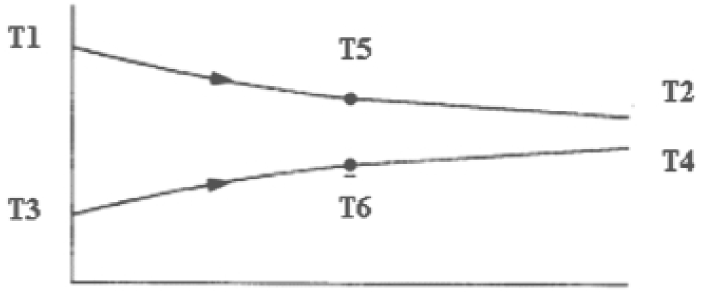
Cp = 4.178 kJ kg^{-1} k^{-1}

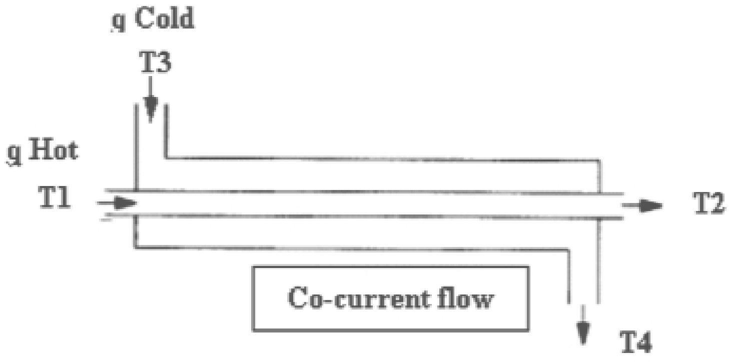
Hence the power emitted from the hot stream $\dot{Q}$ e

$$\begin{aligned}\dot{Q}e &= V_{hot}\,\rho_{hot}\ Cp_{Hot}\ (T1 - T3)\ \text{Watts}\\ &= 35\ \times 0.993 \times 4.178 \times (37.9 - 34.5)\\ &= 459\ \text{Watts}\end{aligned}$$

A useful measure of the heat exchanger performance is the temperature efficiency.

The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.





The temperature efficiency of the hot stream from the above diagram

$$\begin{aligned}\eta_{\text{Hot}} &= \frac{\text{T1-T2}}{\text{T1-T3}}\times 100\% \\ &= \frac{37.9-34.5}{37.9-15.5}\times 100\% \\ &= 15.2\%\end{aligned}$$

The temperature efficiency of the cold stream from the above diagram

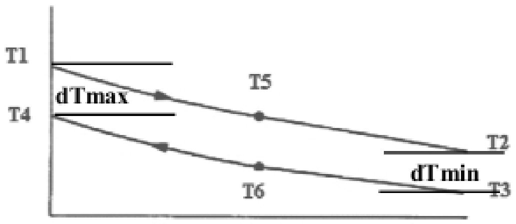
$$\begin{aligned}\eta_{\text{Cold}} &= \frac{\text{T4-T3}}{\text{T1-T3}}\times 100\% \\ &= \frac{21.3-15.5}{37.9-15.5}\times 100\% \\ &= 25.9\%\end{aligned}$$

The mean temperature efficiency

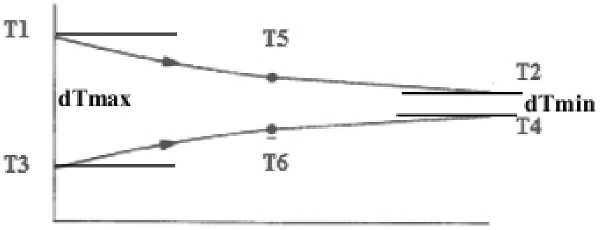
$$\begin{aligned}\eta_{\text{Mean}} &= \frac{\eta_{\text{Hot}}+\eta_{\text{Cold}}}{2} \\ &= \frac{15.2+15.2}{2} \\ &= 20.6\%\end{aligned}$$

As the temperature difference between the hot and cold fluids vary along the length of the heat exchanger it is necessary to derive a suitable mean temperature difference that may be used in heat transfer calculations. These calculations are not only of relevance in experimental procedures but also more importantly to be used in the design of heat exchangers to perform a particular duty.

The derivation and application of the Logarithmic Mean temperature Difference (LMTD) may be found in most thermodynamics and heat transfer textbooks.



Counter current flow



Co-current flow

The LMTD is defined as

$$\mathrm{LMTD} = \frac{\mathrm{dTmax\ -\ dTmin}}{\ln\left(\dfrac{\mathrm{dTmax}}{\mathrm{dTmin}}\right)}$$

Hence from the above diagrams of temperature distribution

$$\mathrm{LMTD} \ = \ \frac{(\mathrm{T1\text{-}T4}) - (\mathrm{T2} - \mathrm{T3})}{\ln\left(\dfrac{(\mathrm{T1\text{-}T4})}{(\mathrm{T2} - \mathrm{T3})}\right)}$$

Note that as the temperature measurement points are fixed on the heat exchanger the LMTD is the same formula for both Counter-current flow and Co-current flow.

Hence for the Counter-current example

$$\begin{aligned} \mathrm{LMTD} &= \frac{(37.9 - 21.3) - (34.5 - 15.5)}{\ln\left(\dfrac{(37.9 - 21.3)}{(34.5 - 15.5)}\right)} \\ &= \frac{-2.4}{\ln(0.8736)} \\ &= \frac{-2.4}{-0.1351} \\ &= 17.8\,\mathrm{K} \end{aligned}$$

In order to calculate the overall heat transfer coefficient the following parameters must be used with

consistent units:-

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

Where

A	Heat transfer area of heat exchanger (m2)
$\dot{Q}$ e	Heat emitted from hot stream (Watts)
LMTD	Logarithmic mean temperature difference (K)

The heat transfer area may be calculated from:-

$$d_m = \frac{d_o + d_i}{2}$$

And

$$A = \pi\, d_m\, L$$

Where

do	Heat transfer tube outside diameter (m)
di	Heat transfer tube inside diameter (m)
dm	Heat transfer tube mean diameter (m)
L	Heat transfer tube effective length (m)

Hence for the heat exchanger from the **USEFUL DATA** section on page A11.

$$d_m = \frac{(0.012)+(0.010)}{2}$$

$$= 0.011 \text{ m}$$

$$A = \pi \times 0.011 \times 2(0.318)$$

$$= 0.02198 \text{ m}^2$$

Hence for the test conditions the overall heat transfer coefficient :-

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

$$= \frac{459}{0.02 \text{ x } 17.8}$$

$$= 1291 \text{ Wm}^{-2}\text{K}^{-1}$$

Παράδειγμα μελέτης του θερμικού ισοζυγίου στον εναλλάκτη H101A με διάταξη ομορροής – αντιρροής σε συνθήκες μόνιμης κατάστασης

OBSERVATIONS
Flow Direction: Counter-Current

Sample No.	T1	T5	T2	T3	T6	T4	V_{hot}	V_{cold}
----	˚C	˚C	˚C	˚C	˚C	˚C	G/sec	G/sec
1	59.6	56.4	51.9	14.7	23.3	28.3	35	17
2								
3								
4								
5								

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}$ e	$\dot{Q}$ a	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Mean}
---	K	K	W	W	%	%	%	%
1	7.3	13.6	1053	964	91.2	30.3	17.1	23.7
2								
3								
4								
5								

Flow Direction: Co-Current

Sample No.	T1	T5	T2	T3	T6	T4	V_{hot}	V_{cold}
----	˚C	˚C	˚C	˚C	˚C	˚C	G/sec	G/sec
1	59.7	56.0	52.5	14.9	22.5	27.9	35	17
2								
3								
4								
5								

Calculated Data

Sample No.	Δt_{hot}	Δt_{cold}	$\dot{Q}$ e	$\dot{Q}$ a	$\eta_{Thermal}$	η_{Cold}	η_{Hot}	η_{Meanl}
---	K	K	W	W	%	%	%	%
1	7.2	13.0	1038	921	88.7	29.0	16.1	22.5
2								
3								
4								
5								

CALCULATIONS

For the examples the calculations are as follows.

Counter-Current Flow

For the Hot stream:

From table 1 and 2 at T2 = 56.4 ˚C

ρ_{hot} = 0.9852 kg litre^{-1}

Cp = 4.183 kJ kg^{-1} k^{-1}

Hence the power emitted from the hot stream $\dot{Q}$ e

$$\begin{aligned}\dot{Q}e &= V_{hot}\rho_{hot}\ Cp_{Hot}\left(T1 - T3\right)\ \text{Watts}\\ &= 35\ \times 0.9852\times 4.183\times\left(59.6-51.9\right)\\ &= 1053\ \text{Watts}\end{aligned}$$

From table 1 and 2 at T5 = 23.3 °C $\rho_{Cold} = 0.9975 \text{ kg litre}^{-1}$
$Cp_{Cold} = 4.180 \text{ kJ kg}^{-1} \text{ k}^{-1}$

Hence the power absorbed by the cold stream $\dot{Q}$ a

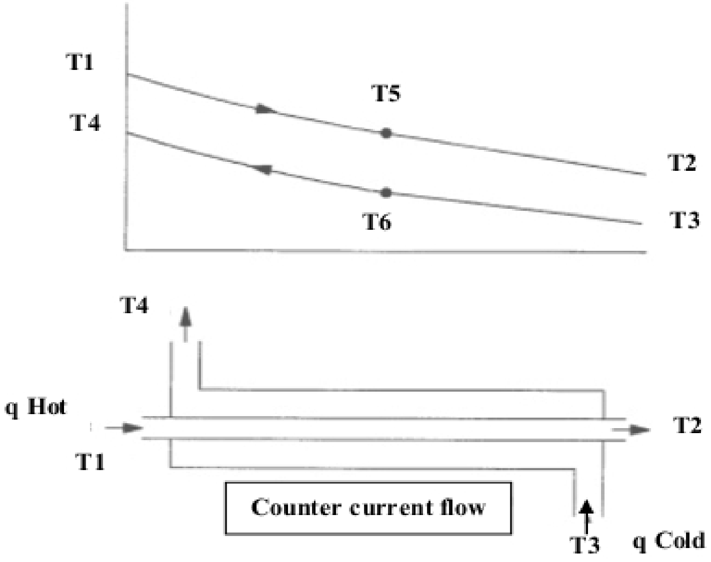
$$\begin{aligned}\dot{Q}a &= V_{cold}\,\rho_{cold}\ Cp_{Cold}\ (T4\text{-}\ T3)\ \text{Watts}\\ &= 17\ \times 0.9975 \times 4.180 \times (28.3 - 14.7)\\ &= 964 \quad \text{Watts}\end{aligned}$$

Reduction in Hot fluid temperature $\Delta t\ hot = T1 - T2$
$= 59.2 - 51.9$
$= 7.3$ K

Increase in Cold fluid temperature $\Delta t\ cold = T4 - T3$
$= 28.3 - 14.7$
$= 13.6$ K

A useful measure of the heat exchanger performance is the temperature efficiency.

The temperature change in each stream (hot and cold) is compared with the maximum temperature difference between the two streams. This could only occur in a perfect heat exchanger of infinite size with no external losses or gains.



The temperature efficiency of the hot stream from the above diagram

$$\begin{aligned}\eta_{Hot} &= \frac{T1\text{-}T2}{T1\text{-}T3} \times 100\%\\ &= \frac{59.6 - 51.9}{59.6 - 14.7} \times 100\%\\ &= 17.1\%\end{aligned}$$

The temperature efficiency of the cold stream from the above diagram

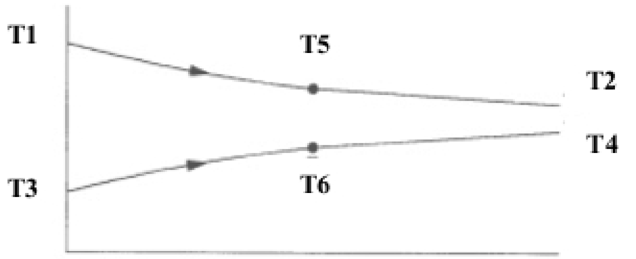
$$\begin{aligned}\eta_{\text{Cold}} &= \frac{\text{T4-T3}}{\text{T1-T3}} \times 100\% \\ &= \frac{28.3-14.7}{59.6-14.7} \times 100\% \\ &= 30.3\%\end{aligned}$$

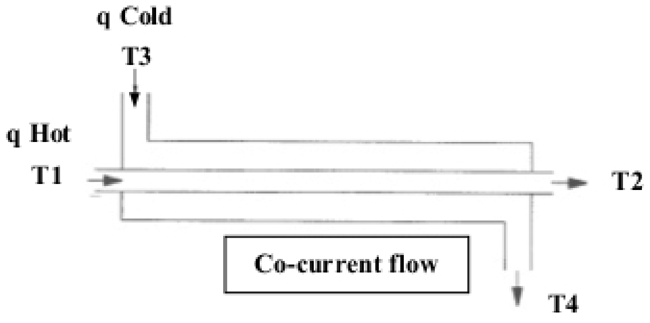
The mean temperature efficiency

$$\begin{aligned}\eta_{\text{Mean}} &= \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2} \\ &= \frac{17.1+30.3}{2} \\ &= 23.7\%\end{aligned}$$

Co-Current Flow

For the co-current flow system the calculation procedure is similar but the formulae are as follows





The power emitted from the hot stream $\dot{Q}e$

$$\dot{Q}e = V_{\text{hot}}\rho_{\text{hot}}\ Cp_{\text{Hot}}\ (\text{T1- T2})\ \text{Watts}$$

The power absorbed by the cold stream $\dot{Q}a$

$$\dot{Q}a = V_{\text{cold}}\rho_{\text{cold}}\ Cp_{\text{Cold}}\ (\text{T4- T3})\,\text{Watts}$$

Reduction in Hot fluid temperature Δt hot = T1 – T2 K
Increase in Cold fluid temperature Δt cold = T4 – T3 K

The temperature efficiency of the hot stream from the above diagram

$$\eta_{\text{Hot}} = \frac{\text{T1-T2}}{\text{T1-T3}} \times 100\%$$

The temperature efficiency of the cold stream from the above diagram

$$\eta_{\text{Cold}} = \frac{\text{T4-T3}}{\text{T1-T3}} \times 100\%$$

The mean temperature efficiency

$$\eta_{\text{Mean}} = \frac{\eta_{\text{Hot}} + \eta_{\text{Cold}}}{2}$$

The tabulated and calculated results show the differences between Counter-Current flow and Co-Current flow and the effect upon temperature efficiency and Δt for the hot and cold streams.

The recorded temperatures T1 to T6 may be plotted on a graph in a similar manner to the Counter-current and Co-current diagrams above in order to give actual temperature profiles for the heat exchanger.