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Topic: Compression refrigeration cycle (practical work in laboratory)

Lecture 11

Helpful Reading:
Vapour Compression Refrigeration Cycles
Ch 9: 9.8 – 9.11 Borgnakke & Sonntag Ed. 8
Ch 11: 11-1 – 11-7 Cengel and Boles Ed. 7

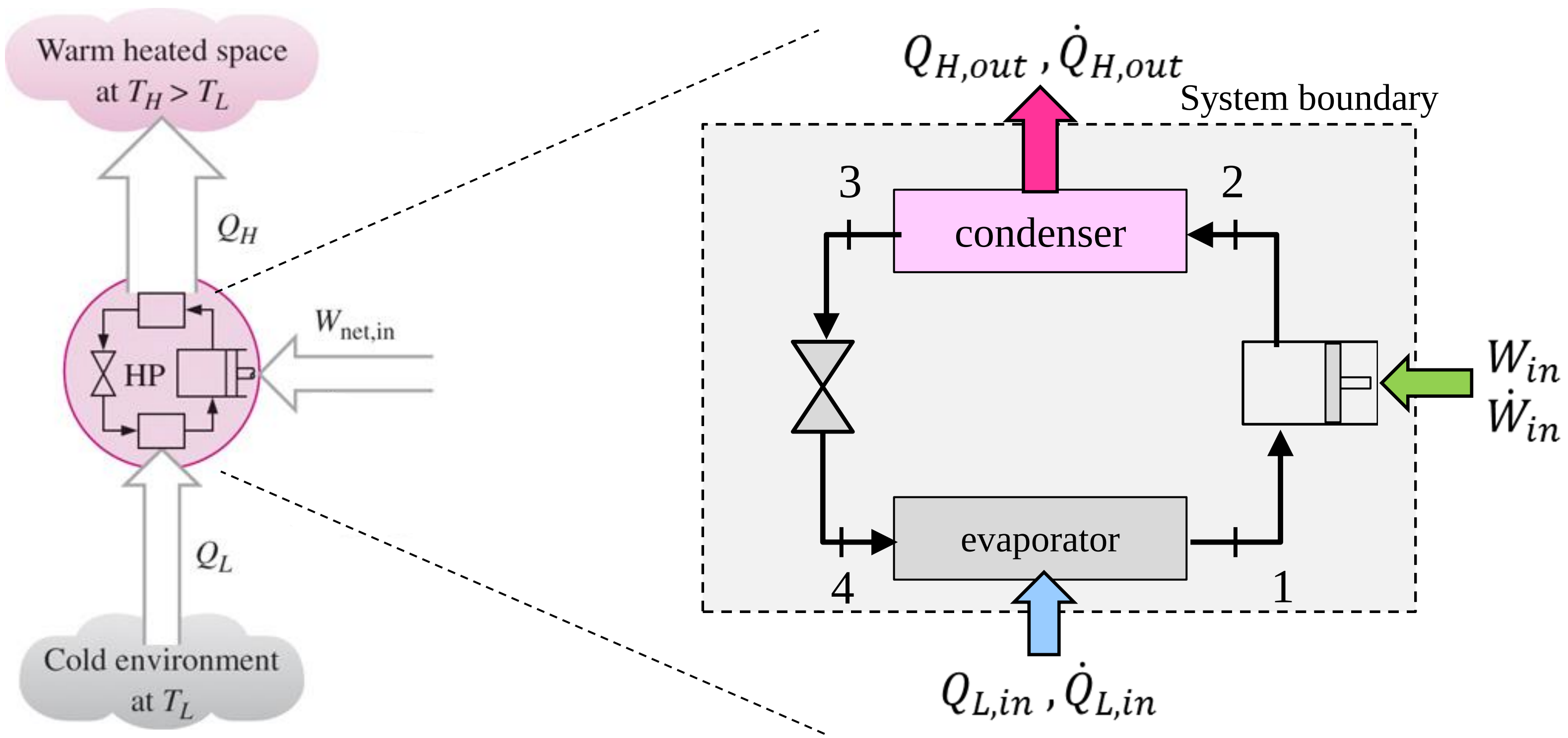
Lab sessions:

- Sign up if you have not already done so
- Details regarding location and remote access have been emailed for most sessions

Engineering Thermo II Laboratory

<u>Task</u>: Ultimately we will evaluate the coefficient of performance of the refrigeration system.

COP = rate of heat flow in from the low temperature reservoir divided by the electrical power of the compressor



<u>Vapour compression cycle</u>

Engineering Thermo II Laboratory

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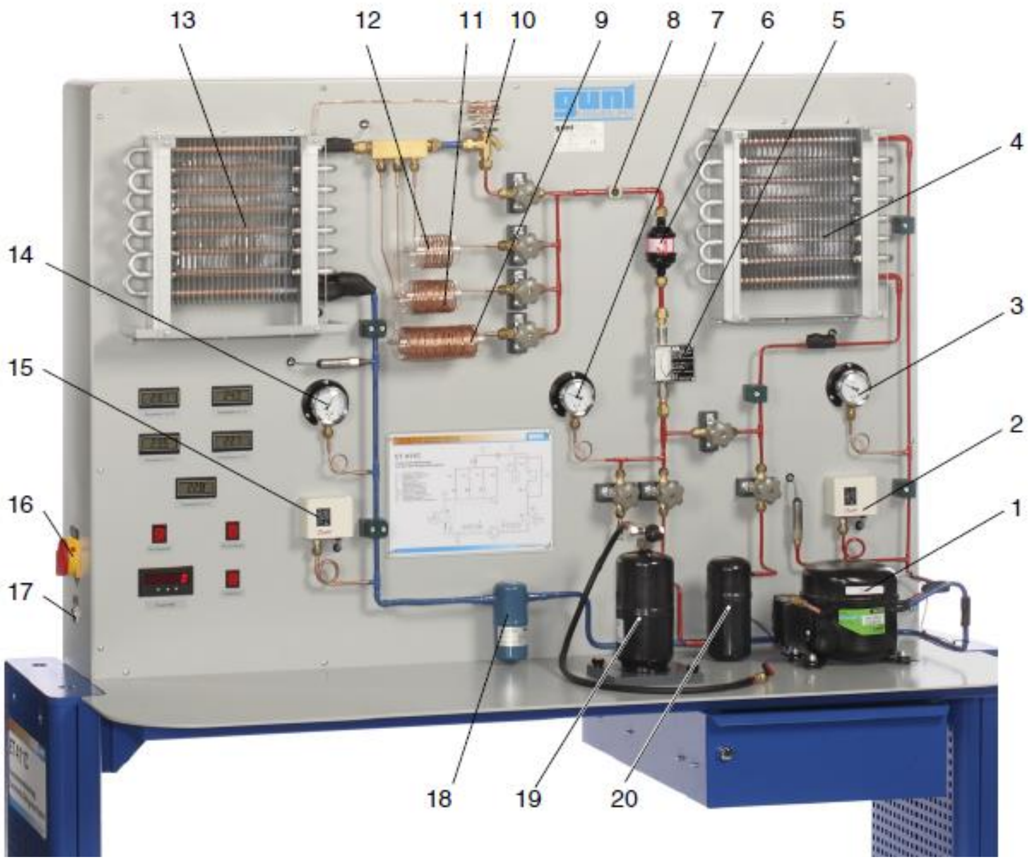
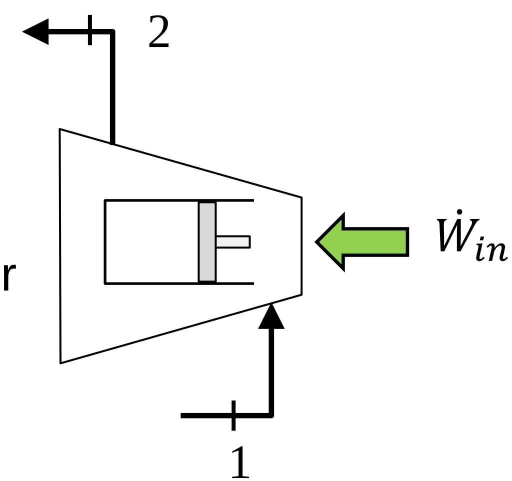


ET 411C COMPRESSION REFRIGERATION SYSTEM

Wed Feb-26 0900-0959 https://app.practable.io/ed0/book/?s=SwkcTz

Refrigerant Working Fluid Analysis



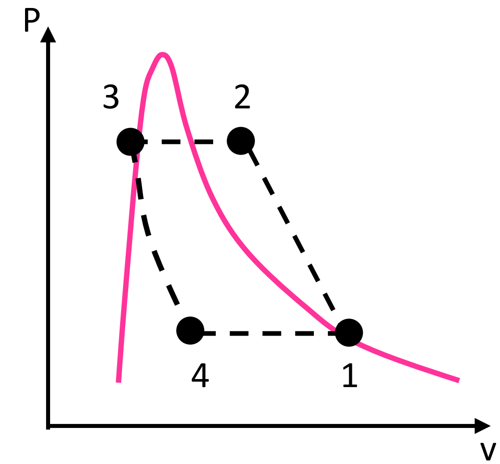
Process 1-2: Compression of working fluid

- Refrigerant compressed from vapour to superheated vapour
- Assumptions: steady-state device, ΔKE, ΔPE is neglected,
- Adiabatic (?)

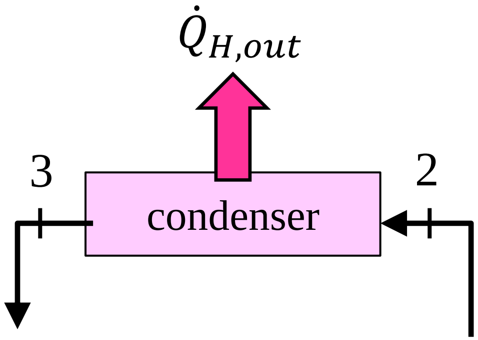
1st Law:

$$0 = \left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \left(\dot{W}_{in} - \dot{W}_{out}\right) + \dot{m}_1 h_1 - \dot{m}_2 h_2$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) - \dot{Q}_{net}$$

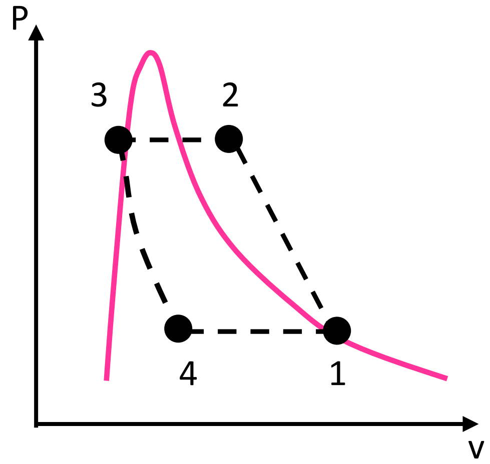


Refrigerant Working Fluid Analysis



Process 2-3: Heat rejection via condensation

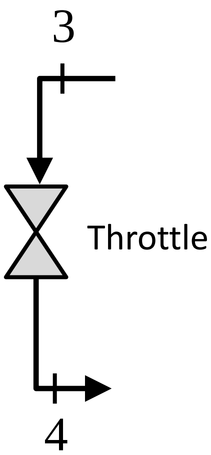
- Refrigerant condenses from vapour to liquid
- Assumptions: steady-state device, ΔKE, ΔPE is neglected, neglect work



1st Law: Refrigerant is system

- $\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \left(\dot{W}_{in} - \dot{W}_{out}\right) + \dot{m}_2 h_2 - \dot{m}_3 h_3 = 0$
- $\dot{Q}_{H,out} = \dot{m}(h_2 - h_3)$

Refrigerant Working Fluid Analysis

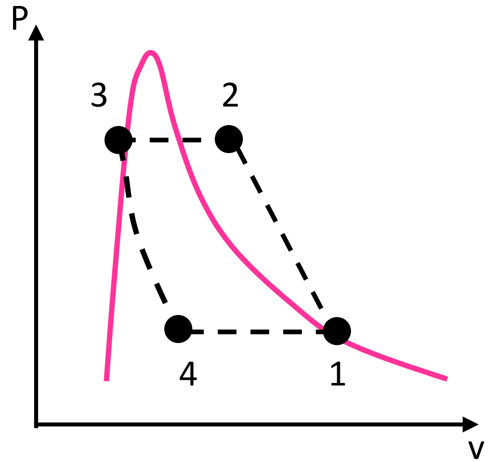


Process 3-4: throttling

- Drop in refrigerant pressure and temperature
- Assumptions: steady-state device, ΔKE, ΔPE is neglected,
- Adiabatic (?), no work

1st Law:

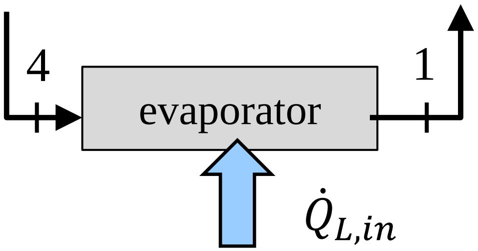
- $\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \left(\dot{W}_{in} - \dot{W}_{out}\right) + \dot{m}_3 h_3 - \dot{m}_3 h_3 = 0$
- $h_3 = h_4$ if adiabatic

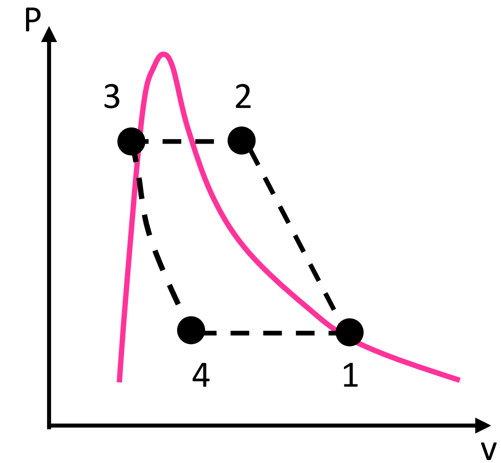


Refrigerant Working Fluid Analysis

Process 4-1: Heat addition, evaporation

- Refrigerant evaporates to a vapour
- Assumptions: steady-state device, ΔKE, ΔPE is neglected, neglect work





1st Law: Refrigerant is system

- $\left(\dot{Q}_{in} - \dot{Q}_{out}\right) + \left(\dot{W}_{in} - \dot{W}_{out}\right) + \dot{m}_4 h_4 - \dot{m}_1 h_1 = 0$
- $\dot{Q}_{L,in} = \dot{m}(h_1 - h_4)$

Overall Lab Setup

Process 1-2: Compression

$$\dot{W}_{in} = \dot{m}_R(h_2 - h_1) - \dot{Q}_{loss?}$$

Process 2-3: Heat rejection

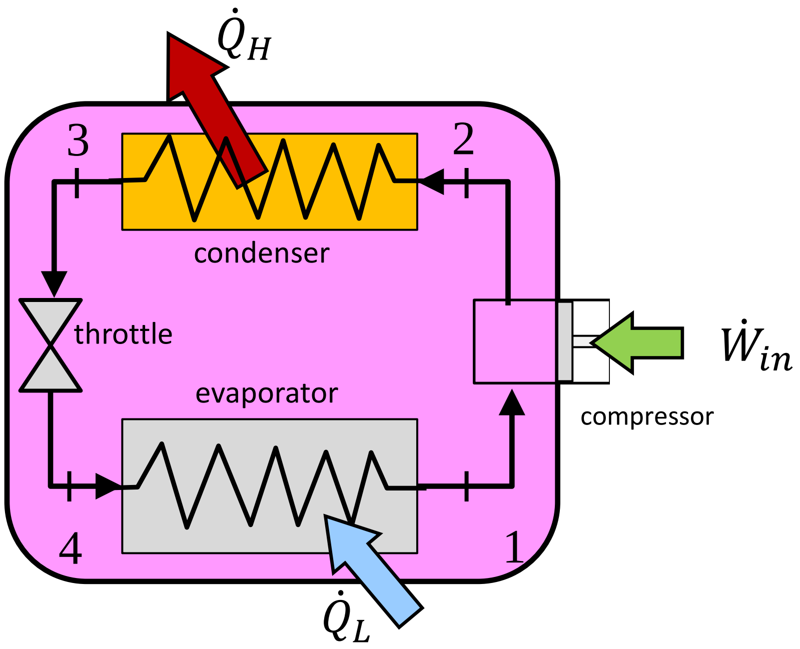
$$\dot{Q}_H = \dot{m}_R(h_2 - h_3)$$

Process 3-4: Throttling

$$h_3 = h_4$$

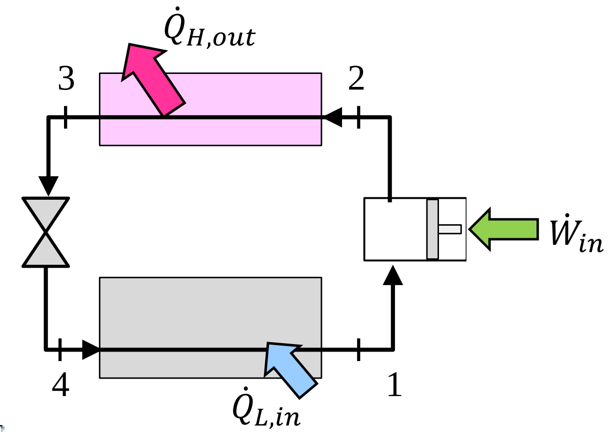
Process 4-1: Heat addition

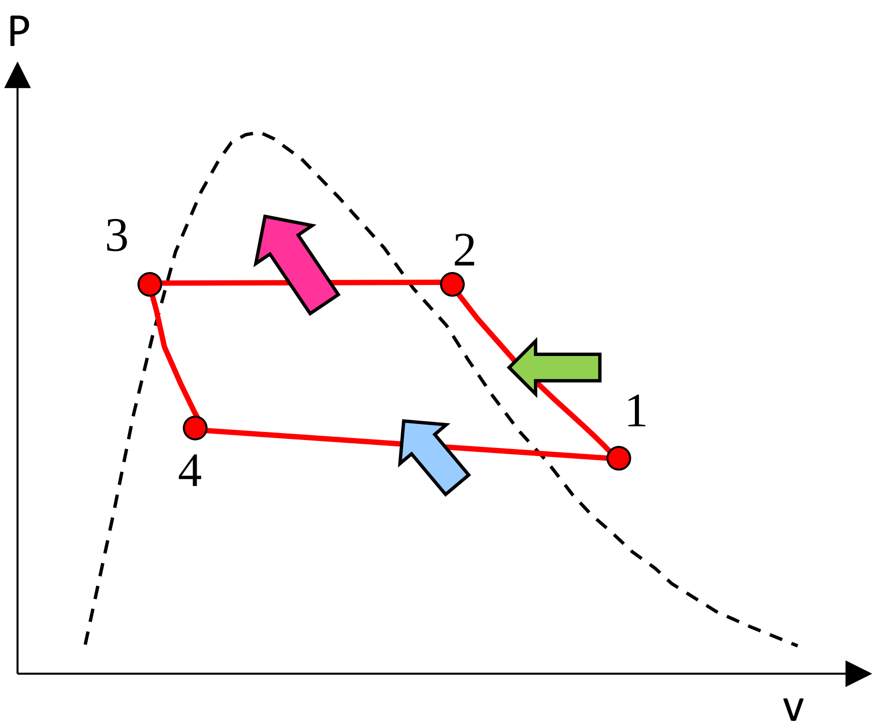
$$\dot{Q}_{L.in} = \dot{m}_R(h_4 - h_1)$$

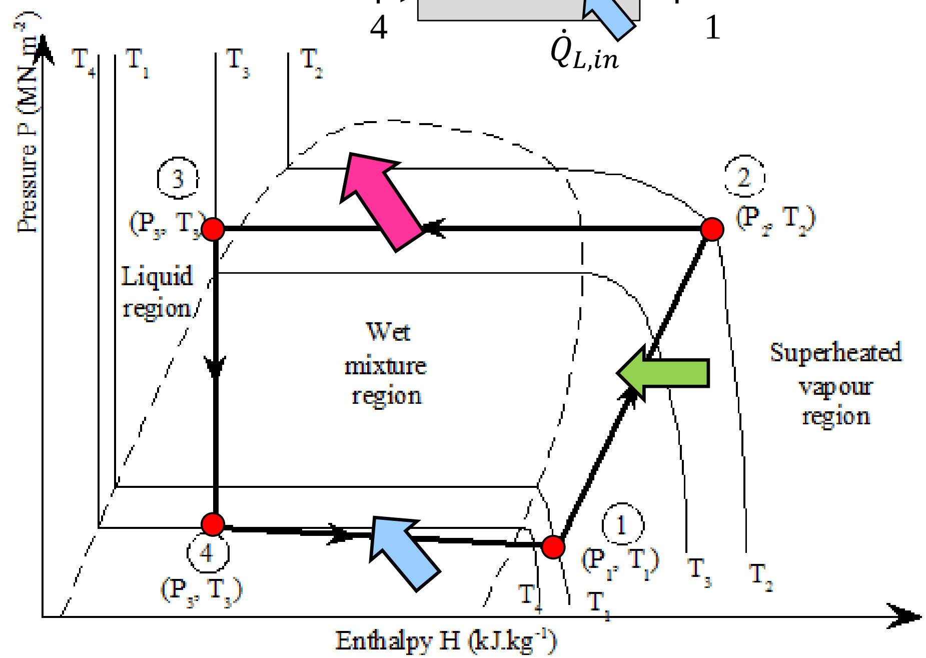


REAL P-v and P-h diagrams

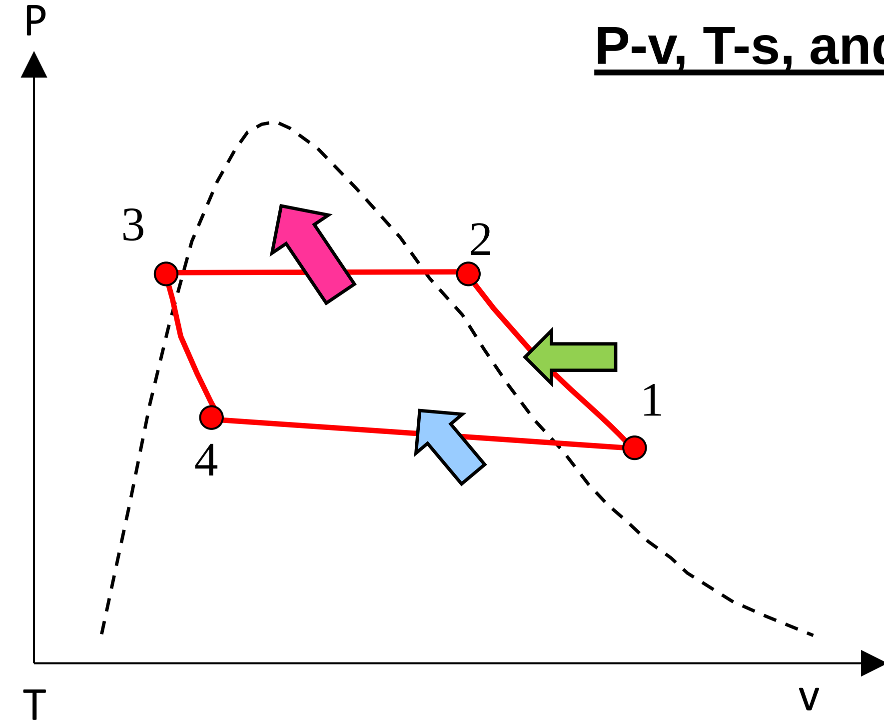
- Notice that these diagrams might deviate from those in the book because our system can deviate from ideal (i.e. we have losses and irreversibilities not accounted for in ideal equations).

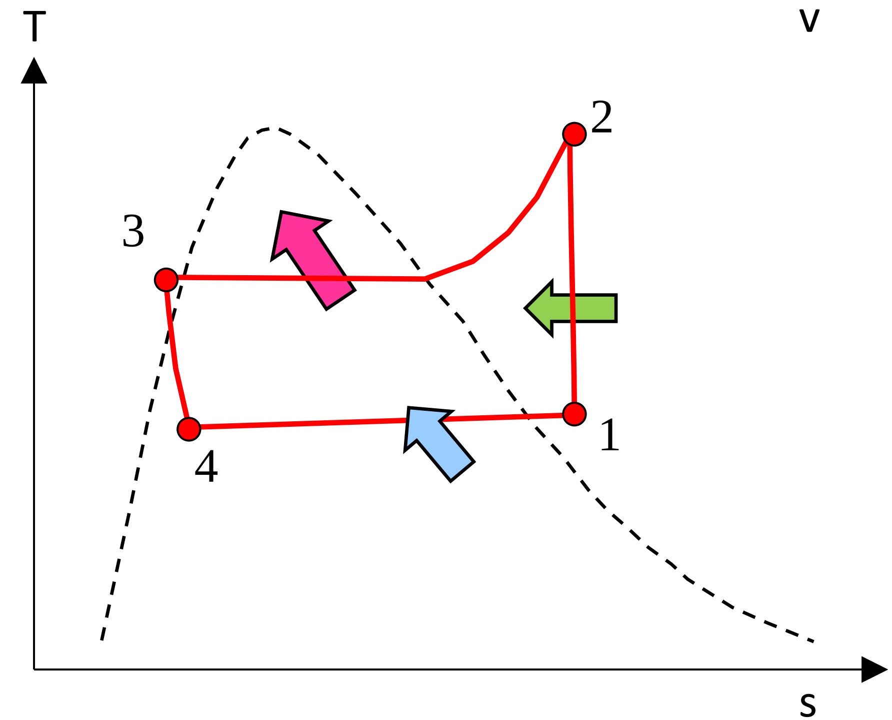


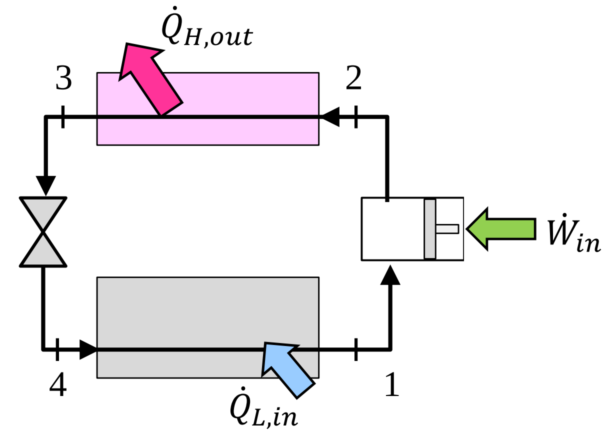


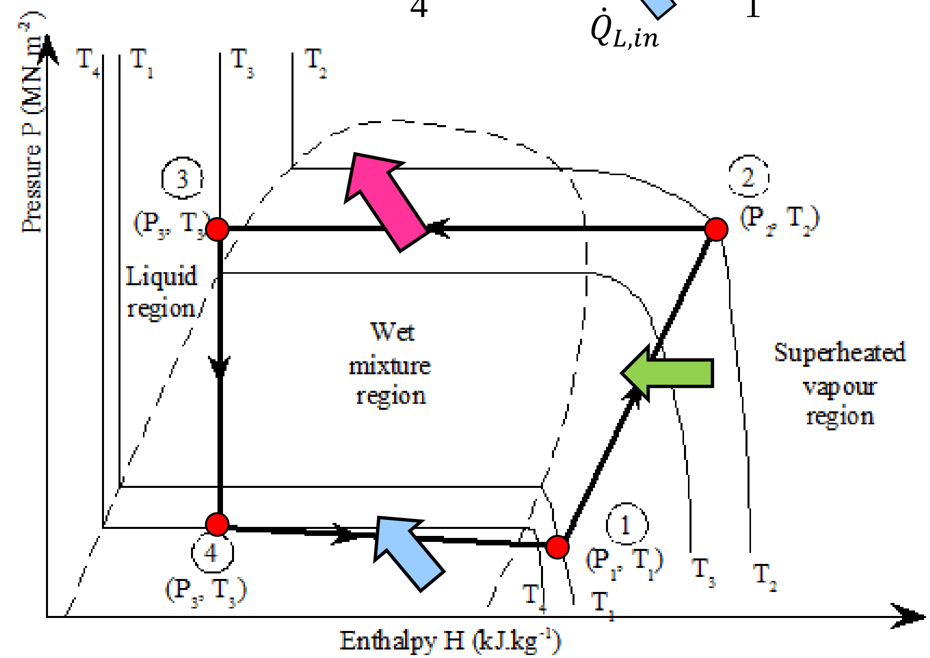


P-v, T-s, and P-h diagrams









The Remote Lab and Calculation App

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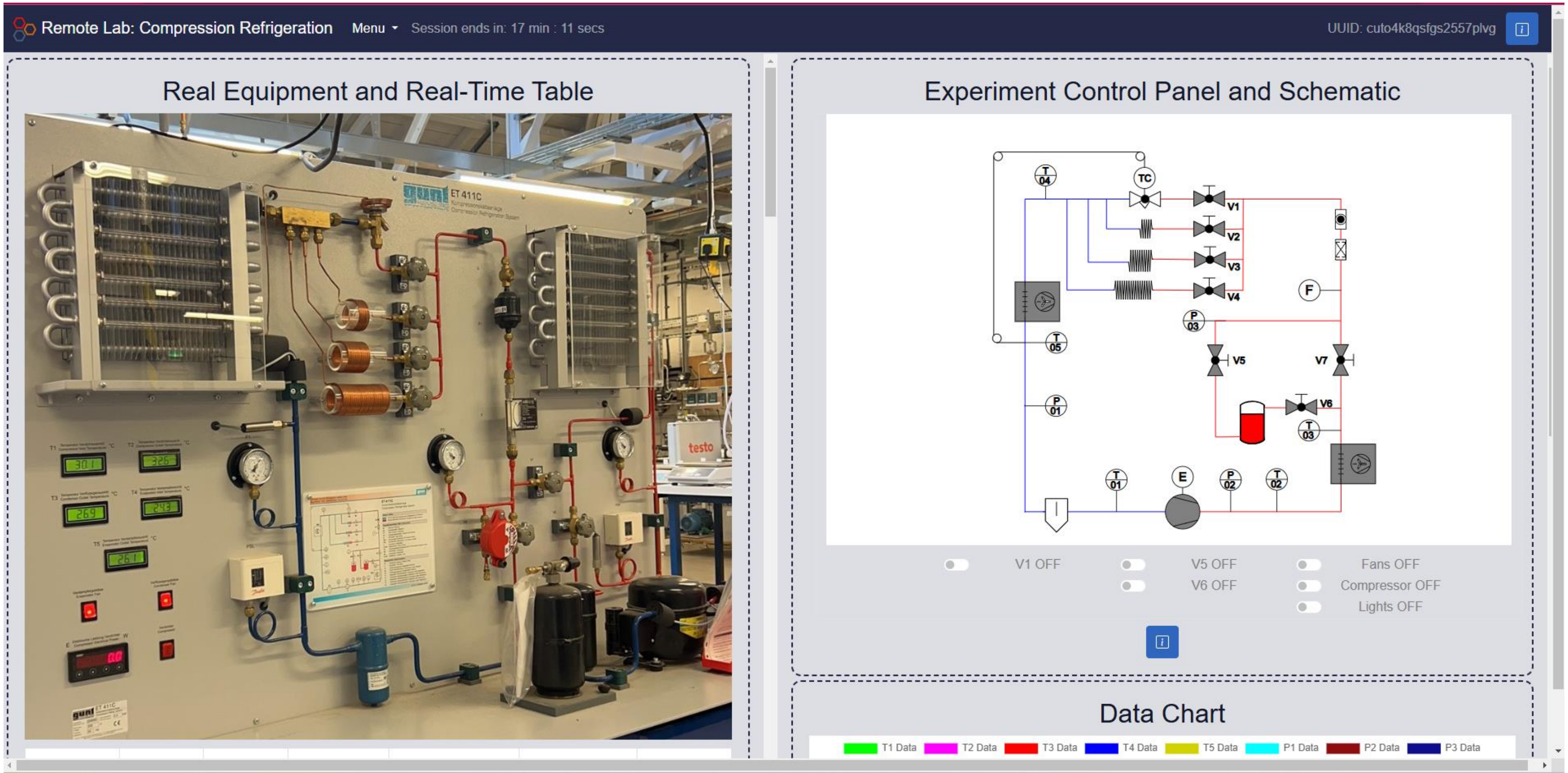

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Making measurements

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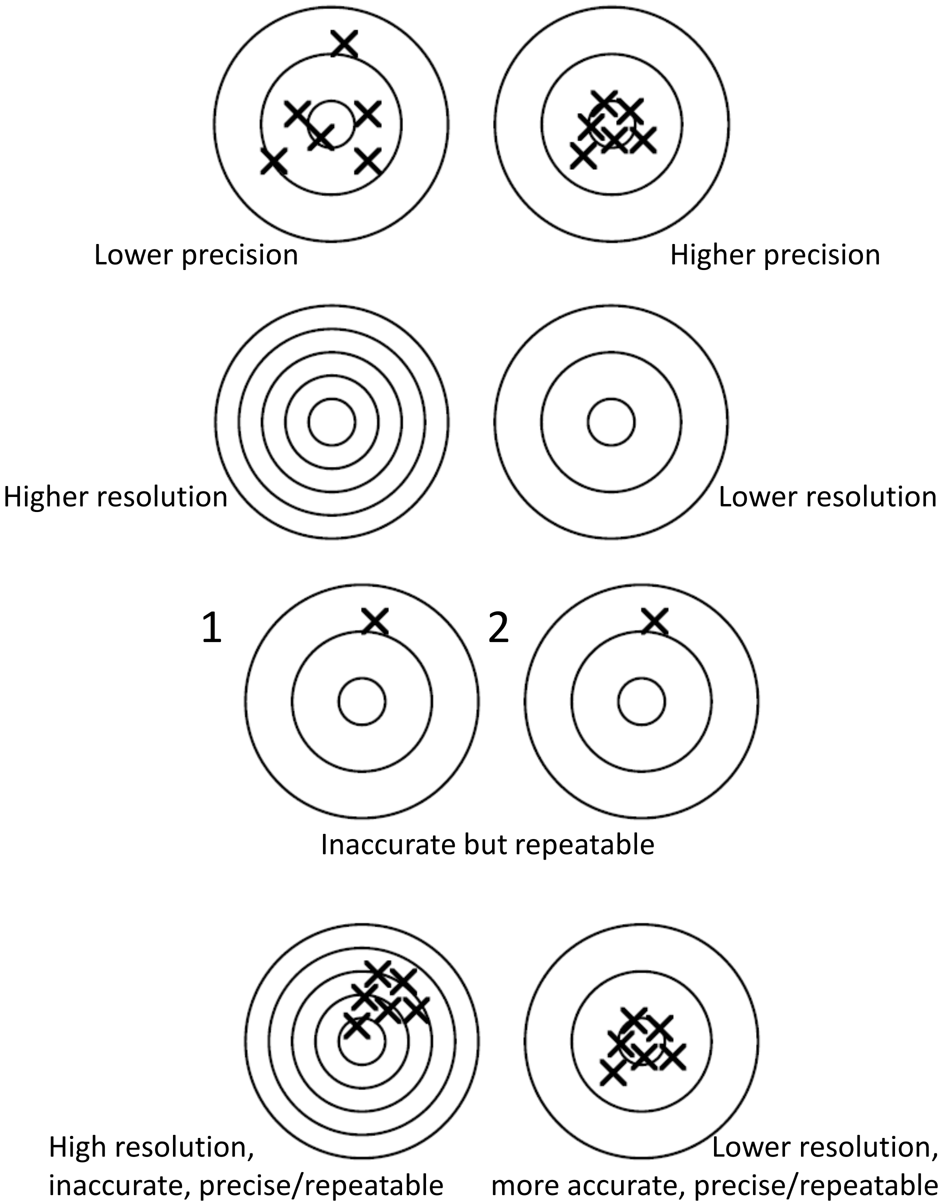
- All measurement devices have potential **errors** associated with measuring a variable of interest

ISSUES TO CONSIDER:

- Precision: how widely spread are your measurements?
- Repeatability: do you get the same results when you do the experiment a second time?
- Accuracy: how close is the measurement to the actual value?
- Resolution: what is the smallest change that can be measured?

Unless otherwise stated assume an instrument is 100% accurate



Unstable gauges

In a **real** experiment, gauges fluctuate.

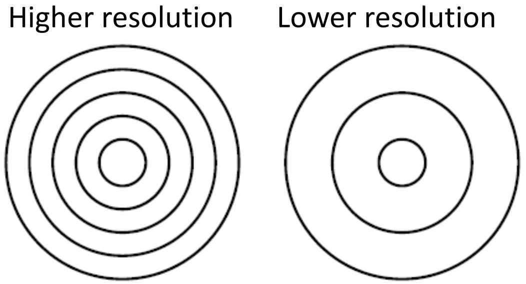
So… take many measurements and average.

Image by fernandozhiminaicela on Pixabay

Potential resolution error

Resolution

- Potential resolution error is typically estimated as ± ½ smallest scale division



- Example
  - Water flow rate (cc/min) → (cm^3/min)
  - Volumetric flow rate
  - Smallest scale division: 0.5 cc/min
  - Uncertainty: 0.25 cc/min
  - <u>Reading</u>: 4.00 cc/min ± 0.25 cc/min

Analysing uncertainty

What is uncertainty?

- Consider some quantity *Y* that is to be measured
- The extracted measurement is *y*
- Let **standard uncertainty** associated with the measurement be $U_{standard}(y)$
- Under certain specified conditions, the probability, *P*, that the ‘true’ value of *Y* lies within the range $y \pm U_{standard}(y)$ is P = 68%.

Analysing uncertainty

Two categories of error: Type A and Type B

Very helpful reference:
https://physics.nist.gov/cuu/Uncertainty/index.html

Type A: ‘random errors’

Type A uncertainty = standard deviation of a set of measurements

Type B: e.g. potential resolution error

Statistical treatment depends on source of error

Type A uncertainties

Example (fictional) - Temperature, *T,* is measured five times:

21.3^{o}C, 21.2^{o}C, 21.5^{o}C, 21.6^{o}C, 21.0^{o}C

$$mean = \langle x \rangle = \frac{\sum_i^N x_i}{N}$$

Mean = (21.3+21.2+21.5+21.6+21.0)/5 = **21.32^{o}C**

$$standard\ deviation = \sigma = \sqrt{\langle x^2 \rangle - \langle x \rangle^2}$$

where $\langle x^2 \rangle = \frac{\sum_i^N x_i^2}{N}$

$\langle x^2 \rangle = (21.3^2 + 21.2^2 + 21.5^2 + 21.6^2 + 21.0^2)/5 = 454.5880$

$\langle x \rangle^2 = 454.5424$

$\sigma = \sqrt{(454.5880 - 454.5424)}$ = **0.2135^{o}C = uncertainty**

With this uncertainty, should only quote mean to 1dp i.e. 21.3^{o}C with uncertainty of 0.2^{o}C. (Note: did not round until the end of the calc.)

Type B uncertainties

Example (fictional) - Temperature, *T,* is measured to be 20.1^{o}C.

- The smallest division on the gauge is 0.1^{o}C.
- The potential resolution error, e, is $\pm$0.05^{o}C.
- In principle, the actual temperature could be anywhere between 20.05^{o}C and 20.15^{o}C.
- Assume that the probability of it lying at a given point in the range is the same as the probability of it lying at any other given point in the range
- Mathematically, this distribution gives rise to a standard uncertainty of $\frac{e}{\sqrt{3}}$

Combining uncertainties

Two scenarios

1. To obtain the value of interest, it was necessary to combine two other values that each had associated uncertainties
2. Two or more different kinds of uncertainty contribute to the overall uncertainty for a given value

Combining uncertainties

Scenario 1

To obtain the value of interest (*y*), it was necessary to combine two or more other values (x_j) that each had associated uncertainties.

(a) $y = a_1 x_1 + a_2 x_2 + a_3 x_3 + \ ... + a_j x_j$

Rule 1a: The uncertainty in *y* is u_c, where

$$u_c^2 = a_1^2 u_{x,1}^2 + a_2^2 u_{x,2}^2 + a_3^2\, u_{x,3}^2 + \cdots + a_j^2 u_{x,j}^2$$

$u_{x,1}$ is the uncertainty in x_1 .

(b) $y = A\, x_1^a x_2^b x_3^c \ldots x_j^p$

Rule 1b:

$$\left(\frac{u_c}{|y|}\right)^2 = a^2 \left(\frac{u_{x,1}}{|x_1|}\right)^2 + b^2 \left(\frac{u_{x,2}}{|x_2|}\right)^2 + c^2 \left(\frac{u_{x,3}}{|x_3|}\right)^2 + \cdots + p^2 \left(\frac{u_{x,j}}{|x_j|}\right)^2$$

Combining uncertainties

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Scenario 2 - Two or more different kinds of uncertainty (u_i) contribute to the overall uncertainty (u) for a given value.

Rule 2: Sum errors in quadrature i.e. $u^2 = \sum_i^N u_i^2$

<u>Example:</u>

- I have extracted a value, y, by taking the mean of a set of N measurements.
- Two sources of uncertainty: random error and 'potential resolution error'
- The standard deviation of the measurements is σ, so $u_1 = \sigma$
- The potential measurement error for each measurement is e
- The uncertainty associated with that is $e/(\sqrt{3})$
- Calculating the mean involved adding up all the individual measurements and dividing by N
- Applying rule 1a from previous slide, $u_2 = e/\sqrt{(3N)}$
- Need to apply **rule 2** to combine u_1 and u_2

$$u^2 = \sigma^2 + \frac{e^2}{3N}$$

Note

It is possible to derive all three rules from first principles

but we are not going to do this today.

See here for more info on

the law of propagation of uncertainty:

https://physics.nist.gov/cuu/Uncertainty/combination.html

Measurement Uncertainty

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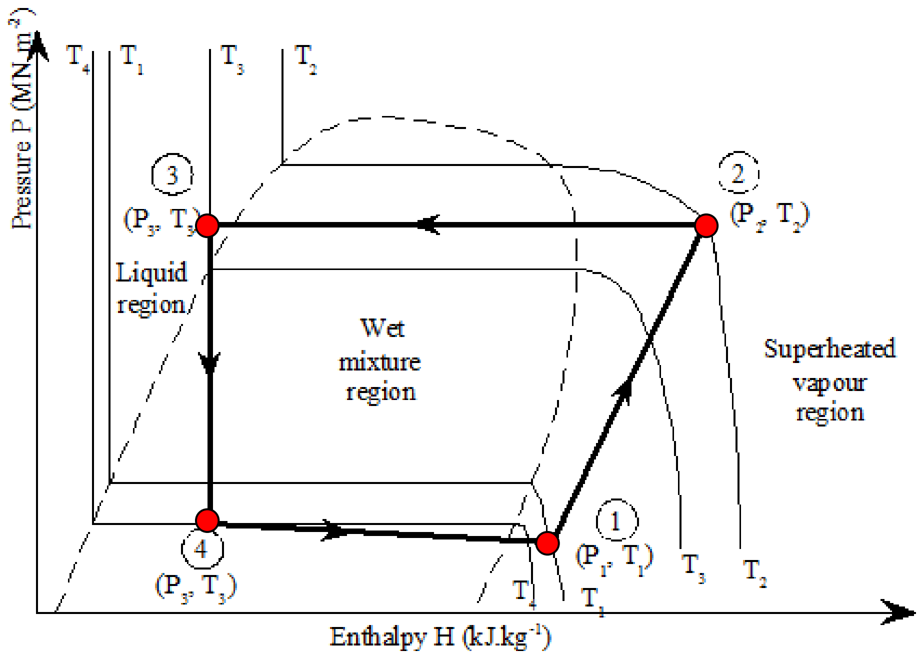

T_{high}, P_{high} → $h_{high,high}$

T_{high}, P_{low} → $h_{high,low}$

T_{low}, P_{high} → $h_{low,high}$

T_{low}, P_{low} → $h_{low,low}$

- Enthalpies are dependent on temperature (less on pressure)
- How do we find the uncertainties of enthalpies
- Find sensitivity of enthalpy for range of temperatures you measure