INTRODUCTION TO HELIUM REFRIGERATION FOR SUPERCONDUCTING DEVICES

REMINDERS ABOUT HEAT EXCHANGERS

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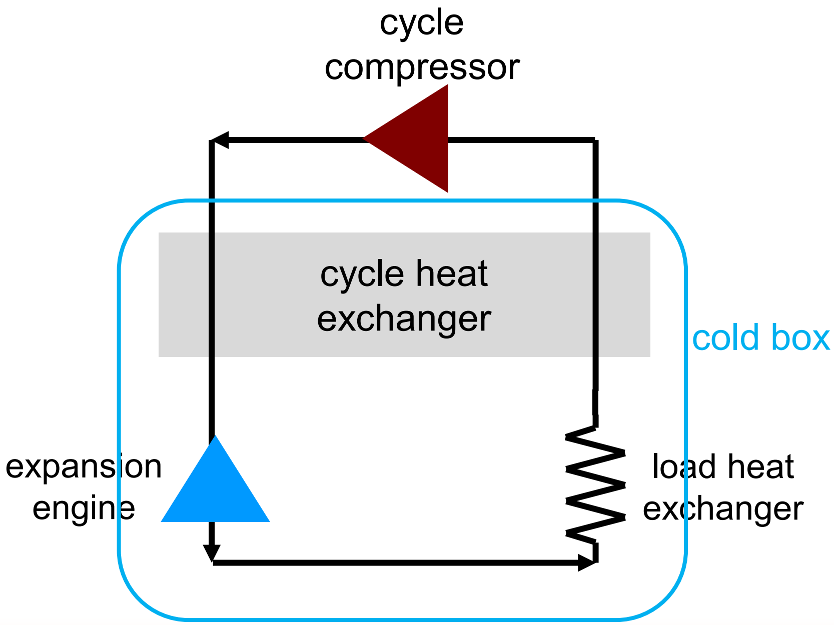
WHY DO WE NEED HEAT EXCHANGERS ?

A helium refrigerator is, at minimum, an assembly of 3 components.

Example for a Brayton refrigerator :

1. A cycle compressor,
2. A heat exchanger,
3. An expansion engine.

The cold components are housed in a thermally insulated cold box.



DUTY OF A HEAT EXCHANGER

A heat exchanger is supposed to **transfer heat** (enthalpy) from one fluid to another.

*(Obviously, heat flows **from warm to cold**…)*

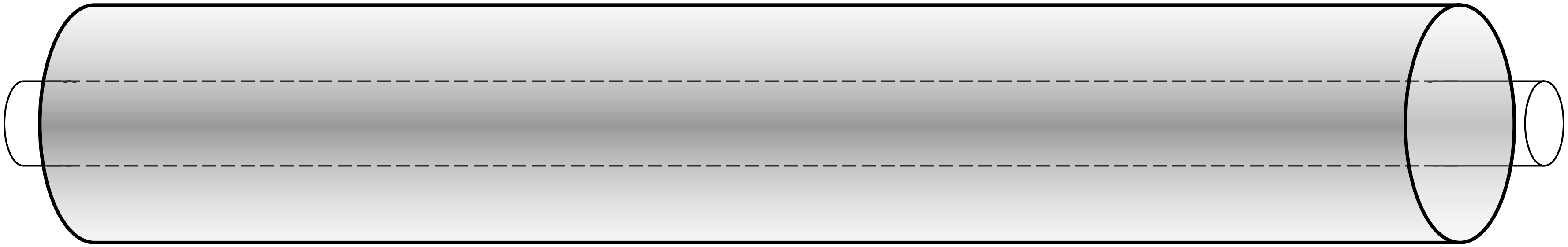
We will consider heat transfer **without mixing** the fluids.

Transferring heat from one fluid to another, without mixing them makes necessary to have a **separation** between them.

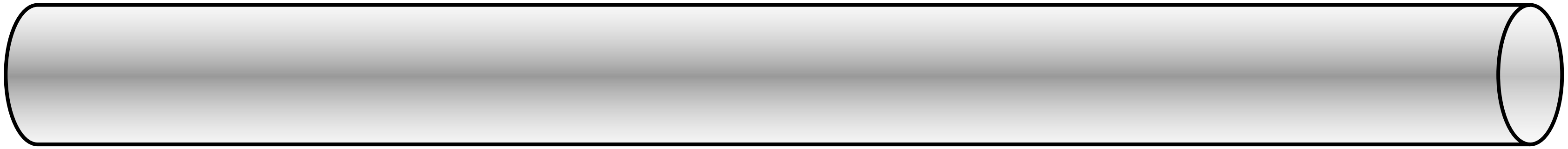
Such a separation between two fluids is a **heat exchanger**.

Never forget that any separating wall behaves as a heat exchanger!

AN " INTUITIVE " HEAT EXCHANGER

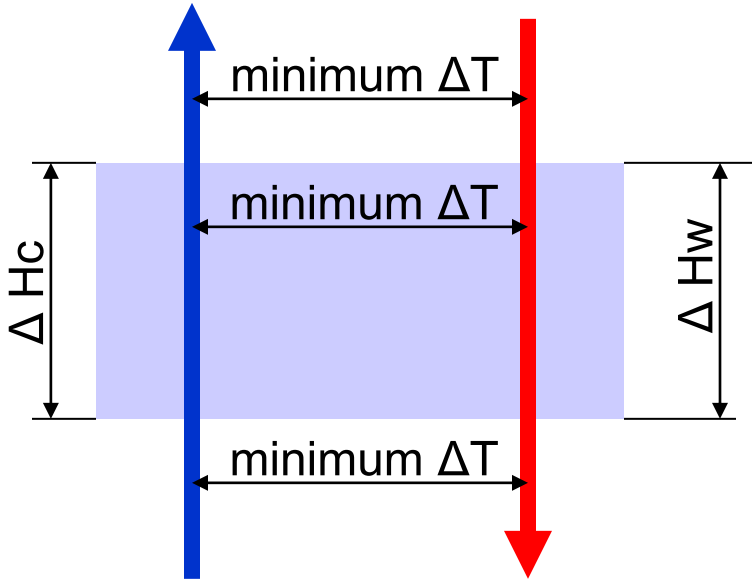


A PARASITIC HEAT EXCHANGER



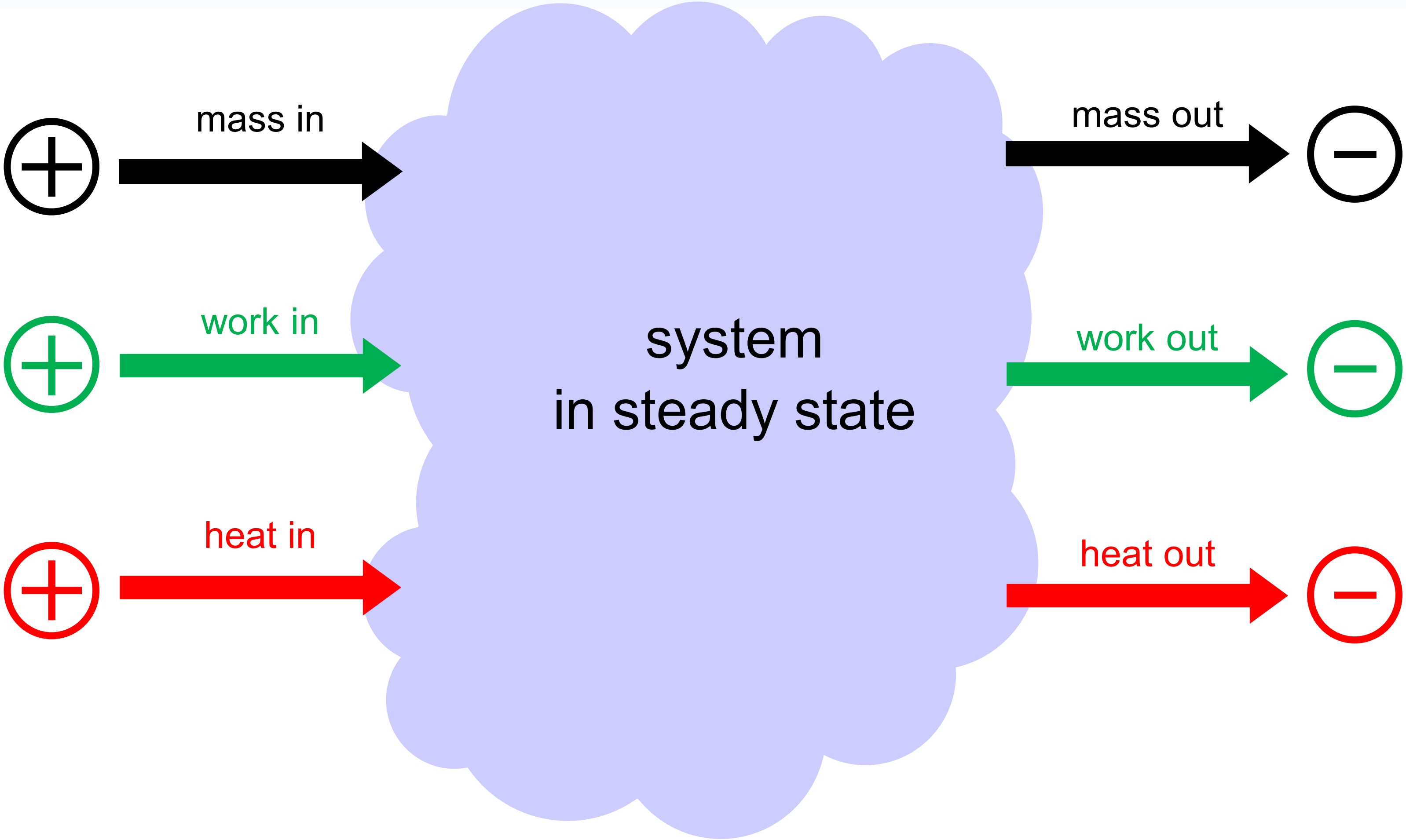
A PERFECT HEAT EXCHANGER

A perfect heat exchanger should recover all the enthalpy that is released by one fluid to transfer it to the other fluid with a temperature difference that is zero at one point.



A zero temperature difference is, obviously, not possible !

MASS AND THERMAL BALANCES



mass in

work in

heat in

system
in steady state

mass out

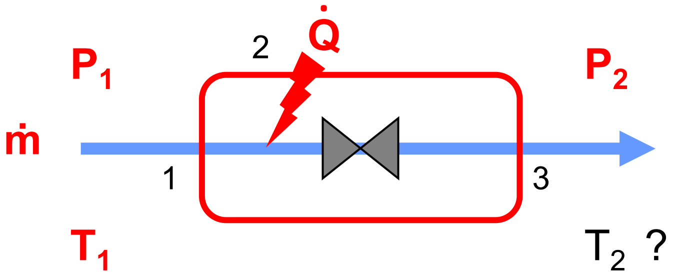
work out

heat out

FREE EXPANSION AND HEATING

A SIMPLE EXAMPLE

Assumption : gas velocity is negligeable



Because the system is in a steady state !

Balance :

$$\dot{m} \text{ x } h_1 + \dot{Q} - \dot{m} \text{ x } h_2 = 0$$

$$h_2 = h_1 + \dot{Q} / \dot{m}$$

P_1 and T_1 + REFPROP → h_1

15.0 bar 300.00 K 1567,89 J/g

$\dot{m}$ $\dot{Q}$

10.0 g/s 0.00 W

$h_2 = h_1$ = 1567,89

P_2 and h_2 + REFPROP → T_2

1.0 bar 1567.89 J/g 300.88 K

Remarks :

If $\dot{Q} = 0$?

Is there any change if $\dot{Q}$ is injected downstream or through the valve ?

HYPOTHESIS FOR SIMPLIFICATION

Steady state

All the enthalpy lost by one fluid is transferred to the other

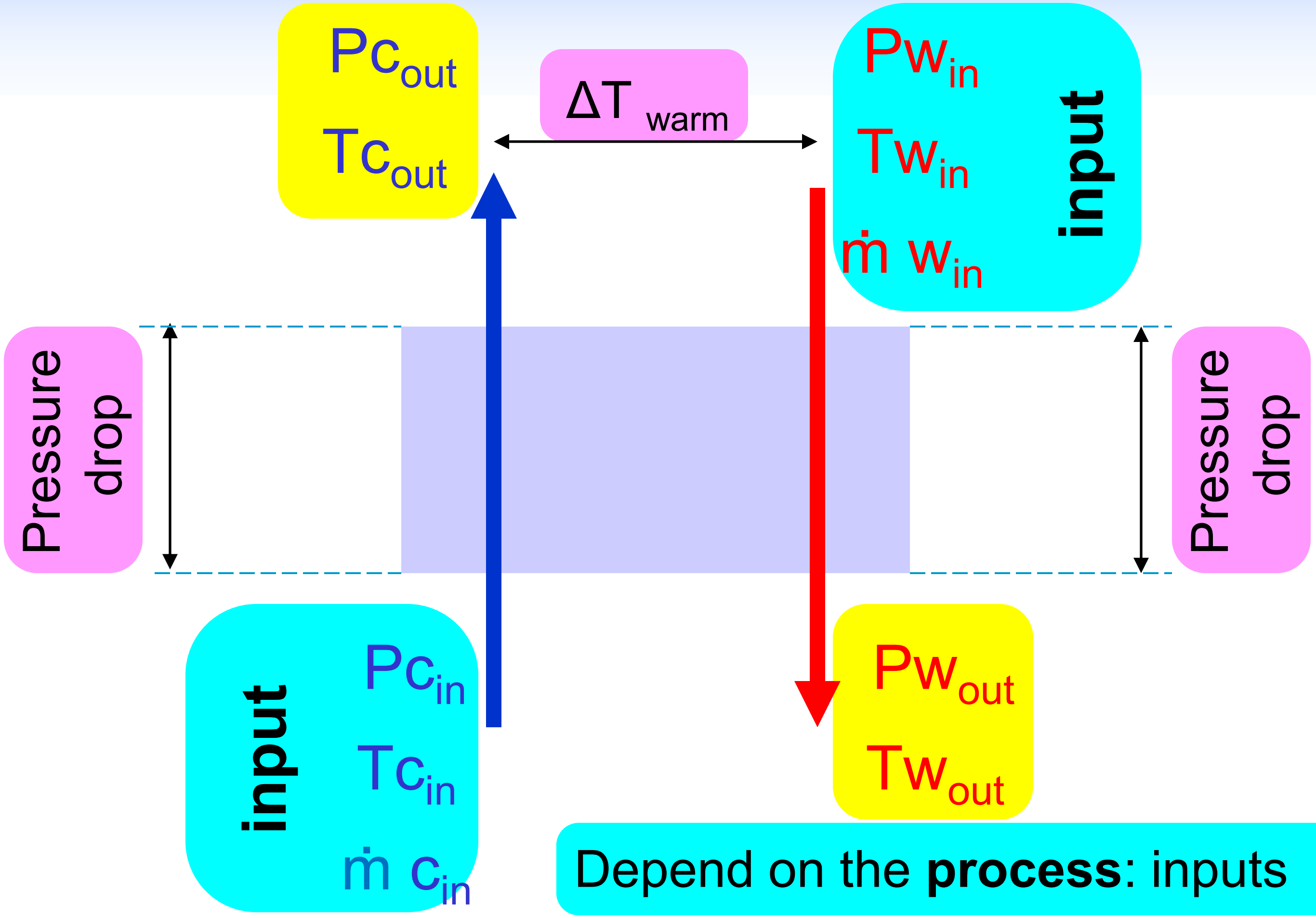
No exchange with external world (no thermal losses)

No heat generated into the exchanger

No pressure drops

Only counter current heat exchangers

LOOKING FROM " OUTDOORS " (1)



Pc_{out}

Tc_{out}

ΔT_{warm}

Pw_{in}

Tw_{in}

$\dot{m}\ w_{in}$

input

Pressure drop

Pressure drop

input

Pc_{in}

Tc_{in}

$\dot{m}\ c_{in}$

Pw_{out}

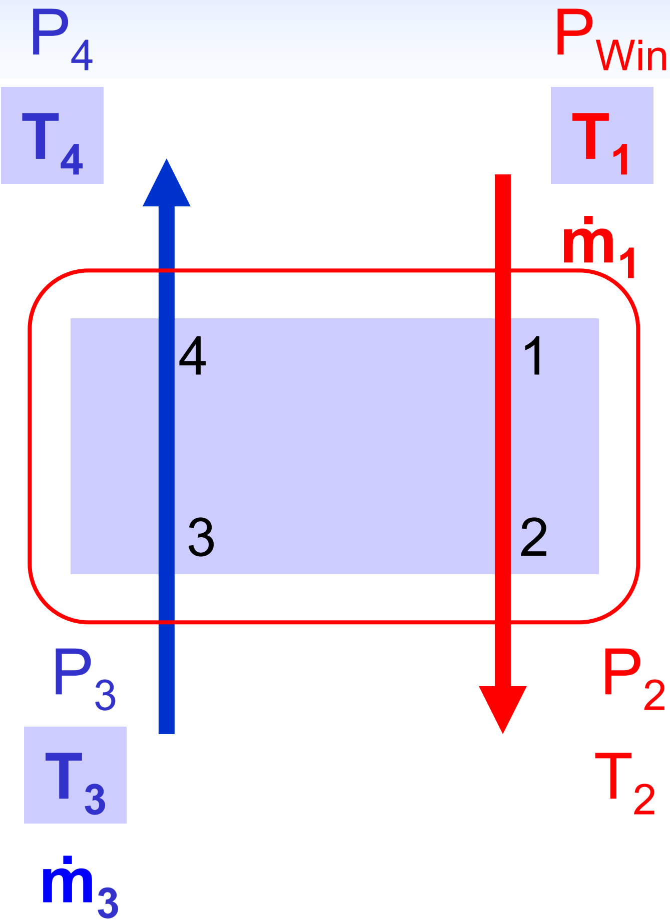
Tw_{out}

Depend on the **process**: inputs

Depend on the exchanger: design

Result of the heat exchanger operation

LOOKING FROM " OUTDOORS " (2)



AT THE LIMITS

Balance :

Because the system is in a steady state !

$$\dot{m}_1 \times h_1 - \dot{m}_2 \times h_2$$

$$+ \dot{m}_3 \times h_3 - \dot{m}_4 \times h_4 = 0$$

$$\dot{m}_1 \times (h_1 - h_2) = \dot{m}_3 \times (h_4 - h_3)$$

When $\mathbf{\dot{m}_1}$, $\mathbf{\dot{m}_3}$, $\mathbf{T_1}$, $\mathbf{T_3}$ and $\mathbf{T_4}$ are known,

$$h_2 = \frac{\dot{m}_3 \times (h_3 - h_4) + \dot{m}_1 \times h_1}{\dot{m}_1}$$

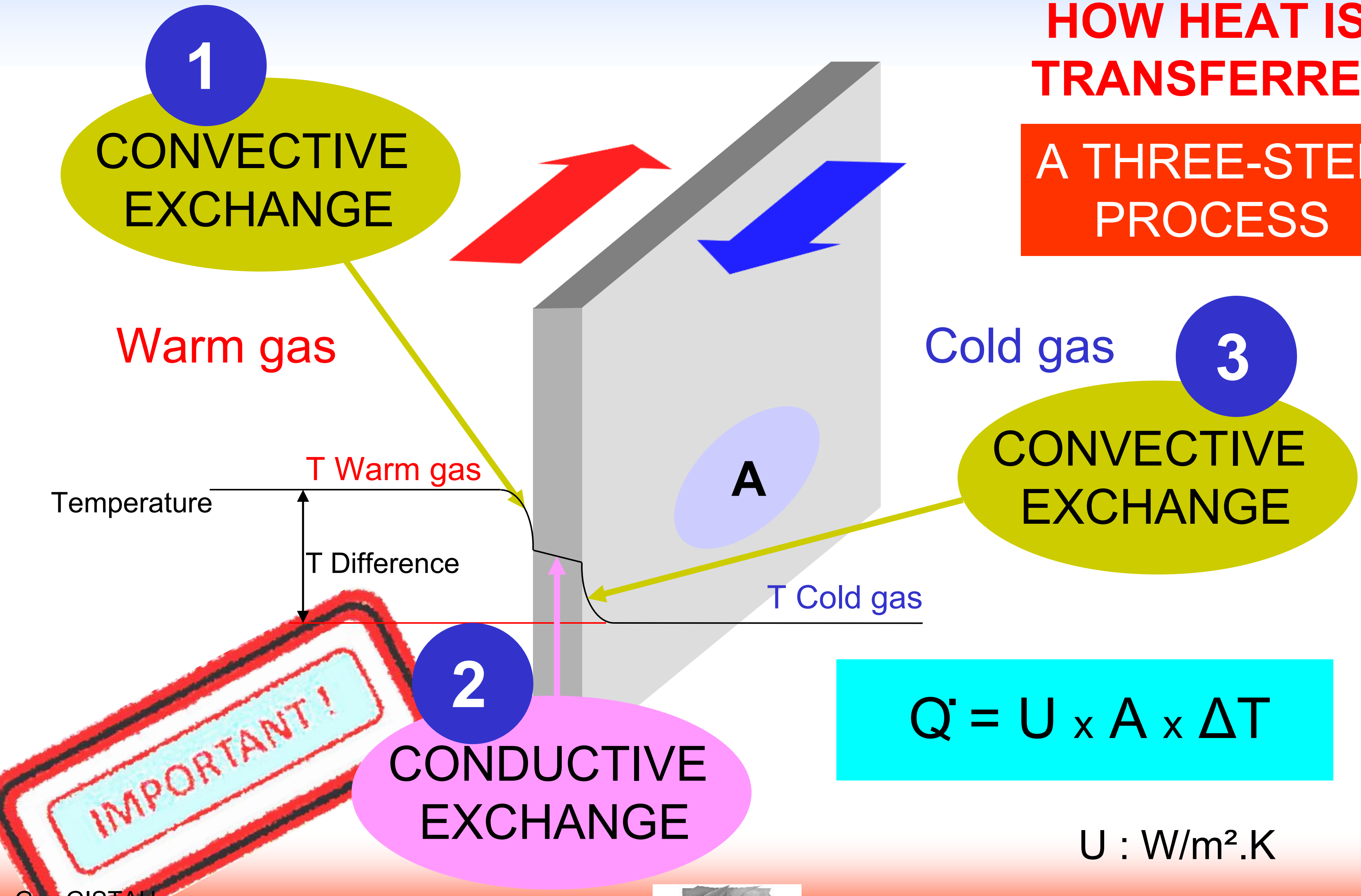
$\mathbf{P_2}$ and $\mathbf{h_2}$ + Hepak ⇒ T_2

"Simple HX"

LOOKING " INSIDE "

HOW HEAT IS TRANSFERRED

A THREE-STEP PROCESS



1 CONVECTIVE EXCHANGE

Warm gas

Cold gas

3 CONVECTIVE EXCHANGE

A

Temperature

T Warm gas

T Difference

T Cold gas

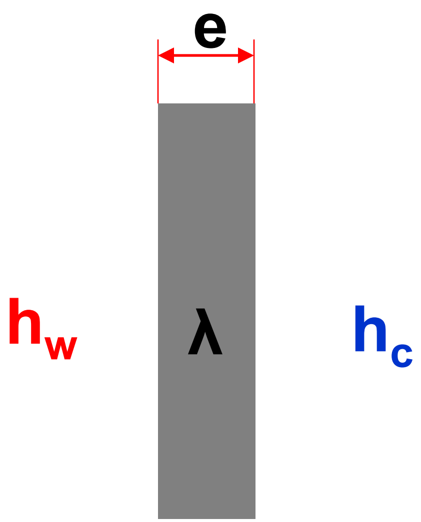
IMPORTANT !

2 CONDUCTIVE EXCHANGE

$$\dot{Q} = U \times A \times \Delta T$$

U : W/m².K

THERMAL RESISTANCES IN A HEAT EXCHANGER



$$\mathcal{R} = 1/h_w + e/\lambda + 1/h_c = 1/U$$

λ : W / m.K

h : W / m².K

INCIDENCE OF THE WALL

IMPORTANT !

Example:

For a gas in forced convection: $30 < h < 300$ W/m².K

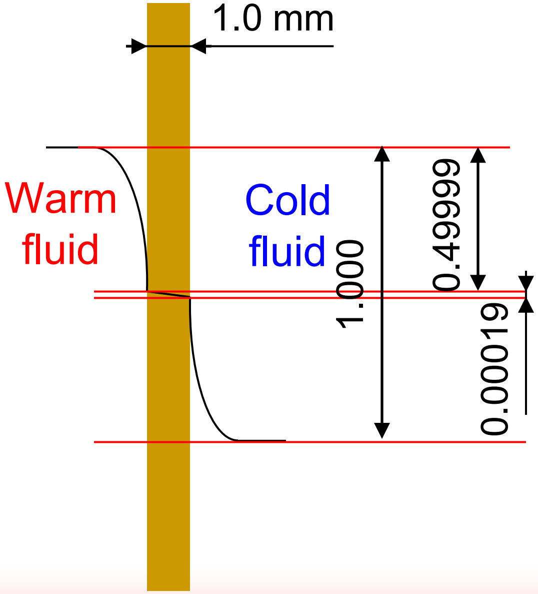
For a 1 m², e = 1 mm copper wall: $\lambda/e \cong 390$ W/m.K

$$1/U = 1/h_w + e/\lambda + 1/h_c$$

$$1/U = 1/150 + 0.001/390 + 1/150$$

$$1 = 0.499999 + 0.000192 + 0.499999$$

The temperature difference through the wall is generally negligible.



A VERY SIMPLE HEAT EXCHANGER

CALCULATION

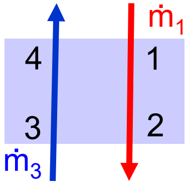
Operating conditions:

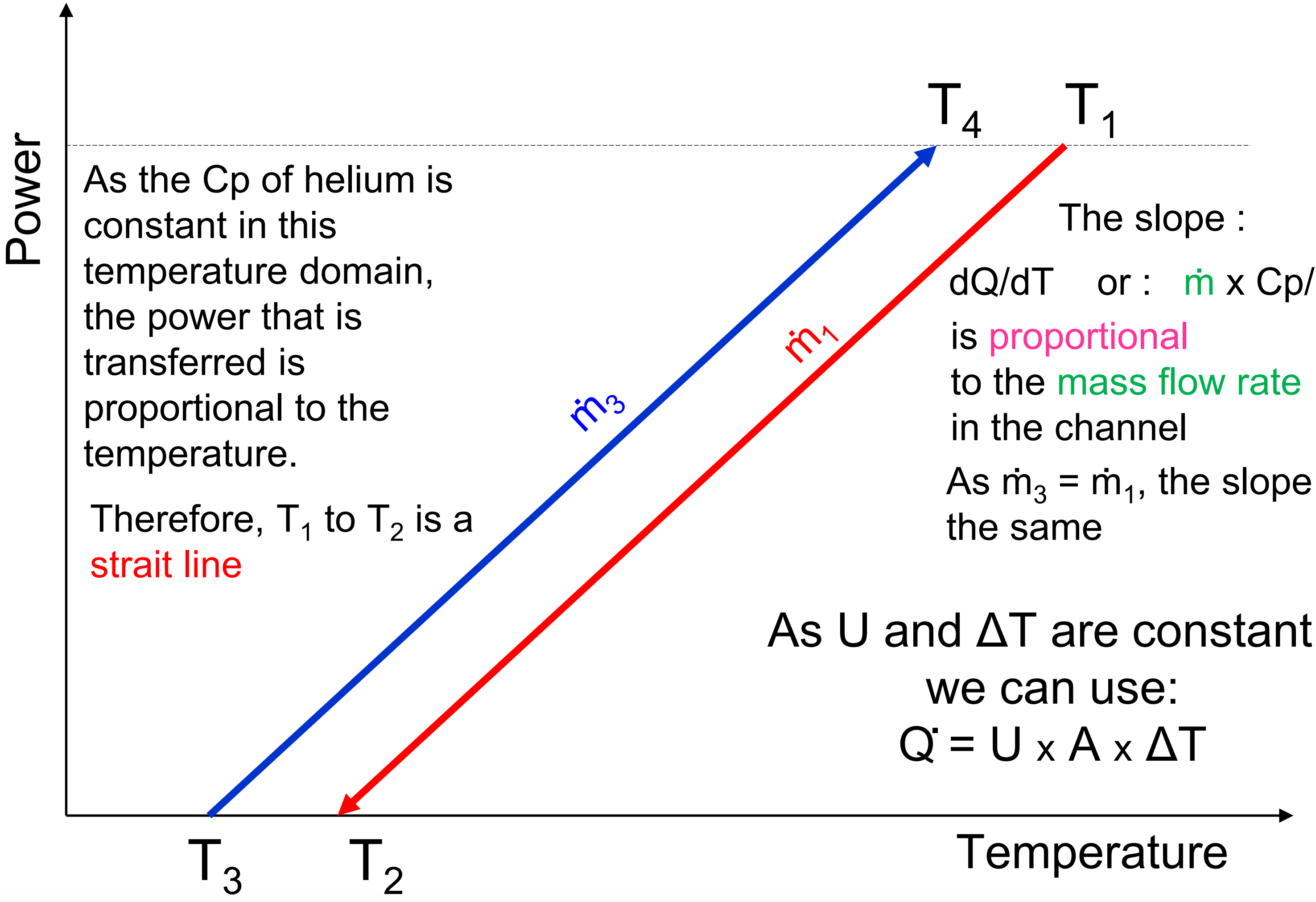
- Equal and constant specific heat of both fluids
- Constant heat exchange coefficient for both fluids
- Constant thermal conductivity of material along the heat exchanger
- Equal cold and warm mass flow rates

“Simple HX"

THE HEAT EXCHANGER DIAGRAMME

Let’s plot the power that is transferred versus the temperature along the heat exchanger.





As the Cp of helium is constant in this temperature domain, the power that is transferred is proportional to the temperature.

Therefore, T_1 to T_2 is a strait line

The slope :

dQ/dT or : $\dot{m}$ x Cp/dT

is proportional to the mass flow rate in the channel

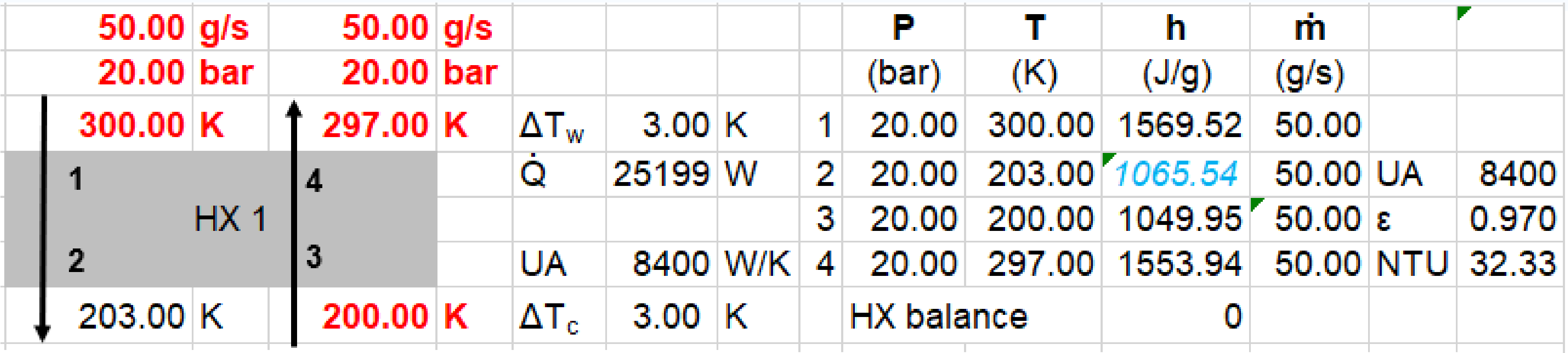
As $\dot{m}_3 = \dot{m}_1$, the slope is the same

As U and ΔT are constant, we can use:

$\dot{Q} = U \times A \times \Delta T$

A VERY SIMPLE HEAT EXCHANGER

0002 HX.xlsx



50.00	**g/s**	**50.00**	**g/s**					**P**	**T**	**h**	**$\dot{m}$**		
20.00	**bar**	**20.00**	**bar**					(bar)	(K)	(J/g)	(g/s)		
300.00	**K**	**297.00**	**K**	ΔT_w	3.00	K	1	20.00	300.00	1569.52	50.00		
1		**4**		$\dot{Q}$	25199	W	2	20.00	203.00	*1065.54*	50.00	UA	8400
	HX 1						3	20.00	200.00	1049.95	50.00	ε	0.970
2		**3**		UA	8400	W/K	4	20.00	297.00	1553.94	50.00	NTU	32.33
203.00	K	**200.00**	**K**	ΔT_c	3.00	K		HX balance		0			

A SIMPLE HEAT EXCHANGER

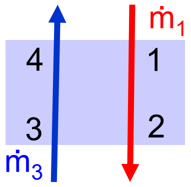
CALCULATION

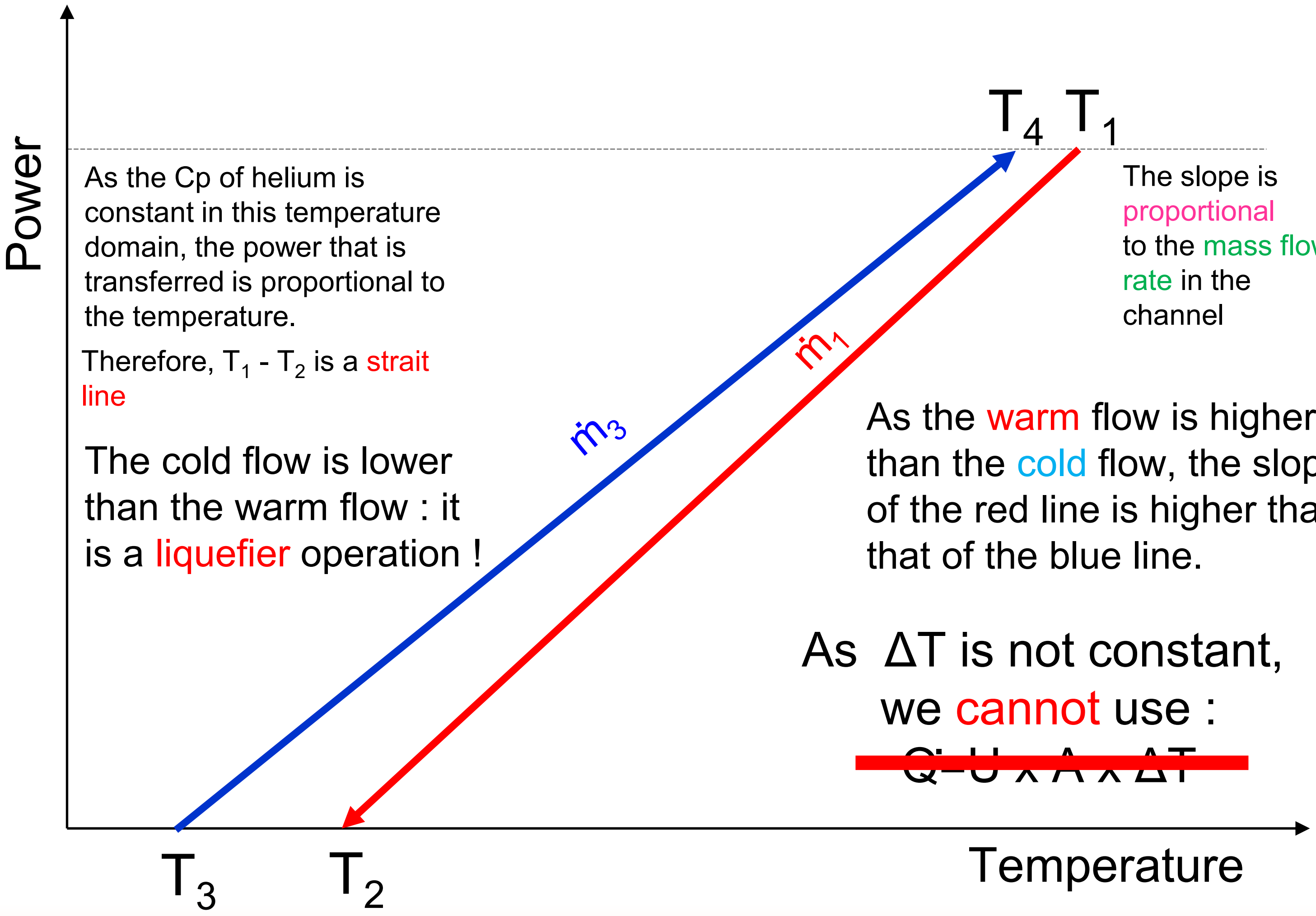
Operating conditions:

- Equal and constant specific heat of both fluids
- Constant heat exchange coefficient for both fluids
- Constant thermal conductivity of material along the heat exchanger
- Different cold and warm mass flow rates

This is an unbalanced heat exchanger

THE UNBALANCED HEAT EXCHANGER





As the Cp of helium is constant in this temperature domain, the power that is transferred is proportional to the temperature.

Therefore, $T_1 - T_2$ is a strait line

The cold flow is lower than the warm flow : it is a liquefier operation !

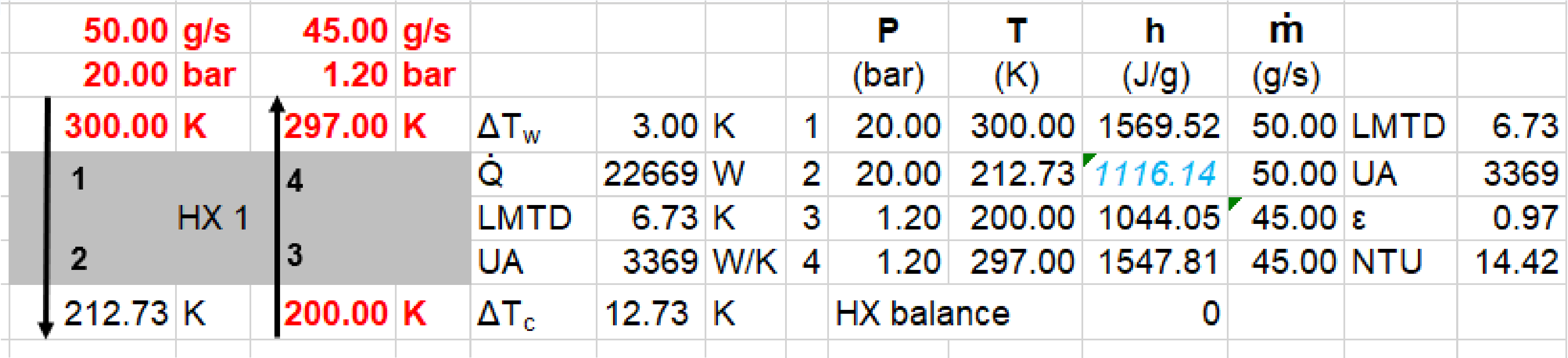
The slope is proportional to the mass flow rate in the channel

As the warm flow is higher than the cold flow, the slope of the red line is higher than that of the blue line.

As ΔT is not constant, we cannot use :

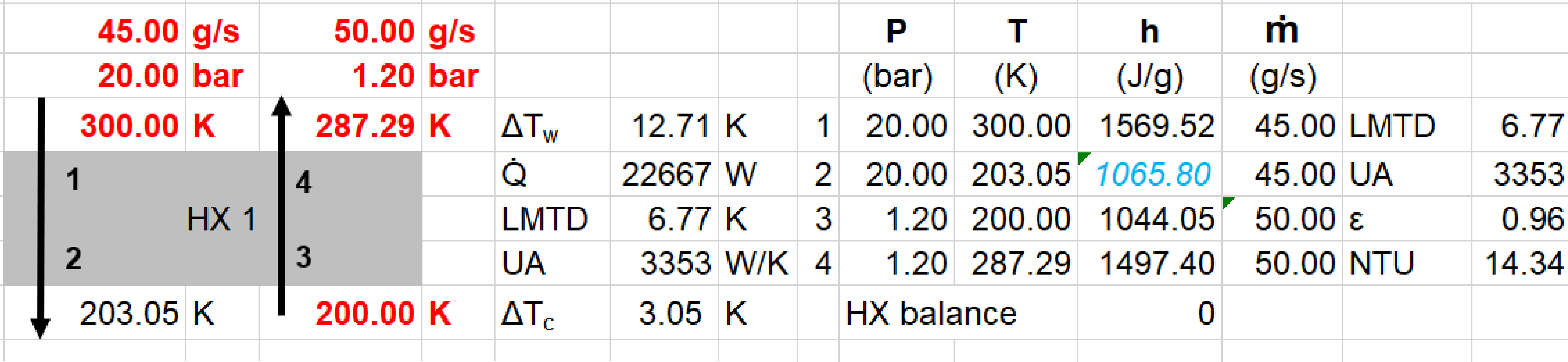
~~$Q=U \times A \times \Delta T$~~

"LIQUEFIER" OPERATION



50.00	**g/s**	**45.00**	**g/s**					**P**	**T**	**h**	**$\dot{m}$**		
20.00	**bar**	**1.20**	**bar**					(bar)	(K)	(J/g)	(g/s)		
300.00	**K**	**297.00**	**K**	ΔT_w	3.00	K	1	20.00	300.00	1569.52	50.00	LMTD	6.73
1		4		$\dot{Q}$	22669	W	2	20.00	212.73	*1116.14*	50.00	UA	3369
	HX 1			LMTD	6.73	K	3	1.20	200.00	1044.05	45.00	ε	0.97
2		3		UA	3369	W/K	4	1.20	297.00	1547.81	45.00	NTU	14.42
212.73	K	**200.00**	**K**	ΔT_c	12.73	K		HX balance		0			

"ECONOMISER" OPERATION



45.00	**g/s**	**50.00**	**g/s**					**P**	**T**	**h**	**$\dot{m}$**		
20.00	**bar**	**1.20**	**bar**					(bar)	(K)	(J/g)	(g/s)		
300.00	**K**	**287.29**	**K**	ΔT_w	12.71	K	1	20.00	300.00	1569.52	45.00	LMTD	6.77
1		4		$\dot{Q}$	22667	W	2	20.00	203.05	*1065.80*	45.00	UA	3353
	HX 1			LMTD	6.77	K	3	1.20	200.00	1044.05	50.00	ε	0.96
2		3		UA	3353	W/K	4	1.20	287.29	1497.40	50.00	NTU	14.34
203.05	K	**200.00**	**K**	ΔT_c	3.05	K		HX balance		0			

LMTD

When operating conditions are:

- Equal and constant specific heat of both fluids
- Constant heat exchange coefficient for both fluids

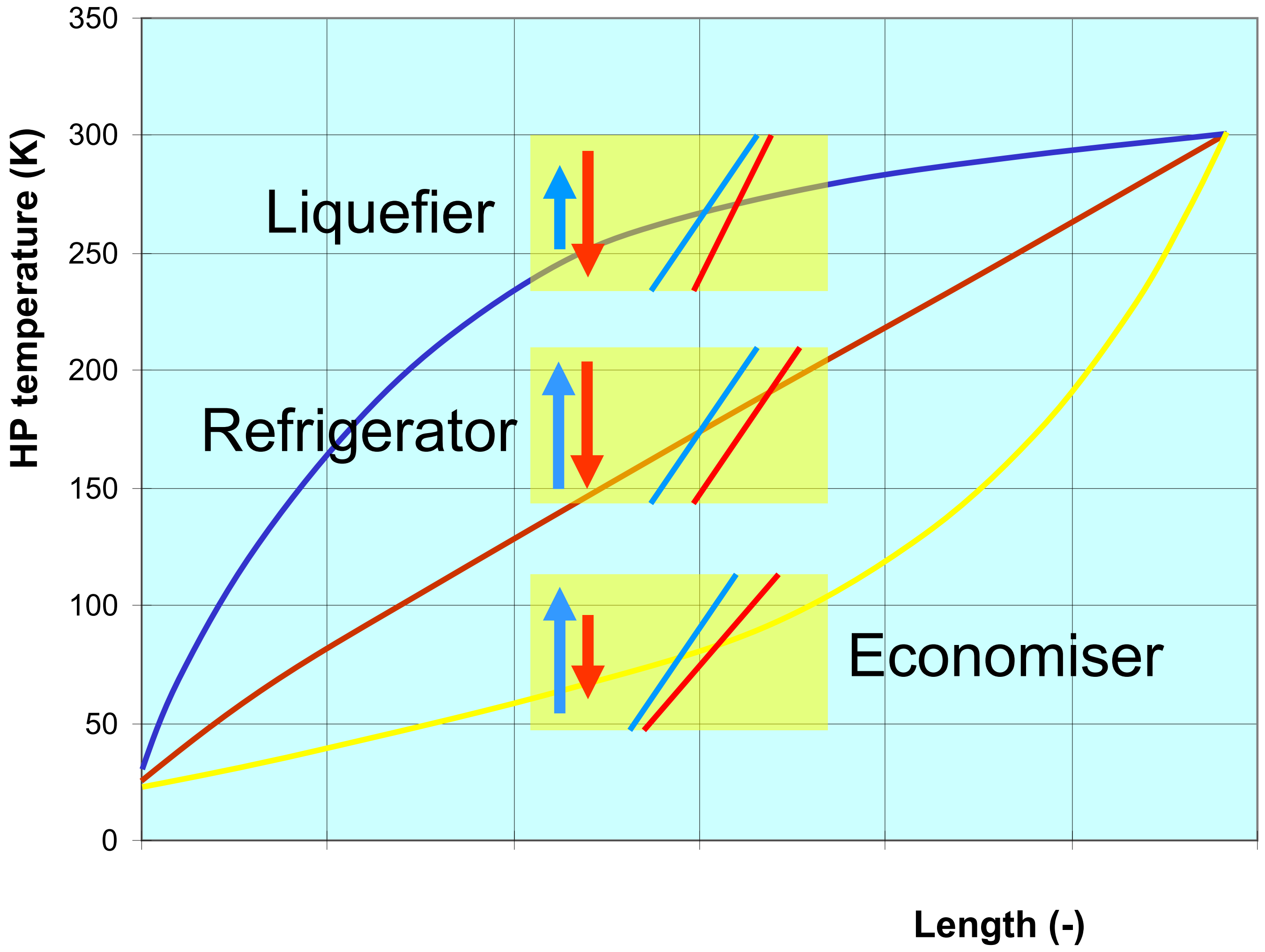
The equivalent temperature difference (TD) can be expressed as:

$$\mathrm{LMTD} = \frac{\Delta T_w - \Delta T_c}{\mathrm{Ln}\,\dfrac{\Delta T_w}{\Delta T_c}}$$

LMTD=Logarithmic Mean Temperature Difference

So, a more general equation is: $\dot{Q} = U \times A \times \mathrm{LMTD}$

TEMPERATURE PROFILES



A NOT SO SIMPLE HEAT EXCHANGER

CALCULATION

Operating conditions:

- Not constant specific heat of both fluids
- Constant heat exchange coefficient for both fluids
- Constant thermal conductivity of material along the heat exchanger
- Different cold and warm mass flow rates

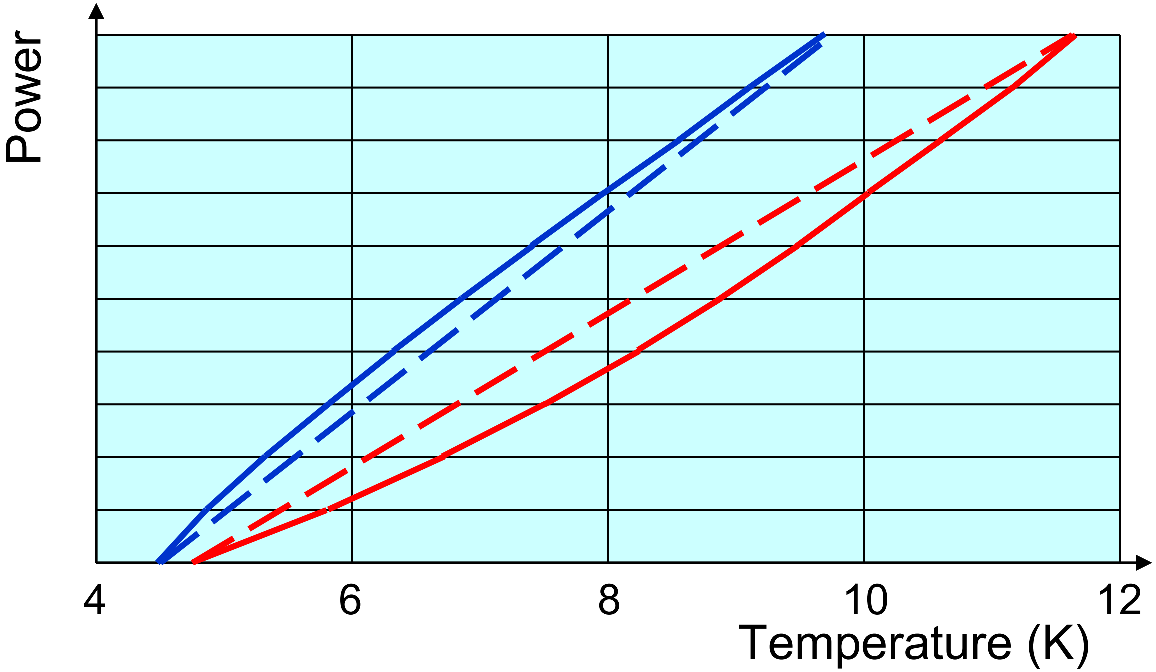
The operating conditions change along the heat exchanger.

Solution: cut the HX into smaller elementary HX and calculate them separately.

A NOT SO SIMPLE HEAT EXCHANGER

The HX is cut into 10 elementary HX, each transferring 1/10 of the total energy.

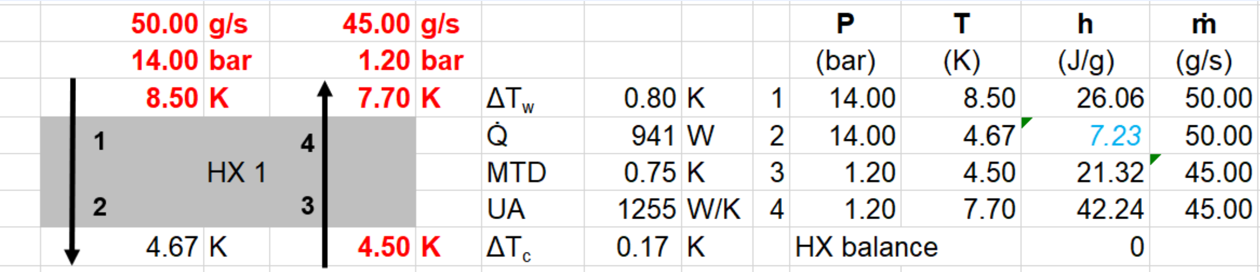
(assuming that operating conditions are constant in each elementary heat exchanger)



UA is the total of the UA's of each elementary HX

"HX3 cold" LMTD is the ratio of power versus UA : LMTD = $\dot{Q}$ / UA

A NOT SO SIMPLE HEAT EXCHANGER



	50.00	g/s	45.00	g/s					**P**	**T**	**h**	**$\dot{m}$**
	14.00	bar	1.20	bar					(bar)	(K)	(J/g)	(g/s)
	8.50	K	7.70	K	ΔT_w	0.80	K	1	14.00	8.50	26.06	50.00
	1		4		$\dot{Q}$	941	W	2	14.00	4.67	*7.23*	50.00
	HX 1				MTD	0.75	K	3	1.20	4.50	21.32	45.00
	2		3		UA	1255	W/K	4	1.20	7.70	42.24	45.00
	4.67	K	4.50	K	ΔT_c	0.17	K		HX balance		0	

CHANGE IN HELIUM AND MATERIAL PROPERTIES WITH TEMPERATURE

Helium

Metals

A REAL HEAT EXCHANGER

Operating conditions:

- Not constant specific heat of both fluids
- Not constant heat exchange coefficient for both fluids
- Not constant thermal conductivity of material along the heat exchanger
- Different cold and warm mass flow rates

The operating conditions change along the heat exchanger.

Solution: cut the HX in small elementary HX and calculate them separately, including the calculation of the heat exchange coefficient and the thermal conductivity in each element !

A VERY REAL HEAT EXCHANGER

On top of the above conditions, one should not forget that the longitudinal conduction in the material along the heat exchanger makes kind of a thermal by-pass, transferring heat from the warm end to the cold end !

HEAT EXCHANGER DIGEST

IMPORTANT !

General balance equation

$$\dot{m}_{HP} \times \Delta h_{HP} = \dot{m}_{LP} \times \Delta h_{LP}$$

Transferred power

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

Log mean temperature difference

(be careful if gas properties are not constant)

$$LMTD = \frac{TDw - TDc}{\mathrm{Ln}\,\dfrac{TDw}{TDc}}$$

The reasonable rule about minimum temperature difference

1 % of the absolute temperature, or > 0.2 K