2022

Thermodynamics

Investigate applications of thermodynamic systems

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Report brief

The following report discusses the properties and differences that might be seen in open and closed thermodynamic systems. Said discussion is based on both the first and second laws of thermodynamics, which is done by discussing the stated laws and their various implications on both systems. Additionally, thorough analysis and evaluation of provided open and closed system examples was done in order to conclude how a system being open or closed might impact the process. The examples used were a piston air compressor for the open systems and the refrigeration cycle for the closed one. Additionally, the information concluded throughout the report is further backed by calculations which to deduce the efficiency of given closed and open systems, while additionally evaluating said efficiency and providing information on possible methods that could be utilized in improving it.

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Introduction to open and closed systems

What is a thermodynamic system?

A thermodynamic system refers to a selected volume or quantity of mass that has been chosen for study relative to that of the thermodynamic field. Said study includes the research of thermodynamic parameters seen within the chosen area to deduce how they might affect the process occurring in order to achieve a required or expected

Open systems

An open thermodynamics system is one that allows for the flow energy as well external parameters such as mass in and out of the boundaries surroundings the system. The keyword mass is utilized in referring to the amount of matter or material seen within the system, and example of which could be gas molecules. In a mechanical perspective, an open system could be any mechanical tool or device that lets out matter through opening such as vents or exhausts and therefore causes matter to be lost.

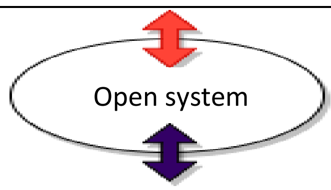
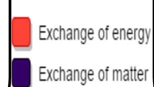


Figure 1 Open system flow of parameters



Closed systems

A closed system is not entirely the opposite to that of an open one, in that although closed systems do not allow for the transfer of matter through their boundaries as the system is enclosed; however, they do permit the flow or transfer energy through them. In a practical sense, a closed system would be a device or natural occurrence that traps all matter within, however, the boundaries or outer edges of the system do not have sufficient insulation capabilities that allow them to block the flow of energy.

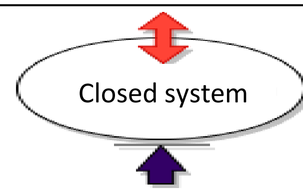


Figure 2 closed system flow of parameters

What is energy?

Energy as a whole can be seen in two different manners, as it can be either given as heat transfer or work done. Heat transfer relates to the transfer of thermal energy from either internally, in which heat transfer to the surroundings, or externally, where the surroundings transfer heat to the system. Heat itself can be transferred in three different ways, with them being conduction, which is the physical transfer of heat due to material conductivity, convection, which is the flow of gas of liquid within the system that increases molecular movement and therefore increasing thermal energy, or radiation, which is transfer of heat through air using heat waves.

The other manner in which energy is transferred – work done – related to the force exerted that is utilized to cause displacement of the system. Forces pushing the system inwards are referred to as work being done on the system, while forces exerted by the system pushing outwards are referred to as work being done by the system.

Conclusion

As such, relating to what was stated, it can be said that both closed and open systems permit the flow of exerted forces by or on the system that might cause displacement and additionally permit the flow of heat either by external objects or heat that is transferred from within the system to its surroundings. However, only open systems allow for physical molecules to pass through its boundaries.

First law of thermodynamics

First law statement

The first law of thermodynamics – more prominently known as the law of conservation of energy – states that energy cannot be created nor destroyed and is only able to be transformed from state to another, which therefore means that the energy found within the universe always remains constant.

However, in a thermodynamic perspective, the first law can be reinterpreted as stating that when a system undergoes a thermodynamic cycle then the net heat supplied to the system from its surroundings is equal to the net work done by the systems on its surroundings. Going with what was stated, it can be deduced that the first law of thermodynamics can only apply to closed systems due to a closed system's inability to exchange matter with its surroundings, and as such the net work and net heat are the only parameters that make up the energy of a closed system. In equation form, the first law of thermodynamics can be given as $\Delta E = Q - W$

Possible equations

Cyclic processes

The first law of thermodynamics mainly applies to closed system which undergo a cyclic process within them, which are processes that have an infinite number of occurrences or cycles, that is the case since both the initial and final processes seen in a cyclic process have the same internal energy, meaning the change in internal energy for the entire process is zero. As such, the first law of thermodynamics for cyclic processes can be given as $(\sum\Delta Q - \sum\Delta W = 0)$*, therefore:*

$$\sum\Delta Q = \sum\Delta W$$

Noncyclic closed processes

If the process were to be noncyclic, a final output would have to occur, and therefore the first law can be stated as the relationship between the change in internal energy, heat transfer, and work done, with the internal energy being given as (ΔE)*. The change in internal energy generally constitutes of multiple parameters, however, due to the lack of physical exchange of matter between the system and the surroundings seen in closed processes, as stated by (Club Technical , 2019), the internal energy is only equal to that of the intermolecular energy* (U)*. Therefore, internal energy of a system is equal to the net heat minus the net work done, which – in symbol form – can be given as:*

$$\Delta U = Q - W$$

Noncyclic open processes

As stated earlier, the first law of thermodynamics only applies to closed systems and not to open ones. That is the case since external parameters intervene with the process and therefore affect the state of equilibrium that closed systems are in which assists in keeping the net heat equal to the net work done.

Said parameters that intervene with the change in internal energy are – in accordance to (Club Technical , 2019) – mainly the intermolecular energy (ΔU)*, change in kinetic energy* (ΔKE)*, and change in Potential energy* (ΔPE)*. Therefore, it can be stated that* (ΔE) *is equal to the stated parameters, and therefore:*

$$\Delta U + \Delta KE + \Delta PE = Q - W$$

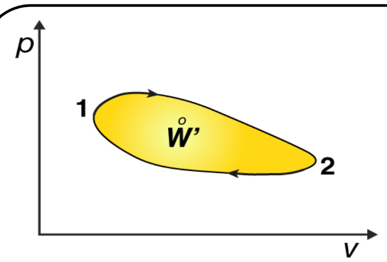


Figure 3 Cyclic process PV diagram

← **Cyclic**

Noncyclic →

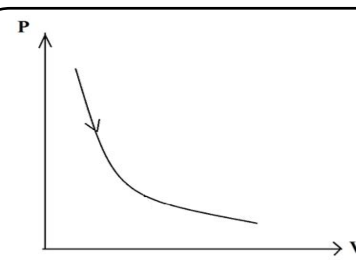


Figure 4 Noncyclic process PV diagram

Second law of thermodynamics

Second law statement

The second law of thermodynamics states that the total entropy of the universe – which is an isolated system – is only able to increase and can never decrease and therefore the change in entropy can never be negative in an isolated system. Another interpretation of the law is that due to the entropy of a system, heat can only flow from hot to cold bodies, and never the other way around.

What is entropy?

Entropy can be given as the numerical probability of molecular disorder within a system. In other words, the entropy is how statistically how likely energy will be dispersed throughout the entire system, and – according to (Phillips, 2017) – low entropy refers to the majority of the system's energy being concentrated in one location, while high entropy corelates to the fact that entropy is dispersed throughout the system and as such can be considered as disordered. The change in entropy of a system be calculated as the following:

$$\Delta S = \frac{\Delta Q}{T} \rightarrow unit: \frac{J}{K}$$

Heat flow according to the second law

As stated earlier, the general flow of heat in a thermodynamics sense is strictly from hot bodies to cold ones. Which is a phenomenon that can be acknowledged and seen commonly throughout daily lives, however, the particular reason behind it can be explained through the use of the second law and entropy.

Initially, it was assumed that in theory, energy should be able to flow from cold objects to hot ones until the concept of entropy was discovered in 1850 by Rudolf Clausius as stated by (Britanica, 2022). That is the case since with the concept of entropy, it was realized that a hot body's heat energy – a body in which its molecules have higher kinetic energy – is much more likely to flow to a colder body due to the combination of an overall higher amount of energy as well as the stated faster kinetic energy as due to said parameters, energy would much easily flow into the microstructure of the cold body's rather than the cold body's energy flowing into the microstructure of the hot body, meaning entropy increases as energy will be more dispersed, which goes in agreement with what was stated by (Phillips, 2017). And that although it is theoretically possible for energy to flow from cold bodies to hot ones, it is statistically extremely improbable to a point in which it can be deemed impossible.

Going back to the first interpretation of the law, it can be deduced that in an isolated system, entropy can only increase as energy would only be dispersed throughout the system as it is statistically impossible for energy to decrease due to the gain of energy from the hot section.

Heat flow diagram

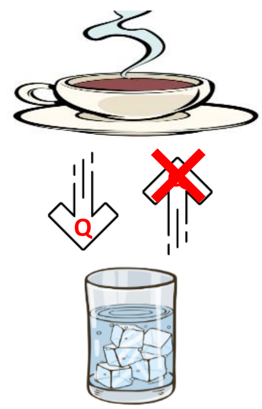


Figure 5 The flow of heat

Relation to open and closed systems

Due to the flow of external parameters through both open and closed systems, it can be deduced that the entropy in either system would be unable to maintain consistency, as said parameters would be entering and leaving the boundaries of the systems and therefore disrupting the entropy balance as it would be either increasing or decreasing. From this, it can also be determined that reversible reactions cannot be held within neither open nor closed systems since according to (Lumen, 2022), entropy within a reversible process must be maintained at a consistent manner, and as such open and closed processes are irreversible.

Conclusions

Similarities between closed and open systems

Although open and closed systems differ in a variety of ways, a certain share of similarities can be seen between the two. The first – and main – similarity that could be noticed is the fact that both systems allow for the transfer of energy through their systems, with this, it can be deduced that external properties could go through the system – unlike an isolated one – which means that there's major discussion room for system inefficiency in both systems. The other similarity that could be noticed between was recently stated, with it being that neither system is able to maintain a reversible reaction, which is the case due to neither system being able to possess the ability of keeping their entropy at a constant form.

Differences between closed and open systems

The major difference that can be noticed between either system is the fact that open systems allow for the transfer of matter through the system's boundaries, while closed systems don't. Due to the stated fact, it should also be noted that the overall mass of the system could vary over time throughout open systems while it will remain constant in closed systems since other parameters such as heat, work, pressure, temperature, etc. do not have an effect on the number of particles within the system, and therefore cannot change the mass.

Open system pros and cons

Advantages

An advantage that can be noticed when working with open systems is the fact that they lack the dependency on insulation in comparison to closed systems. although insulation might still be required in certain application, in a variety of cases it is not necessary. That is the case since energy is constantly going into the system through the use not only the energy supply, but also through the use of the natural energy that the matter flowing into the system already possesses. As such helping in decreasing the overall cost of the system or allowing for the budget to be used on other sections.

Disadvantages

Due to the fact that as well as energy matter flows through open systems, a higher potential of inefficiency would be seen as both energy and matter inefficacy would have to be taken into account due to the mechanical limitations of the systems making it so it is unable to use the full potential of the matter that has been take in. In addition, another drawback is that the calculation related to open systems are much more complicated and have a higher change of inaccuracy due to the higher chance of interference that would be caused by external effects on the system.

Closed system pros and cons

Advantages and disadvantages

The main pros and cons of closed systems are simply the opposite to that of the ones seen in the open system. In that the overall efficiency of a closed system would in general be higher in comparison to open systems due to the fewer opportunities in which energy could leave. Additionally, the calculations that might be used for closed system of lower complexity for the same reason just stated, which is the case due to the fact that when there are fewer potential of parameters flowing through the system, and therefore the overall magnitude of the calculations would be less since a fewer number of variables would have to be taken into account. In terms of the disadvantages of closed systems, it is the fact that they have a much higher dependency on insulation, and consequently resulting in an increase in the overall cost of the system.

Example of a closed system

The refrigeration cycle

The vapor compression cycle has the primary application of decreasing the temperature and cooing an environment or a given body. It is one of many refrigeration cycles that are utilized for the same application, however, it is one of the most used in comparison to the others as it utilized in a variety of known application, some of which being air conditioning, refrigerators, and heat pumps according to (Engineer Waqar, 2022).

Before the initial process starts, a gas known as the refrigerant is situated within the area in which the first process is going to operate. Said refrigerant is the main component that is utilized in the cooling process of the vapor compression cycle. The refrigerant is going to be the matter that is going to cycle through the system, which is going to be studied/analyzed. The process does not permit the transfer of matter through the boundaries of the surroundings, but rather only heat from said refrigerant is transferred, and as such the cycle can be considered to be a cyclic closed system process.

Process analysis

Refrigeration cycle diagram

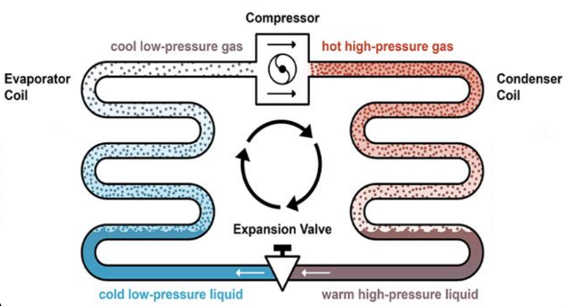


Figure 6 The refrigeration cycle

PV diagram

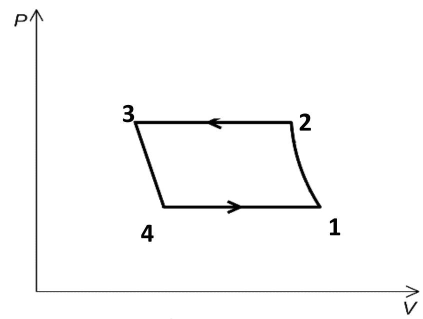


Figure 7 Refrigeration cycle PV diagram

Process 1-2	*Process 2-3*	*Process 3-4*	*Process 4-1*
Adiabatic	*Isobaric*	*Adiabatic*	*Isobaric*

Process 1-2

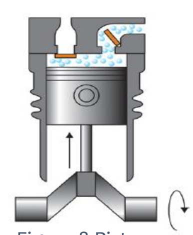


Figure 8 Piston compressing the refrigerant

The main function of the initial process is to increase the temperature of the refrigerant as said increase in temperature would be of extreme importance during the following condensation process, this would discussed in further detail during process 2-3. The compression of the refrigerant is done with the employment of a piston, which is utilized to push the gas of the refrigerant into a small area, which causes the decrease in volume and increases the pressure – as can be seen in the PV diagram – which consequently results in an increase in temperature as decreasing the pressure increases the movement rate of gas molecules which increases the thermal energy of the gas, hence the temperature increase. It should also be noted that at this point of the process the refrigerant is at its highest temperature. The manner in which compression occurs is – as stated by (Engineer Waqar, 2022) – adiabatic, which assists in the aforementioned process of increasing the temperature as external heat would not affect the process. Due to the adiabatic nature of the process (process1-2), the equation used in calculating the work done would be ($W = \frac{p1v1 - p2v2}{y-1}$) and the heat transfer (ΔQ) would be zero. Due to the process being compression, it can be deduced that work done is on the system.

Process 2-3

The second process that the refrigerant goes through is the condensation stage. Going by definition, condensation is the opposite to evaporation, in that it is the transformation of a material or substance from a gaseous to a liquid state, and therefore during this stage the refrigerant will turn from its initial gas state to a liquid. The method employed for this section is the utilization of a condenser cabinet, a component that acts as a heat reservoir as mentioned by (Engineer Waqar, 2022). A heat reservoir allows for the transfer of heat energy from the refrigerant to the reservoir's body, therefore heat is lost from the refrigerant, meaning 'Q' would be negative, this causes the refrigerant's temperature to decrease and for it to turn into a liquid, which consequently means that the refrigerant will take up a smaller area, thus leading to the decrease in volume as well as temperature, which can be noticed from the PV diagram. As stated earlier, the compression process (process 1-2) is done to assist in the condensation process, that is the case sine – as stated by (Evans, 2015)– the decrease in temperature caused during the compression process ensures that the temperature of the refrigerant would be higher than that of the heat reservoir, which is essential when requiring efficient transfer of heat, which in this case is needed to turn the refrigerant into its liquid state. Overall, the condensation process is isobaric since the gained pressure caused from the decrease in volume is equivalent to the gained pressure caused by the increase in temperature, and therefore the equation utilized when calculating that work done is ($W = P(V3 - V2)$), the work done itself would be done on the system as V3 is smaller than V1. In terms of heat transfer, ($Q = \Delta U + W$) would be used.

Process 3-4

Process 3-4 is known as the throttling process as mentioned by (Engineer Waqar, 2022). The process employs a component known as a throttling valve, the function of said components is to restrict the flow of fluid by narrowing down the cross-sectional area of the fluid by pushing down a thread into the pipe in which the fluid flows, with the amount of volume the valve takes up being dependent on how much it has been turned. This process of obstructing the flow of fluid is known as the Venturi constriction, which is an affect which states that whenever the flow of fluid is restricted, said fluid would have to increase its velocity throughout the restricted area in order to flow through it, and if not, the flow would simply cease. According to Bernoulli's principle, the increase in velocity of the fluid – which in this case is caused by the Venturi constriction/throttling valve – works in inverse proportions to pressure, in that due to the increase in the refrigerant's flow rate, the overall pressure of the fluid decreases, additionally, due to the decrease in pressure, both temperature and volume decrease, which can be noticed from the PV diagram. This also decreases the temperature as the decrease in pressure would less result in a lower colliding potential between the refrigerant's particles, which in consequence decrease the thermal energy and temperature of the liquid. The heat transfer and overall enthalpy change during the throttling process is maintained at a consistent manner as stated by (Byju's, 2022), therefore the process can be defined as an adiabatic expansion, and therefore the heat transfer (ΔQ) would be zero. In addition, in order to calculate the work done, the following equation would be utilized: ($W = \frac{p1v1 - p2v2}{y-1}$). Due to the process being an expansion of the fluid, it can be deduced that work is done by the system.

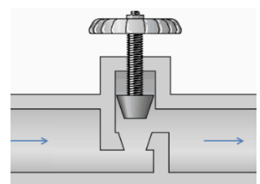


Figure 9 Throttling valve

Process 4-1

The final process – also known as the evaporation process – is similar to that of process 2-3, in that it also involves the transfer of heat from the refrigerant to a reservoir. During the process, the refringent goes into a section of the vapor compressor known as the evaporator as mentioned by (Engineer Waqar, 2022). A cold reservoir – which is a body that maintains a high temperature – is located within the evaporator and transfers heat to the liquid refrigerant, meaning 'Q' would be positive. After the absorption of the refrigerant to the heat, it evaporates and turns back into initial gas form. Just as seen earlier, the decrease in pressure from process 3-4 was essential to ensure efficient absorption of the heat as decreasing the temperature makes certain that the refrigerant would be at a sufficient temperature so that the entire volume of the fluid absorbs the heat. As can be noticed from the PV diagram and as stated by (Engineer Waqar, 2022), a change in both the enthalpy and volume occur, however, the pressure remains constant due to same affect that occurs in process 2-3 occurring here although occurring in opposite fashion, in that the lost pressure due to the increase in volume is equivalent to the gained pressure due to the increase in temperature, and therefore ($W = P(V1 - V4)$) would be used for the work done and ($Q = \Delta U + W$) would be used for the heat transfer. In terms of the work done, it can be calculated that it will be work done by the system as V1 is bigger than V4.

Closed system calculations

The Stirling engine

The process that is going to be utilized for the following calculation analysis is the Stirling engine, that is the case since it is generally considered as one of the main icons used in representing thermodynamic calculations and overall theory as it is well documented and is able to easily convey closed system processes.

In terms of the engine itself, it is defined as a cyclic closed system and is a mechanical application that operates by compressing and expanding a fixed quantity of gas – hence why it's a closed system – which in consequence causes a pushing and pulling movement which is generally utilized to rotate a wheel which could then be used in operating a variety of mechanical tools, some of which being pistons.

The reason the following calculations are done is to calculate the overall efficiency and determine the flow of energy parameters through the system, and as such, the following parameters are going to be calculated: ***Work done, Energy loss, Output energy, Energy transfer,*** *and* ***Efficiency.***

Stirling engine image

Figure 10 Miniature Stirling engine

PV diagram

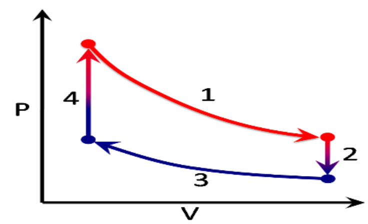


Figure 11 Stirling engine cycle's PV diagram

Process 1-2	Process 2-3	Process 3-4	Process 4-1
Isothermal	isochoric	isothermal	isochoric

Given parameters

R = $2077\frac{J}{kg \cdot K}$ **C$_v$** = $717\frac{J}{kg \cdot K}$ **T$_{hot}$** = 850K **T$_{cold}$** = 353K

V$_{max}$= 0.6m^3 **V$_{min}$**= 0.4m^3

Work done:

$$W_{out} = mRTln\left(\frac{V2}{V1}\right) \rightarrow \text{Work done formula in isothermal processes (Process 1 - 2)}$$

$$W_{out} = 1 \times 2077 \times 850 \times \ln\left(\frac{0.6}{0.4}\right) \rightarrow \text{Substitution, } T_{hot} \text{is used as heating occurs during compression process}$$

$$W_{out} = 715828.3751J \rightarrow KJ = 715828.3751 \div 1000$$

$$\boxed{W_{out} = 715.83KJ}$$

Calculating the energy loss:

$W = mRT\ln\left(\frac{V4}{V3}\right)$ → Work done formula in isothermal processes $\left(\text{Process } 3-4, \text{hence} \frac{V4}{V3}\right)$

$W = 1 \times 2077 \times 353 \times \ln\left(\frac{0.4}{0.6}\right)$ → Substituion, T_{cold} is used as process 3 to 4 is expansion ∴ endothermic process

$W = -297279.3134J \rightarrow KJ = -297279.3134 \div 1000$

$\boxed{W = -297.28KJ}$ → The answer is given in negative since energy is lost

Output energy:

$Q_{in} = Q_{out} + Q_{loss}$ → Total energy gained is equal to wasted energy minus useful work

$Q_{out} = Q_{in} - Q_{loss}$ → Rearrange to make output energy the subject

$Q_{out} = 715828.3751 - 297279.3134$ → $\sum \Delta Q = \sum \Delta W$ in cycic processes ∴ $W_{in} = Q_{in}$

$Q_{out} = 418549.0617J \rightarrow KJ = 418549.0617 \div 1000$

$\boxed{Q_{out} = 418.55KJ}$

Energy transfer:

$Q = mC_v\Delta T$ → The equation used for finding heat transfer throughout a given process

$Q = 1 \times 717 \times (850 - 353)$

$Q = 356349J \rightarrow KJ = 356349 \div 1000$

$\boxed{Q = 356.35KJ}$

Efficiency:

$\eta = \frac{Q_{out}}{W_{in}}$ → Efficiency equation, the ratio of provided energy and meaningful utilized energy

$\eta = \frac{418549.0617}{715828.3751}$ → $\sum \Delta Q = \sum \Delta W$ in cycic processes ∴ $W_{out} = Q_{out}$

$\eta = 0.5847058824 \rightarrow \% = 5847058824 \times 100$

$\boxed{\eta = 58.5\%}$

Efficiency according to the second law:

$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}}$ → Formula for efficiency using the second law, ratio of lost heat over inital heat

$\eta = \left(\frac{850 - 353}{850}\right) \times 100$

$\boxed{\eta = 58.5\%}$ → As the number is the same as the one found earlier, it can be made sure of that the system is closed

Efficiency evaluation

Causes and significance

As can be noticed, the amount of efficiency that has been calculated from the Stirling engine is at 58.5%, which – when looked at solely – seems to be relatively alright, however, 41.5% of the provided energy input is not being utilized in producing useful work, but rather it is being lost and is going to useless aspects of the systems, with the major reason to which being that the heat simply leaves the systems as thermal energy without being converted into useful work, which is the case due to friction, as when the piston or wheel that is operated rubs onto another solid surface, friction is produced, which in consequence transforms the potentially useful kinetic energy of the wheel back into thermal energy In addition to that, issues such as high dead volumes could also decrease the overall efficiency percentage.

As stated, although the given percentage might not seem bad, it does not excuse the fact that the overall efficiency is relatively low and could certainly be improved. The major drawbacks to low efficiency are significant, with them being that much more energy would be required in order to produce a require amount of work, as in if it was hypothetically required for the machine to produce 150Kj, then around 600Kj of energy would have to be inputted. This amount of energy being lost means that both time and money would be wasted in producing a given amount of work when put in comparison against a more efficient engine.

Efficiency improvement methods

Dead volume reduction

The dead volume is the empty space in which gas gets trapped in and is not utilized for performing work on the piston which in consequence decreases the overall efficiency as it is not being converted to any meaningful form of energy. The main method that could be used in order to fix this issue is to make the hot, cold, and overall piston compartment as small as possible as to minimize the dead volume. In addition to that, certain types of Stirling engines have additional openings in the piston compartment that might be for additional operation of the crankshaft, something like the connection tube seen in gamma Stirling engines. These openings should also be kept as small as possible in order to decrease the amount of overall gas that might be trapped in them, and to ensure that the majority of the gas is being utilized for performing meaningful work.

Lubrication

As stated earlier, one of the main areas in which energy is lost is due to conversion of potentially useful kinetic energy to thermal energy as a consequence of frequency. As such, in order to reduce this effect, the main method that would be used is to simply lubricate section of the Stirling engine that might generate thermal energy as a cause of friction. The major areas which would require lubrication are the rod which connects the piston/displacer of the Stirling engine to the crankshaft as well as the flywheel itself since both of the stated components have a crucial part in ensuring the operation of the system as they are directly tied to the function of the Stirling engine. This would minimize potential friction in the most effected and therefore ensure that most energy that is being converted converts to kinetic energy that would be used in producing useful work.

Increased temperature difference

Due to the fact that the Stirling engine's operation and main movement depends on the heating and cooling of the provided gas, it should be stated that increasing the difference between T_{cold} and T_{hot} will increase the overall useful work done by the Stirling engine, as increasing the temperature of the hot side will cause a higher gas expansion, while cooling the gas at a faster and more efficient manner will push the piston further downwards. A method of doing the stated change is – as stated by (GlevoTec, 2016) – to change the traditional cooling method of utilizing a heat sink and a fan to something more efficient such as water cooling, which operates by pushing water onto the surface of the cold side and therefore acts as a heat reservoir for the gas to transfer its thermal energy to, which acts in a much more efficient manner in comparison to that of the traditional air cooling. While the stated change to water cooling assists in decreasing the cold side's temperature, the hot side has yet to be discussed. The method in which the temperature of the hot side could be increased is by simply utilizing a stronger fuel source, this could range from a variety of operations, some of which being the use of better fuel and by utilizing a device which outputs higher heat energy such as a blow torch. Additionally, insulating the area of the heat source will ensure that the heat provided will not be absorbed by the surroundings, therefore the majority of the heat produced will be absorbed by the system only, which would assist in increasing the temperature.

Example of an open system

Single stage piston air compressor

The example that is going to be utilize in order to represent a closed system's is a single state piston air compressor. Generally speaking, an air compressor is a device that sucks in air from its surroundings and compresses it by decreasing the overall volume in which the trapped gas is held. Following that, the gas is released while it is held at the lower volume, which in consequence causes the gas to be realized at a high pressure compared. And due to the stated process, it can be determined that an air compressor is an open system as it takes in air from it surroundings and therefore matter – which in this case is the air molecules – passes through the boundaries of the system and into the process in which the process is going to occur.

A single stage air compressor follows the same principles that were just stated, however, according to (BigRentz, 2020), it does so by utilizing a piston to compress the gas. The term "single stage" refers to the fact that the air is compressed only once per cycle, in comparison to other types of compressors that follow multiple stages that compress that air which provide and overall higher pressure.

Compressor diagram

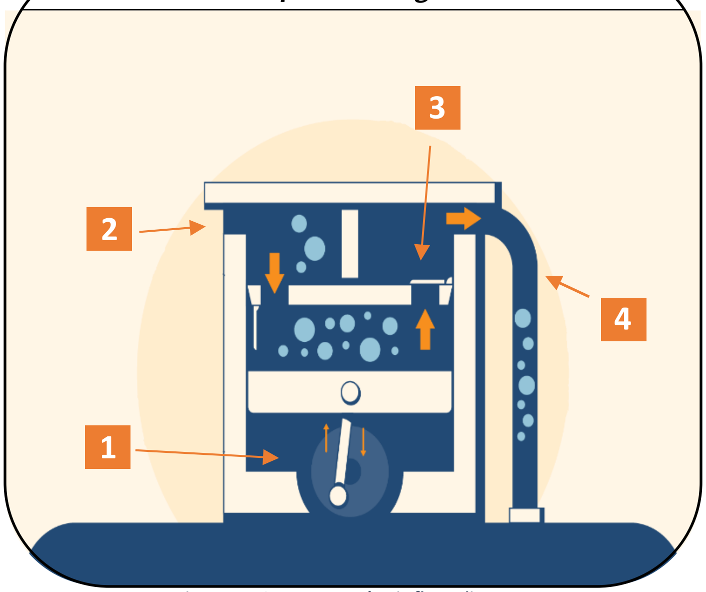


Figure 12 Compressor's air flow diagram

1: *Rotating mechanism moving a piston utilized to compress gas.*

2: *Entry valve used to allow the air to enter whenever the piston pulls back.*

3: *Exit valve that opens whenever the piston pushes upwards.*

4: *Exit tube that takes the compressed air to the required destination.*

Process analysis

PV diagram

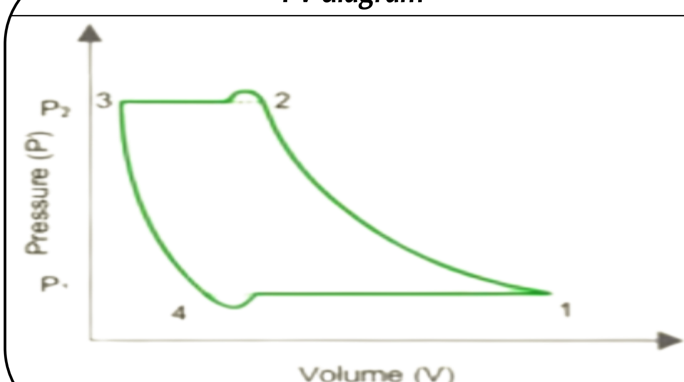


Figure 13 Air compressor PV diagram

1-2	2-3	3-4	4-1
Polytropic	*isobaric*	*Polytropic*	*isobaric*

Process 1-2

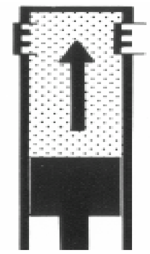


Figure 14 Gas compression

During process 1-2 is when the compression procedure occurs, as it is the point where piston pushes the air and into a relatively small area, therefore decreasing the volume which in consequence means work is done on the system which leads to an increase in the pressure. Although a variety of compression processes could occur during process 1-2, the one that is mostly seen in real world applications and test is a polytropic compression in accordance to (Coker, 2014) , and therefore the work done in this part of the process can be found using ($w = \frac{p1v1-p2v2}{n-1}$) with the work being done on the system due to the process being the compression of gas. The other possible types of compression processes would be either isothermal or adiabatic compression, however, the reason most compression processes are polytropic is due to the fact that in real life applications, most compression processes and devices do not have the consistency nor stability to block the transfer of heat or to maintain temperature consistency as that which would be seen in adiabatic or isothermal processes, but rather said process would usually be in a range seen somewhere in the middle of adiabatic or isothermal, which comes in the form of a polytropic process.

Process 2-3

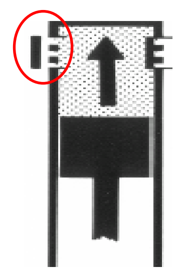


Figure 15 Discharge valve opening

The second section of the process is when the pressurized air is released through the valves of the compressor and onto the surroundings of the system. For the most part, this process involves the isobaric discharge of air, however, as can be noticed from the PV diagram, an initial spike in the pressure occurred during the discharge, said spike occurred due to the valves seen in (figure 2) at the top of the compressor initially limiting the flow of air as the air would have to push them in order to flow through the opening while the piston is additionally decrease the volume and increasing the pressure, which consequently increases the delivery pressure of the air for that duration where the air would have to push open the valves as stated by (Supreme_Engineer, 2017), which consequently causes the observed spike in pressure. After which, the rest of the process is – as stated earlier – isobaric after the gas initially leaves through the outlet valve which is what causes the spike, the gas remaining inside the system that has not left remains at the same pressure, and therefore the heat transfer could be found using ($Q = \Delta U + W$), and ($W = P(V3 - V2)$) for the work done, however, the spike would have to be taken into account when conducting accurate analysis. In terms of the work done, it can be worked out that it will be done on the system as V3 is smaller than that of V2.

Process 3-4

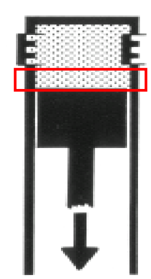


Figure 16 clearance area

Process 3-4 is during the retreating stage of the piston, said stage is also when the piston carries all the air that it has captured from the opening valve as it is retreating. The line seen representing process 3-4 refers to the polytropic expansion of gas, which is the case for the same reason stated in process 1-2. Ideally, process 3-4 would be isochoric to preserve the pressure of the captured gas, however, the reason to which it is not can be seen in (figure 3). As can be noticed, the piston does not go all the way upwards towards the valves, but rather it stops slightly under, meaning that there is a small room in which compressed gas is stationed at the top of the compressor, which is the gas that is captured and is going to be compressed by the piston, according to (Supreme_Engineer, 2017), the stated area in which the gas is held is known as the clearance bump, and during retreating process of the piston, the gas within it expands, and therefore causing slight inefficiency as the volume would increase, which in consequence decreases the pressure. In terms of calculating the work done by the system during the process, the same equation utilized in process 1-2 could be seen here as both processes are considered to be polytropic, however, here work is done by the system rather than on it since the final volume is bigger in comparison to the initial one.

Process 4-1

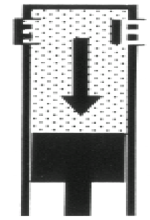


Figure 17 Opened inlet valve during suction

The last process of the cycle – process 4-1 – represents the stored volume of air that has been taken into the compressor after the inlet valve has opened when during suction process at process 3-4 as can be seen in (figure 4). As can be noticed from the PV diagram, the majority of the process is isobaric, which can be deduced from the line being straight, however, just like the discharge process (process 2-3), a slight decrease spike in the pressure can be noticed. The reason for said spike is the same as the one seen in the discharge process with the difference being that this time the valve causing the spike is the one that the air enters the compressor from rather than the one that is utilized for the discharge of air, which means that an increase in volume would occur as the suction valve opens, and therefore decrease the pressure. In terms of finding the work done during the process, $(W = P(V1 - V4))$ *and* $(Q = \Delta U + W)$ *for the heat transfer. It can also be concluded that the work is done by the system as V1 is bigger than V4. The stated work done formula could be utilized for the majority of the process as it is isobaric since there is no compression nor expansion occurring to the overall volume as the piston is simply held in place, however – just like process 3-2 – the decreasing spike in pressure would have to be taken into account if accurate analysis were to be necessitated.*

Open system calculations

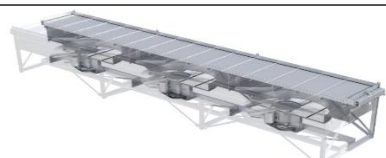
Air-cooled heat exchanger

An air-cooled heat exchanger is a relatively simple mechanism that pushes air with the use of a number of fans onto the system that allows for the flow of a liquid through its boundaries, hence it being considered an open system. Said operation is done in order to allow for the transfer or "exchange" of heat from the flowing liquid onto the air that is being blown onto the liquid, which accordingly decreases the temperature of the liquid.

The following calculations are going to focus on determining the ***Work done, energy transfer,*** *and* ***efficiency****.*

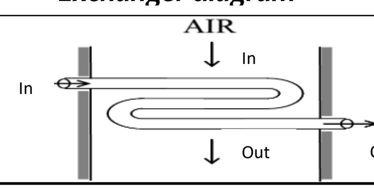
Cross-sectional view

Figure 18 Cross section view of an air cooled heat exchanger



Exchanger diagram

Figure 19 Flow of air in the heat exchanger



Given parameters

Q$_{in}$ = 500KJ **Cp** = $1\frac{KJ}{Kg \cdot K}$ **V** = 0.6m^3 **T**$_{hot}$ = 450K **T**$_{cold}$ = 323K

<u>Work done:</u>

$\boxed{W = 0}$ → An air cooled heat exchanger simply allows for the transfer of heat, and said transfer does not cause any impact on the given volume pipes in which the fluid flows is fixed, due to the that, it can be deduced that the overall work done (W_{in} and W_{out}) is equal to zero.

Energy transfer:

$E_{in} = E_{out}$ → original equation (E represents energy)

$H_{in} + Q_{in} + W_{in} = H_{out} + Q_{out} + W_{out}$ → $E = H + Q + W$

$Q_{in} = 0$ and $W = 0$ → $Q_{in} = 0$ since heat goes from hot to cold objects only − second law (From the fluid to the air)

$\therefore H_{in} = H_{out} + Q_{out}$

$Q_{out} = H_{in} - H_{out}$ → Rearrange to make energy transfer the subject

$Q_{out} = mC_pT_{in} - mC_pT_{out}$ → $H = mC_pT$

$\therefore Q_{out} = mC_p\Delta T$

The shown equation cannot be used as the mass is unabaible, meaning it would have to be found before proceeding

$m = \rho \times V$ → mass is equal to density times the volume

$m = 1.225 \times 0.6$ → density of air $= 1.225\text{kg/m}^3$

$m = 0.735\text{Kg}$

Now that the mass is known, the previously shown equation could be utilized

$Q_{out} = 0.735 \times 1 \times (450 - 323)$

$\boxed{Q_{out} = 93.345\text{KJ}}$

Energy loss:

$Q_{in} = Q_{out} + W_{out}$ → Total energy gained is equal to wasted energy minus useful work

$Q_{loss} = Q_{in} - Q_{out}$ → Rearrange to make the energy loss the subject

$Q_{loss} = 500 - 93.345$

$\boxed{Q_{loss} = 406.655\text{KJ}}$

Efficiency:

$\eta = \dfrac{Q_{out}}{Q_{in}}$ → Efficiency equation, the ratio of useful utilzed energy and the total gained energy

$\eta = \dfrac{93.345}{500}$ → Efficiency equation, the ratio of useful utilzed energy and the total gained energy

$\eta = 0.18669 \times 100$ → To change from decimal to percentage

$\boxed{\eta = 18.7\%}$

→ The final efficiency percentage is relatively very low, which backs the disadvantage stated earlier of open systems being worse in terms of efficiency due to the increased potential of energy loss

Efficiency evaluation

Causes and significance

As can be deduced, the overall efficiency of the heat exchanger is extremely low at only …%, and therefore …%, of the provided energy is simply wasted. Although there are a variety of reason as to why this could occur, some of which being the fact that heat is being added to the air being blown onto the fluid from external sources, which in consequence decreases the overall amount of heat that the fluid can transfer into the blown air. In addition to that, the utilized fans for the exchanger can potentially be the cause of the inefficiency, as certain types fan designs might be less efficient and in consequence utilize more power but end up producing lower airflow.

The very low efficiency of the system and overall magnitude of energy that is being lost is relatively significant, and would potentially lead to both a power and possibly financial deficit in the long term of the system because the overall power being used would be too high for the amount of actual

Efficiency improvement methods

Adding insulation

As stated, one of the major issues that causes the inefficiency of the system is the fact that the external sources transfer their heat to the blown air, which increases the air's temperature, and decreases the potential dissipation of energy from the fluid to the air. The main method to counteract this issue is to simply insulate the interior of the system towards the side of the fans. As such, less energy is being provided from the surroundings of the system, which consequently allows for the blown air to maintain a cool temperature. Although it was also stated that insulting open systems is not always necessary, it will nonetheless prove its value when used in an air-cooled heat exchanger

Using more efficient fans

Due to the fact that the main source of the air that is being blown onto the fluid is the fans, it should come with no surprise that the efficiency of the fans utilized is of extreme importance to the overall efficiency of the system. That is the case since – as stated by (Boes, 2017) – using higher efficiency fans with improved aerodynamics such tapered fans made out of better material would be able to increase the overall airflow being provided in comparison to straight bladed fans. An example of a type of material that could be utilized is Fiberglass Reinforced Plastic as the material is lighter which means less power is going to be consumed to rotate it, and therefore resulting in an increase in the overall efficiency.

Efficiency comparison

Open system efficiency

The efficiency gotten from the air-cooled heat exchanger was deduced to be 18.7%, meaning a vast and significant section of the energy gained is lost.

Closed system efficiency

The efficiency of the Stirling engine was calculated to be around 58.5%, which although is not great, it isn't necessarily bad either.

Verdict

As can be deduced, overall, the efficiency provided by the closed system is rather much higher in comparison to that of the open one, which goes in agreement with what was stated within the advantages section, in that due to the increased amount of potential energy loss caused by the ability of matter to flow through the boundaries of the system, more energy is likely to be lost. The stated issue can be even further reinforced when considering that the air-cooled heat exchanger is a simpler mechanism with fewer operations in comparison to that of the Stirling engine, meaning there are a smaller number of opportunities in which energy could be lost, nevertheless is still provided higher inefficiency.

References

BigRentz. *(2020, January 3).* How Air Compressors Work: An Animated Guide*. Retrieved from bigrentz: https://www.bigrentz.com/blog/how-air-compressors-work*

Boes, S. *(2017, January).* Improve Air-Cooled Heat Exchanger Performance*. Retrieved from chartindustries: https://files.chartindustries.com/ImproveACHXPerformance.pdf*

Britanica. *(2022).* entropy*. Retrieved from britannica: https://www.britannica.com/science/entropy-physics*

Byju's. *(2022).* What Is Throttling Process In Thermodynamics*. Retrieved from byjus: https://byjus.com/jee-questions/what-is-throttling-process-in-thermodynamics/*

Club Technical *. (2019, March 10).* First Law of Thermodynamics [Open and Closed Systems]*. Retrieved from clubtechnical: https://clubtechnical.com/first-law-of-thermodynamics*

Coker, A. K. *(2014).* Ludwig's Applied Process Design for Chemical and Petrochemical Plants*. Elsevier.*

Engineer Waqar. *(2022).* How does a Refrigeration Cycle work? | What is Refrigeration? *Retrieved from mechanicalboost: https://mechanicalboost.com/refrigeration-cycle/#What_is_Refrigeration_Cycle*

Evans, P. *(2015, June 7).* Refrigeration cycle, essential knowledge*. Retrieved from theengineeringmindset: https://theengineeringmindset.com/the-refrigeration-cycle-essential-knowledge/*

GlevoTec *(Director). (2016).* 6 ways to get more power from your stirling engine | Create a powerful stirling engine *[Motion Picture].*

Lumen. *(2022).* Entropy and the Second Law of Thermodynamics: Disorder and the Unavailability of Energy*. Retrieved from lumenlearning: https://courses.lumenlearning.com/physics/chapter/15-6-entropy-and-the-second-law-of-thermodynamics-disorder-and-the-unavailability-of-energy/*

Phillips, J. *(2017).* What is entropy? - Jeff Phillips*. Retrieved from ed.ted: https://www.youtube.com/watch?v=YM-uykVfq_E*

Supreme_Engineer *(Director). (2017).* Air Compressor Operating principle *[Motion Picture]. Retrieved from https://www.youtube.com/watch?v=z7ObXfn9Q9g*

“Accurate and minute measurement seems to the non-scientific imagination, a less lofty and dignified work than looking for something new. But nearly all the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labor in the minute sifting of numerical results.”

-Sir William Thomson

Inventor of the absolute temperature system, Kelvin