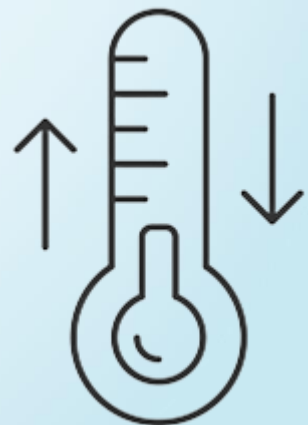


Investigate thermodynamic principles and polytropic processes

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Report aim

The following report describes rudimentary knowledge of thermodynamics principles by presenting facts relating to various temperatures scales, explaining the four thermodynamic processes and presenting example for each. While additionally going over latent and sensible heats as well as thermal energy and power. After which three thermodynamic related questions were solved with each representing foundational understanding of general parameters that are utilized and calculation done in thermodynamic processes. Concluding the report is an analysis of reversible and irreversible expansion of gas within isolated or open systems.

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Temperature

What is temperature?

Temperature a measure for the amount of thermal energy found within matter and is used to convey how hot or called said matter is, with the hotter the temperature representing faster particle movement and colder representing slower motion within matter particles, and as such, the change of temperature is required during the process of changing one state of matter to another.

Temperature scales

Temperature scale sections

Boiling point	The boiling point is the temperature in which water particles are heated until they are moving fast enough to turn water into vapor.
Freezing point	The freezing point is the opposite of the boiling point, in which it is when water particles are cooled down until they are slow enough to turn water to ice, however, there is still some movement seen within particles due to vibrations.
Absolute zero	Absolute zero conveys when thermal energy is nonexistent at all within matter, meaning that particles of matter that is at absolute zero have no show motion whatsoever.

Celsius:

As has been stated by (Bellis, 2019), the Celsius temperature scale was invented by a Swedish astronomer, named Andres Celsius (Figure 1) in 1742. The temperature scale was initially named the centigrade scale but later was then changed to honor its inventor when he passed. It was invented so that there is only a 100 unit difference between the freezing and boiling point of water. When it was initially developed, the boiling point used to be 0 degrees, and the freezing was 100 but was then switched around. Celsius is used for everyday temperature measurements as well as general scientific equations, and according to (Zamboni, 2020), it is implemented in countries that utilize the metric system, although both Liberia and Burma use it, which are countries that use the imperial system.



Figure 1

Boiling point: 100°C	Freezing point: 0°C	Absolute zero: -273.15°C
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Fahrenheit:

As claimed by (Britannica, 2021) The Fahrenheit temperature scale was first created in 1724 by a German physicist known as Daniel Gabriel Fahrenheit (Figure 2), as such it was the first temperature scale to be widely used. When Fahrenheit originally invented the scale, he used the freezing and boiling points of a 1:1:1 mixture of ice, salt, and water, and chose 30 for the freezing point and 210 for the boiling point, making the difference between them 180, with the reason for choosing those two numbers being arbitrary. However, after Fahrenheit passed, these numbers were changed to 32 and 212 to match the freezing and boiling points of water without the ice and salt. Nowadays, Fahrenheit

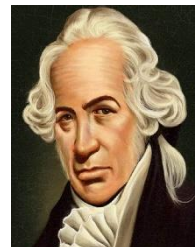


Figure 2

is used for casual temperature measurements however as stated by (lumen, 2021), it is generally avoided for scientific equations and according to (Kiger, 2021) it is only used in the United States and the Cayman Islands.

Boiling point: 212°F	Freezing point: 32°F	Absolute zero: -459.67°F
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Kelvin:

According to (Magnet Academy, 2021) the temperature scale known as kelvin was developed by a Scottish physicist called William Thomson, also known Lord Kelvin (Figure 3), in 1848. The difference between the freezing and boiling points in Kelvin is 100, meaning it uses the same scale as Celsius, however, the Kelvin temperature scale's zero is at absolute zero. The intention for this scale is so that when scientists were working with anything that is related with absolute zero, they did not want negative numbers within their equations, as that could make them nonfunctional, and as such the Kelvin temperature was created and is widely used in temperature physics and other scientific fields such as astrophysics, its also generally avoided for general temperature measurement applications.

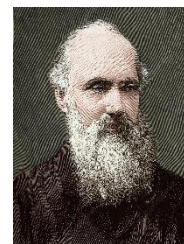


Figure 3

Boiling point: 373.15°K	Freezing point: 273.15°K	Absolute zero: 0°K
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Scale conversions

Celsius and Fahrenheit

$C = 5/9(F - 32)$		$F = 9/5(C) + 32$	
Example 1: $F = 32$	Example 2: $F = 180$	Example 1: $C = 0$	Example 2: $C = 57$
$C = 5/9(32 - 32)$	$C = 5/9(180 - 32)$	$F = 9/5(0) + 32$	$F = 9/5(57) + 32$
$C = 5/9(0)$	$C = 5/9(148)$	$F = 0 + 32$	$F = 102.6 + 32$
$C = 0^\circ$	$C = 82.2^\circ$	$F = 32^\circ$	$F = 134.6^\circ$

The theory behind the formula

The formula used to convert Celsius to Fahrenheit is that way because a Fahrenheit unit is bigger than a Celsius unit by 9/5 times, this can be found by dividing the difference between the freezing and boiling point of the two scales, which would be $(212 - 32)/(100 - 0)$, which gives us 180/100, and after the fraction has been simplified, it would come to 9/5. The 32 is then added at the end of the equation to make up for the difference between 0 and freezing point in the Fahrenheit temperature scale. The equation for converting Fahrenheit to Celsius was then simply found by making Celsius the subject of the equation.

Celsius and Kelvin

$K = C + 273.15$		$C = K - 273.15$	
Example 1: $C = 100$	Example 1: $C = -35$	Example 1: $K = 350$	Example 1: $K = 64$
$C = 100 + 273.15$	$C = -35 + 273.15$	$C = 350 - 273.15$	$C = 64 - 273.15$
$K = 373.15^\circ$	$K = 238.15^\circ$	$C = 76.85^\circ$	$C = 209.15^\circ$

Fahrenheit and Kelvin

There isn't a set formula that is used to convert from Fahrenheit to Kelvin or vice versa, as such the only way of doing so is to convert either scale to Celsius, and afterwards convert the Celsius value into the required scale.

Thermodynamic processes

What are thermal processes?

Thermal processes are the magnitudes of pressure, volume, and temperature that act upon a solid liquid or gas. Thermal processes consist of four different types, with them being isobaric, isochoric, isothermal, and adiabatic.

Isobaric process

An isobaric is a process in which the pressure throughout the entirety of procedure remains either entirely constant ($\Delta P = 0$) or has negligible variations pressure.

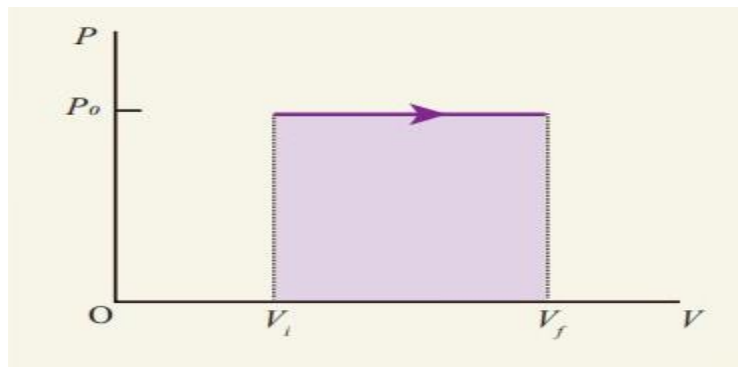


Figure 4 - Isobaric PV diagram

Theory: The way that this process functions is that whenever the pressure tries to either increase or decrease, the volume immediately changes in order to counteract the change of pressure that was meant to occur, which – as seen in (Figure 4) – leads to a change in volume but insignificant variation to the Pascal value.

Example: As mentioned by (BYJUS, 2021), a major example of an Isobaric process is the freezing of water (Figure 5). That is the case because although the process requires for the decrease in the water's temperature, and freezing causes it to expand which alters the volume, however, the pressure does not change and remains constant due to the change in volume countering the change in pressure.



Figure 5

Isochoric process

During an isochoric process, both pressure and the temperature of the system fluctuates however the parameter that remains constant is the volume ($\Delta V = 0$).

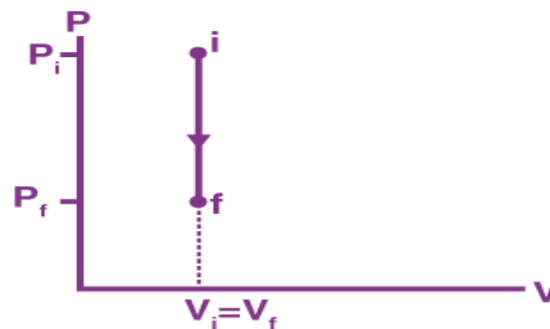


Figure 6 - Isochoric PV diagram

Theory: The theory behind an isochoric process is that although the temperature of the object does increase and decrease, and the pressure being applied does fluctuate, the object itself is strong enough to resist any expansion or contraction by said changes, thus the volume remains either constant throughout the entire process or varies by an extremely small amount that can be unaccounted for, this also indicated to the work being done on or by the system being zero (Figure 6).

Example: An ideal example of an isochoric process is cooking with the utilization of a pressure cooker (Figure 7), which is the case due to an although inconstant extreme amount of heat is applied, and the pressure within it is as well varying, the volume and size of the cooker itself remains the same.



Figure 7

Isothermal

An isothermal process is a process that varies in both pressure and volume but its temperature is either constant ($\Delta T = 0$) or extremely little and is therefore is of no consequence to the process itself.

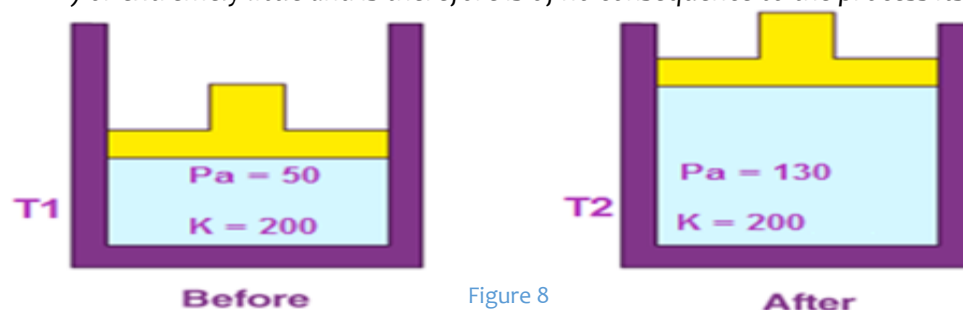


Figure 8

Theory: As stated by (BYJUS, 2021), the temperature change that occurs within the process is very slow, as such the equilibrium of the process is preserved, meaning the amount of thermal energy that is gained or lost by the system due to the change in temperature is immediately used up or recovered, thus leading to the internal change in energy being zero (Figure 8).

Example: According to (Wilkes University, 2021), the boiling of water within a closed system (Figure 9) is considered to be an isothermal process, that is the case because although the pressure of the water vapor alternates due to it being in closed system, and the volume of the water also changes as it is changing from a gas to a liquid, however, the water remains at 100°C whether it is a water or a gas.



Figure 9

Adiabatic

Within an adiabatic process, all parameters fluctuate according to the activity. However, the operation is thermally insulated, and as such no heat flows (Q) into or out of the process.

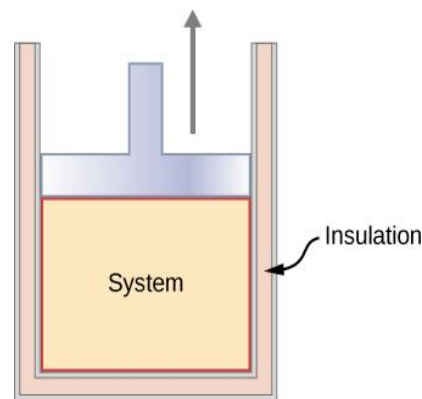


Figure 10 – An insulated chamber diagram

Theory: The heat flow (Q) is the amount of heat that goes into or out of the process during it, however due to an adiabatic process a process in which no heat flows into or out of it, the chamber in which the process occurs has to be entirely thermally insulated (Figure 10). However, heat could still flow in from component that causes the process. In the case of a piston, it would have to be moving at an extremely fast rate in as to not allow for heat to pass through during its the rise and descend. Thus, an adiabatic process is the opposite of an isothermal one in that the movement of the gas has to occur at a very fast rate while in an isothermal it occurs at a very slow one. However, as stated earlier, although no heat flows in, all other parameters – including temperature – could still change according to the movement of the gas within the chamber.

Example: As stated by (BYJUS, 2021), an example of an adiabatic process is the release of air from pneumatic tires (Figure 11), in that when air is released with the use of an air compressor tire nozzle, the temperature changes, and the pressure and volume decrease as the tire inflates, however, no heat will flow in through the tire or through the nozzle.



Figure 11

Latent and Sensible heat

Sensible Heat

Sensible heat is the heat that increases a body's temperature but does not cause it to change its state of matter but rather is the heat applied to get the temperature points that lead up to the either the melting or boiling points of a material or substance ($>0^{\circ}\text{C}$ and $1-99^{\circ}\text{C}$ for water)

Latent Heat

Latent heat is the heat applied for a substance to change its state of matter without changing the body temperature, with the melting/freezing point being known as the latent heat of fusion (0°C for water) and the boiling/condensation point being known as latent heat for vaporization (100°C for water)

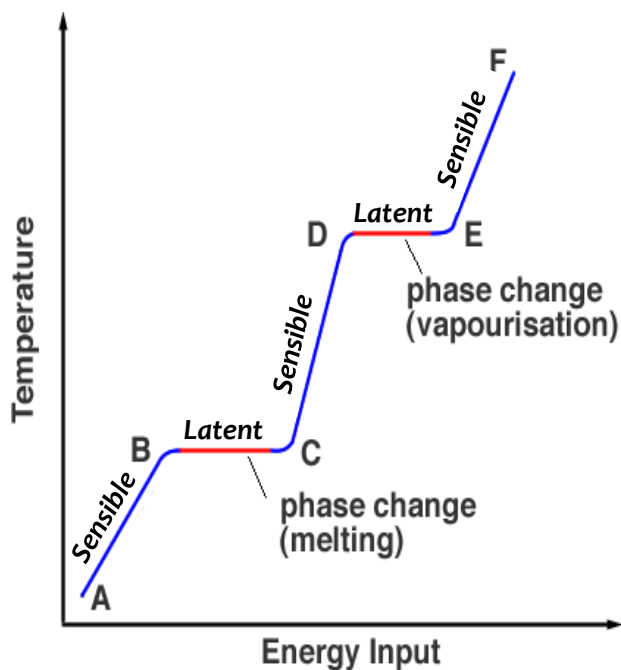


Figure 12 - Sensible and Latent heat diagram

Thermodynamic parameters

Parameter	Symbol	Unit
Heat	Q	Joules (J)
Heat capacity	C	Joules per Kilo gram kelvin (J/kg k)
Polytropic process index	n	N/A
Gas constant	R	Joules per kelvin mole (J/k • mol)
Power	P	Joules (J)
Mass	m	Kilograms (Kg)
Time	t	Seconds (s)
Temperature	T	Kelvin (K)
Pressure	P	Pascal (Pa)
Volume	V	Centimeter Cubed (cm ³)

The heat capacity of certain materials	
Material	Specific heat capacity
Aluminum	0.88
Steel	0.63
Copper	0.39
Water	4.19
Hydrogen (at 101325 Pa)	14.5
Oil	1.97

Thermal energy and Power

Thermal energy

Thermal energy describes the amount of energy that is contained within matter or within a system that directly effects said system's overall heat and temperature. With higher thermal energy being the cause for faster particle vibration or movement within matter.

$$Q = mC\Delta T$$



Thermal power

As has been states by (Afework, Hanania, Stenhouse, & Donev, 2020), thermal power refers to the speed at which thermal energy is produced. A prominent example of thermal power could be the how fast a type of fossil fuel can be transformed into a source of thermal energy

$$P = Q \div t$$



Relationship: Thermal power indicates the speed at which thermal energy is produced.

Calculation Example:

Parameters given			
Mass	Temperature change	Heat capacity	Time
0.4kg	12°C	1.25J/kg°C	15s

Calculate the thermal energy as well as thermal power of a gas while using the stated parameters

Finding thermal energy:

$$Q = mC\Delta T$$

$$Q = 0.4 \times 1.25 \times 12$$

$$Q = 6J$$

Finding thermal power:

$$P = \frac{Q}{t}$$

$$P = \frac{6}{15}$$

$$P = 0.4W$$

Thermodynamic Calculations

Question one

A piston contains 0.05 kg of air at temperature 710 °C and pressure 120 kPa. The air is heated to 1200°K while being kept at a constant volume of 1 liter. Calculate the mass and pressure of the air following heating. Assume the gas constant for air is 0.287 kJ/kg·K



Parameters

$$m_1 = 0.05 \text{ kg}$$

$$T_1 = 710^\circ\text{C}$$

$$P_1 = 120 \text{ kPa}$$

$$T_2 = 1200^\circ\text{K}$$

$$P_2 = ?$$

$$m_2 = ?$$

$$V = 1 \text{ L}$$

$$R = 0.287 \text{ kJ/kg} \cdot \text{K}$$

Conversions:

$$T_1: 710^\circ\text{C} \rightarrow ^\circ\text{K} = 710 + 273.15 = 983.15^\circ\text{K}$$

$$V: 1 \text{ L} \rightarrow \text{m}^3 = 1 \div 1000 = 0.001 \text{ m}^3$$

Finding Pressure:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \rightarrow \text{(General gas formula)}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \rightarrow \text{(We remove volume for the general formula if it's constant)}$$

$$\frac{120}{983.15} = \frac{P_2}{1200}$$

$$\frac{120}{983.15} \times 1200 = P_2 \rightarrow \text{(Algebra)}$$

$$P_2 = 146.4679856 \text{ kPa}$$

Finding mass:

$$PV = mRT \rightarrow \text{(Ideal gas law)}$$

$$146.4679856 \times 0.001 = m \times 0.287 \times 1200$$

→ (We used the final values (P2 and T2) since we want to find the final mass value)

$$\frac{146.4679856 \times 0.001}{0.287 \times 1200} = m$$

$$m = 0.0004252845109\text{kg}$$

Question two

A cylinder contains a gas at temperature 310°F and pressure 1.7MPa . It is then cooled to 380°K when the pressure is 2.4MPa . Find the polytropic process index value (n) for the gas.



Parameters

$T_1 = 310^\circ\text{F}$

$P_1 = 1.7\text{MPa}$

$T_2 = 380^\circ\text{K}$

$P_2 = 2.4\text{MPa}$

$n = ?$

Conversions:

$$T_1: 310^\circ\text{F} \rightarrow ^\circ\text{K} = \left(\frac{5}{9} \times (310 - 32) \right) + 273.15 = 427.594^\circ\text{K}$$

$$P_1: 1.7\text{MPa} \rightarrow \text{kPa} = 1.7 \times 1000 = 1700\text{kPa}$$

$$P_2: 2.4\text{MPa} \rightarrow \text{kPa} = 2.4 \times 1000 = 2400\text{kPa}$$

Finding the polytropic process index value:

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1} \right]^{\frac{n-1}{n}} \rightarrow \text{(Used for the polytropic index if pressure and temperature are known)}$$

$$\frac{380}{427.594} = \left[\frac{2400}{1700} \right]^{\frac{n-1}{n}}$$

$$0.8886925566 = (1.411764706)^{\frac{n-1}{n}}$$

$$\log(0.8886925566) = \log(1.411764706) \times \frac{n-1}{n}$$

→ (introduce logs to split the pressure value from the $\frac{n-1}{n}$, which allows us to solve normally)

$$\frac{\log(0.8886925566)}{\log(1.411764706)} = \frac{n-1}{n} \rightarrow \text{(Algebra)}$$

$$-0.3421986067 = \frac{n-1}{n}$$

$$-0.3421986067n = n-1 \rightarrow \text{(Algebra)}$$

$$-1.3421986067n = -1 \rightarrow \text{(Algebra)}$$

$$n = \frac{-1}{-1.3421986067n} \rightarrow (\text{Algebra})$$

$$n = 0.7450462212$$

Question three

A fluid at 8.15 bar is expanded reversibly according to a law $PV = \text{constant}$ to a pressure of 1.15 bar until it has a specific volume of $0.12 \text{ m}^3/\text{kg}$. It is then cooled reversibly at a constant pressure, then is cooled at constant volume until the pressure is 0.62 bar; and is then allowed to compress reversibly according to a law $PV^n = \text{constant}$ back to the initial conditions. The work done in the constant pressure is 0.525 kJ, and the mass of fluid present is 0.22 kg. Calculate the value of n in the fourth process, the net work of the cycle and sketch the cycle on a P-V diagram



Parameters

P1 = 8.15 bar	P2 = 1.15 bar	Specific V2 = 0.12 m ³ /kg	P4 = 0.62 bar	w2 = 0.525 kJ
m = 0.22 kg				

Conversions:

$$P1: 8.15 \text{ bar} \rightarrow \text{kPa} = 8.15 \times 100 = 815 \text{ kPa}$$

$$P2: 1.15 \text{ bar} \rightarrow \text{kPa} = 1.15 \times 100 = 115 \text{ kPa}$$

$$P4: 0.62 \text{ bar} \rightarrow \text{kPa} = 0.62 \times 100 = 62 \text{ kPa}$$

Isothermal process:

$$w1 = mRT \ln \left(\frac{P2}{P1} \right) \rightarrow (\text{Formula for work done in isothermal processes})$$

$$w1 = P1V1 \ln \left(\frac{P2}{P1} \right) \rightarrow (\text{We don't have enough info for } mRT, \text{ however, } PV \text{ is equivalent to it})$$

We don't have V1 so we need to find that before proceeding

$$P1V1 = P2V2 \rightarrow (\text{General gas formula for isothermal processes})$$

$$815 \times V1 = 115 \times (0.12 \times 0.22) \rightarrow (\text{we get } V2 \text{ by multiplying specific volume with mass})$$

$$V1 = \frac{3.036}{815} \rightarrow (\text{Algebra})$$

$$V1 = 0.003725153374 \text{ m}^3$$

Now that we have V1, we cause $w1 = P1V1 \ln(P2 \div P1)$

$$w1 = 815 \times 0.003725153374 \times \ln\left(\frac{115}{815}\right)$$

$$w1 = 5.94526517\text{kJ}$$

Isobaric process:

$$w2 = 0.525 \rightarrow \text{(Given in the question)}$$

We have the work done, however we would need the volume to assist with the following process

$$w2 = p2(V3 - V2) \rightarrow \text{(Work done formula in isobaric processes, can be rearranged for V2)}$$

$$V3 = \frac{w}{p2} + V2 \rightarrow \text{(Algebra)}$$

$$V3 = \frac{0.525}{115} + (0.12 \times 0.22)$$

$$V3 = 0.03096521739\text{m}^3$$

Isochoric process:

$$w3 = 0 \rightarrow \text{(Due to the volume being constant in an isobaric process, the work done is zero)}$$

$$V3 = V4 \rightarrow \text{(The change in volume is zero, meaning both V3 and V4 are equal)}$$

$$V4 = 0.03096521739\text{m}^3$$

Adiabatic process:

$$w4 = \frac{P4V4 - P1V1}{n - 1} \rightarrow \text{(Work done formula for adiabatic processes)}$$

We don't have n, so we have to find it before proceeding with finding the work done

$$\frac{P1}{P4} = \left[\frac{V4}{V1}\right]^n \rightarrow \text{(Used for the polytropic index if the pressure and volume are known)}$$

$$\frac{815}{62} = \left[\frac{0.03096521739}{0.003725153374}\right]^n$$

$$\log\left(\frac{815}{62}\right) = \log\left(\frac{0.03096521739}{0.003725153374}\right) \times n \rightarrow \text{(Introducing logs to the equation)}$$

$$\log(13.14516129) = \log(8.312467778) \times n$$

$$\frac{\log(13.14516129)}{\log(8.312467778)} = n \rightarrow (\text{Algebra})$$

$$n = 1.216406934$$

Now that we have n , we can continue with finding the work done for the adiabatic process

$$w_4 = \frac{P_4V_4 - P_1V_1}{n - 1}$$

$$w_4 = \frac{(62 \times 0.03096521739) - (815 \times 0.003725153374)}{1.216406934 - 1}$$

$$w_4 = 5.157674484 \text{ kJ}$$

Net work:

$$W_{\text{net}} = w_1 + w_2 + w_3 + w_4$$

$$W_{\text{net}} = 5.94526517 + 0.525 + 0 + 5.157674484$$

$$W_{\text{net}} = 11.62793965 \text{ kJ}$$

The PV diagram of the processes proposed in question 13:

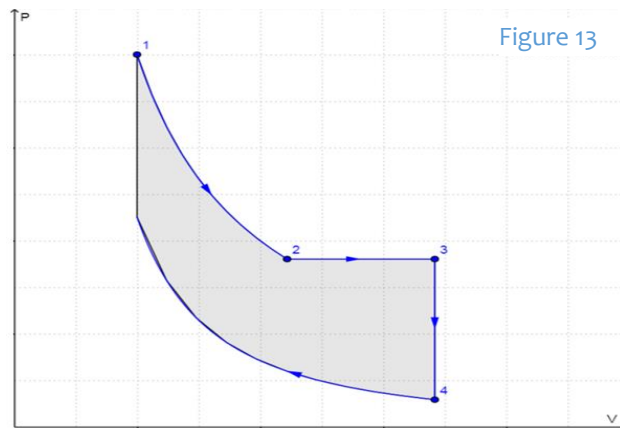


Figure 13

The initial process (1-2) in the system proposed by question 3 was an isothermal process. During isothermal processes, both the pressure and volume are not constant, as such – as can be noticed – neither parameter in the diagram is a straight line as can be seen in (Figure 13). The subsequent process (2-3) was an isobaric one, in which, the pressure is at a constant state, thus leading to the diagram being a straight forward line since no change in pressure has occurred as noticed in the diagram. The third process (3-4) was

an isochoric process, which is a process in which no change in volume occurs, thus – for the same reason as the isobaric process – the line is a straight line, however its direction goes downwards since the constant parameter is the volume. The final process (4-1) concluding the transformation was an adiabatic process. Just like in an isothermal process, neither the change pressure of volume is zero, as such the diagram is changing in a non-constant pattern. However, it can be noticed in (Figure 13) that the line representative of the adiabatic process is steeper than that of the isothermal one, the reason for which as stated by (toppr, 2020) is that the area under the line is used to represent the work done, and the work done in adiabatic processes is higher than the one done in isothermal ones, hence the steeper curve.

Reversible and irreversible expansion of gas in isolated or open systems

Second law of thermodynamics

The second law of thermodynamics states that the total entropy of an isolated system can never decrease.



What is entropy?

Entropy relates to the amount of disorder and the randomness in the atomic movement in a system, with the higher the entropy indicating a higher degree of disorder.

Reversible processes

As stated by (cnxuniphysics, 2021), a reversible reaction in thermodynamics is a reaction in which all process parameters and the process itself can transform into a different state and then subsequently be able to return to its initial state, and is an almost idealistic process that can rarely ever occur. As well as that, according to (OpenStax College, 2021), during a reversible process entropy remains at a constant state.



Irreversible processes

An irreversible reaction in thermodynamics can't return into its exact initial form. An irreversible one is much more commonly seen, with most process that ever occur being irreversible reactions. As claimed by (OpenStax College, 2021), within irreversible processes – in contrast to reversible ones – the entropy of the process can only increase, and cannot remain constant.



Relationships to open and isolated systems

As mentioned by (Thompson, 2002), during a process occurring within an open system anything within or out of it could either leave or enter, thus causing the entropy of said system to decrease and the net entropy of the universe to increase. As such, within open systems the entropy fluctuates, resulting in any expansion being done within them to be an irreversible process.

In contrast to open systems, as stated in the second law of thermodynamics, an isolated system the entropy can never decrease due to the system being unable to react to its surroundings, thus it can be concluded that it can either remain constant or increase. As such, it can be theoretically said that with the use of the necessary insulation – albeit rare – an expansion can be deemed to be a reversible transformation.

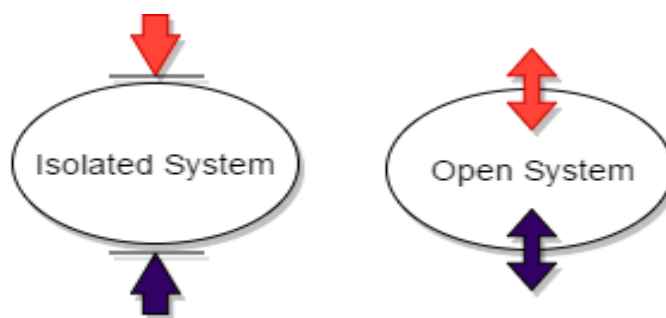


Figure 14 – The flow of energy in an isolated open compared to an open system

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“Iron and heat are... the supporters, the bases, of the mechanic arts”

-Nicolas Léonard Sadi Carnot
The father of thermodynamics