

ATKINSON-STIRLING ENGINE

[Paritosh Rustogi, Rahul Chhabra, Shivang Batra]

Abstract—In Atkinson engine, residual heat in the form of exhaust is quite a fraction of the energy produced in the combustion of gasoline. With an ever increasing demand for fossil fuels depleting their reserves to their limit, there is an inherent need for better engines which can utilize residual heat. ATKINSON-STIRLING ENGINE can be the solution to this problem. The heat exchanged with the refrigeration system in which R-12 is the working fluid is used to power the Stirling engine; however gasoline is used for the initiation of the process. We intend to make normal gasoline powered engine more efficient, green and cheaper in the long run.

Keywords— Atkinson Engine, Stirling Engine, R-12, Thermal Sensor, Vapour compression.

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INTRODUCTION:

The name ‘ATKINSON-STIRLING ENGINE’ stands for the conflation of ATKINSON engine and STIRLING engine along with Vapour compression cycle. Atkinson engine works on gasoline while the working fluid of Stirling engine is helium and R-12 is used to relay the residual heat from Atkinson engine to Stirling engine via vapour compression cycle.

ATKINSON ENGINE:

The original Atkinson engine allowed the intake, compression, power, and exhaust strokes of the four-stroke cycle to occur in a single turn of the crankshaft [2]. Due to the unique crankshaft design of the Atkinson, its expansion ratio can differ from its compression ratio and, with a power stroke longer than its compression stroke, the engine can achieve greater thermal efficiency than a traditional petrol engine based on the Otto cycle [1]. Nowadays, many modern engines use unconventional valve timing to produce the effect of a shorter compression stroke/longer power stroke, thus realizing the fuel economy improvements the Atkinson cycle can provide but Atkinson has a lower power density than Otto engines [1].

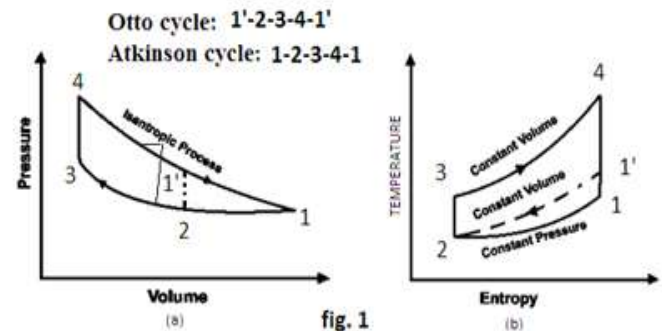


Fig. 1: Otto cycle, Atkinson cycle

In this cycle the isentropic expansion of an Otto cycle is further allowed to proceed to the lowest cycle pressure so as to increase the work output. With this modification the cycle is known as Atkinson cycle. The cycle is shown on p-v and T-s diagrams in Fig. 1. Processes involved are: [1] [14]

Process 1-2: Constant pressure heat rejection.

Process 2-3: Reversible adiabatic compression (v_2 to v_3).

Process 3-4: Constant volume heat addition.

Process 4-1: Reversible adiabatic expansion (v_4 to v_1).

For any state in the cycle,

$$P v = RT \quad (1)$$

$$\text{Heat Supplied} = C_v (T_4 - T_3) \quad (2)$$

$$\text{Heat Rejected} = C_p (T_1 - T_2) \quad (3)$$

We Know,

$$\gamma = C_p/C_v \quad (4)$$

$$\text{Work In} = (P_2 v_2 - P_3 v_3) / (\gamma - 1) \quad (5)$$

$$\text{Work Out} = (P_4 v_4 - P_1 v_1) / (\gamma - 1) \quad (6)$$

$$\text{Thermal Efficiency, } \eta_{th} = 1 - \gamma (T_1 - T_2) / (T_4 - T_3) \quad (7)$$

$$\text{Let Compression Ratio } r_c = v_2/v_3 \quad (8)$$

$$\text{Expansion Ratio } r_e = v_1/v_4 \quad (9)$$

For Adiabatic Processes,

$$P_2 v_2^\gamma = P_3 v_3^\gamma \quad (10)$$

$$P_4 v_4^\gamma = P_1 v_1^\gamma \quad (11)$$

$$P_2^{1-\gamma} T_2^\gamma = P_3^{1-\gamma} T_3^\gamma \quad (12)$$

$$P_4^{1-\gamma} T_4^\gamma = P_1^{1-\gamma} T_1^\gamma \quad (13)$$

For Isochoric Processes,

$$T_3/P_3 = T_4/P_4 \quad (14)$$

For Isobaric Processes,

$$T_1/v_1 = T_2/v_2 \tag{15}$$

$$Q_{41} = -C_v(T_1 - T_2); W_{41} = 0 \tag{19}$$

$$\eta = 1-T_3/T_2 \tag{20}$$

STIRLING ENGINE:

Stirling engine is a heat engine [7] operated by cyclic compression and expansion of air or other gas, the working fluid, at different temperature levels such that there is a net conversion of heat energy to mechanical energy or, a closed-cyclic regenerative heat engine with a permanently gaseous working fluid, where closed-cycle is defined as a thermodynamic system in which the working fluid is permanently contained within the system and regenerative describes the use of a specific type of internal heat exchanger and thermal store, known as the regenerator [3]. It is the inclusion of a regenerator that differentiates the Stirling engine from other closed cycle hot air engines. The p-v and t-s diagrams of Stirling engine are shown in fig. 2 Advantages of Stirling engine:

- High efficiency compared to steam engines.
- Quiet operation
- Compatibility with alternate and renewable energy sources has become increasingly significant due to rising prices of conventional fuel and global warming.

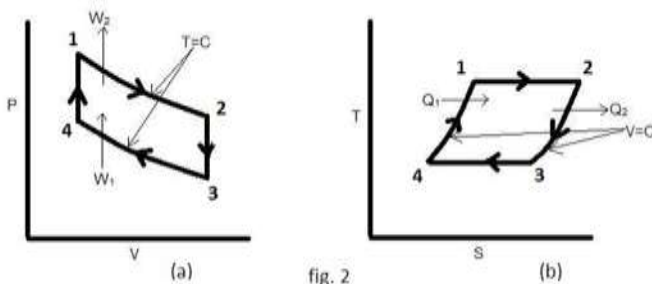


Fig. 2: Stirling cycle

WORKING: [3]

1. Power piston has compressed the gas, the displacer piston has moved so that most of the gas is adjacent to the hot heat exchanger.
2. The heated gas increases in pressure and pushes the power piston to the farthest limit of the power stroke.
3. The displacer piston now moves, shunting the gas to the cold end of the cylinder.
4. The cooled gas is now compressed by the flywheel momentum. This takes less energy, since its pressure drops when it is cooled.

Different strokes of Stirling engine are shown in fig. 3.

$$Q_{12} = W_{12} = RT_1 \ln (v_2/v_1) \tag{16}$$

$$Q_{23} = -C_v(T_2 - T_1); W_{23} = 0 \tag{17}$$

$$Q_{34} = W_{34} = -RT_2 \ln (v_3/v_4) \tag{18}$$

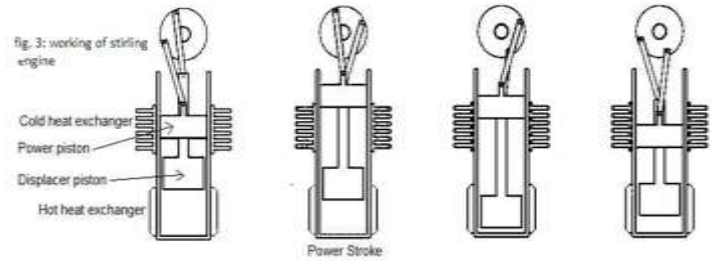


Fig. 3: Working of Stirling engine

VAPOUR COMPRESSION CYCLE: [4]

The vapour-compression system uses a circulating liquid refrigerant as the medium which absorbs and extracts heat from the space to be cooled and subsequently emits that heat elsewhere. It consist of four components: a compressor, a condenser, a thermal expansion valve (also called a throttle valve), and an evaporator. Circulating refrigerant enters the compressor in the thermodynamic state known as a saturated vapour and is compressed to a higher pressure, resulting in a higher temperature as well. The hot, compressed vapour is then in the thermodynamic state known as a superheated vapour and it is at a temperature and pressure at which it can be condensed with either cooling water or cooling air. That hot vapour is routed through a condenser where it is cooled and condensed into a liquid by flowing through a coil or tubes with cool water or cool air flowing across the coil or tubes. This is where the circulating refrigerant rejects heat from the system and the rejected heat is carried away by either the water or the air (whichever may be the case).

The condensed liquid refrigerant, in the thermodynamic state known as a saturated liquid, is next routed through an expansion valve where it undergoes an abrupt reduction in pressure. That pressure reduction results in the adiabatic flash evaporation of a part of the liquid refrigerant. The auto-refrigeration effect of the adiabatic flash evaporation lowers the temperature of the liquid and vapour refrigerant mixture to where it is colder than the temperature of the enclosed space to be refrigerated.

The cold mixture is then routed through the coil or tubes in the evaporator. A fan circulates the warm air in the enclosed space across the coil or tubes carrying the cold refrigerant liquid and vapour mixture. That warm air evaporates the liquid part of the cold refrigerant mixture. At the same time, the circulating air is cooled and thus lowers the temperature of the enclosed space to the desired temperature. The evaporator is where the circulating refrigerant absorbs and removes heat which is subsequently rejected in the condenser and transferred elsewhere by the water or air used in the condenser.

To complete the refrigeration cycle, the refrigerant vapour from the evaporator is again a saturated vapour and is routed

back into the compressor. The cycle is shown on p-v and T-s diagrams in Fig. 4 [4]

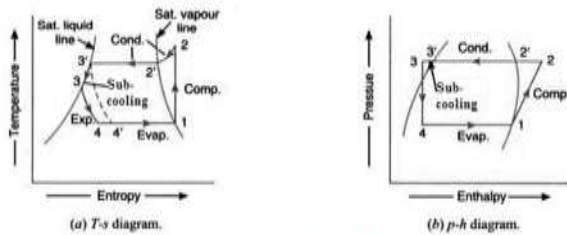


fig. 4: vapour compression cycle

Fig. 4: vapour compression cycle

$$h_{3'2'} = h_{2'} - h_{3'} \tag{19}$$

$$h_{41} = h_1 - h_4 \tag{20}$$

$$h_3 = h_4 \tag{21}$$

$$s_1 = s_2 \tag{22}$$

Let, $\gamma_r = C_p / C_v \tag{23}$

Sensible Heat (Superheated) = $C_v (T_2 - T_{2'}) \tag{24}$

Sensible Heat (Sub-cooled) = $C_v (T_{3'} - T_3) \tag{25}$

Adiabatic Compression Work = $(P_2 v_2 - P_1 v_1) / (\gamma_r - 1) \tag{26}$

OPEN CYCLE:

The Atkinson engine (2) used, works on the 4-stroke mechanism: Suction, Compression, Power/ Combustion, and Exhaust [2]. The combustion stroke provides the initial power.

Due to combustion, the exhaust gases escape out through the outlet valve and are fed into the evaporator (E) of vapour compression cycle [4] for heat addition as shown in fig. 5 and this residual heat is further used in the processes of vapour compression cycle. Still some residual heat is left in exhaust of Atkinson which will be used in Stirling engine [3] and the exhaust, after through Stirling is emitted into atmosphere.

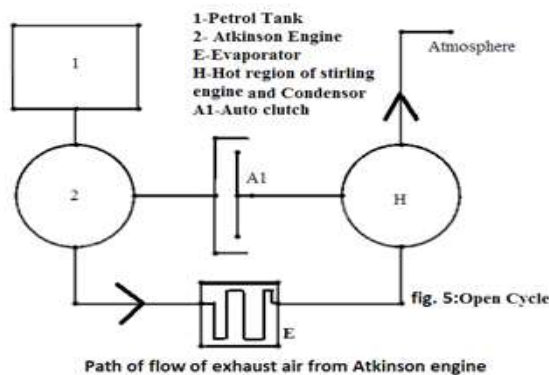


Fig. 5: Open cycle

CLOSED CYCLE:

The vapour compression cycle, whose working fluid is R-12 (Dichlorodifluoromethane), is connected to the Atkinson engine and Stirling engine via heat exchangers (R-12 is used as working fluid because it has the maximum temperature range available from the list of commonly used refrigerants, therefore the work output range of Stirling also increases). The exhaust of Atkinson engine exchanges its heat via heat exchanger with evaporator (E) of vapour compression cycle giving R-12 the desired heat so that it can reach its saturated vapour state at constant temperature. This saturated vapour is then fed in compressor (C) of vapour compression cycle so that it can reach superheated stage (now both the temperature and pressure of R-12 has increased) , the next stage of vapour compression is condensation, in which heat is exchange by two means i.e. whenever the gas is under saturation curve (i.e. latent heat of vaporization) it exchanges heat with hot region of Stirling engine (H) and in rest cases(sensible heat) it exchanges heat with air (because Stirling engine needs a constant temperature heat source we cannot transfer all the heat of condenser to Stirling engine i.e. from superheated region till sub-cooling region, temperature is changing constantly, but in saturated region). Heat is exchange in sub-cooling and superheated region via air and sub-cooling is done till temperature of R-12 reaches the atmospheric conditions. Sub-cooling is done to minimize the throttling work so that we can attain a lower value of enthalpy of gas before throttling which will subsequently increase the amount of heat needed by evaporator and refrigeration effect will be more.

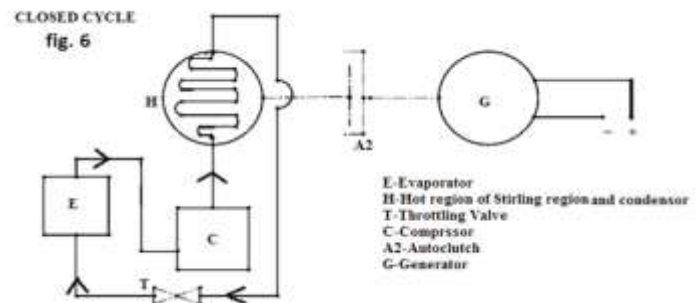


Fig. 6: Closed cycle

Stirling engine [3] has a β type arrangement. It has Helium [5] as working fluid because it has very high thermal conductivity [12] than other inert gases which means that almost all the heat supplied is converted into work(internal energy of helium does not increase) and when the pressure change occurs temperature of helium in all parts of Stirling chamber will increase simultaneously. The condenser of vapour compression cycle and exhaust (after passing through evaporator), acts as heat source and high speed atmospheric air acts as heat sink. Both of the sources are isolated from each other. In theories and calculations the heat processes are isothermal but this will not be possible because it is an extremely slow process, so we are taking them as adiabatic processes in actual practice. External compressor is not needed because compression is done by kinetic energy stored in the flywheel of Stirling engine crankshaft.

This way, closed cycle works in coordination to produce extra work output in the expense of residual heat of Atkinson engine, this extra work will increase the power output of the system. Hence ATKINSON-STIRLING ENGINE continues to work with R-12 as fuel till any reduction in power output and required operating temperature of the Stirling engine.

COMBINED CYCLE:

The Atkinson, vapour compression and Stirling cycles are assembled respectively in cascade manner with the help of heat exchangers and auto clutches [9]. Heat is flown from Atkinson engine (2) to Stirling engine (H) through vapour compression cycle. In running condition whenever the output RPM of Stirling engine will be in proximity of Atkinson engine, the E.C.U. [8] installed in the system will engage auto clutch A1 with the help of thermal sensors (T) and the action of petrol valves [1] and the open cycle comes into role once again only for re-establishing the conditions for Stirling engine to work. This will reduce the petrol intake without changing the output power of the system. E.C.U. also changes the temperature limits and compressor work of vapour compression cycle and Stirling engine so that system can provide us the maximum output with the minimum input thus increasing the efficiency of the engine. On the other side of Stirling engine its shaft is connected with a generator with the help of auto clutch A2. Whenever there is a chasm between the respective R.P.M of Stirling and Atkinson engine the E.C.U will couple generator and Stirling engine. This generated electricity can be used to run the compressor (C) of vapour compression. The priority of Stirling engine is to connect with Atkinson engine, so, if there is a small difference between R.P.M of both cycles then shaft of Stirling engine will go in no load condition by disengaging itself with generator, this will increase the R.P.M of shaft of Stirling engine and now both the engines can be coupled. The E.C.U will also control the air flow through condenser, thus maintaining the changing value of heat required as input in Stirling engine.

The exhaust of Atkinson engine after passing through evaporator (E) is send to the hot region of Stirling engine so that exhaust can act as an option for the extra heat requirement whenever needed.

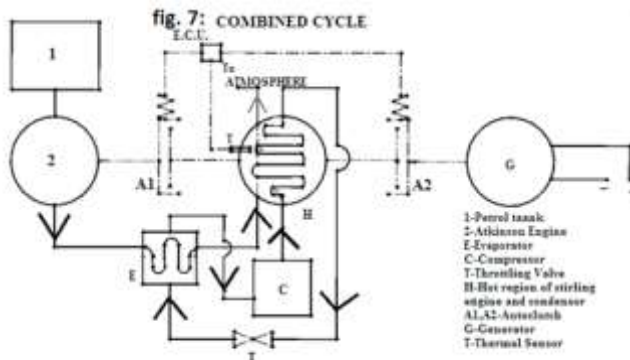


Fig.7: Combined Cycle

ANALYSIS AND CALCULATIONS:

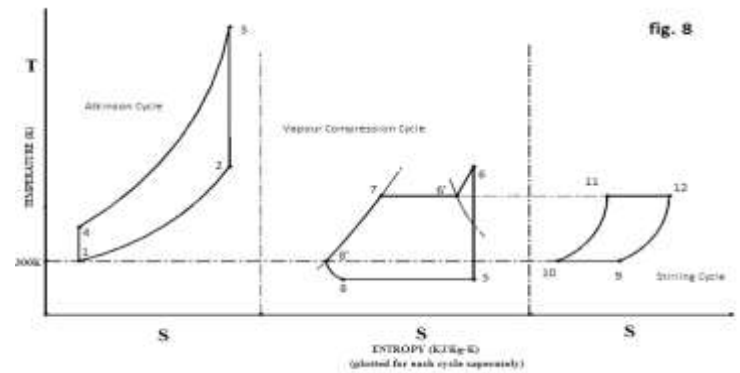


Fig. 8 Graphical representation of all cycles on a common temperature scale

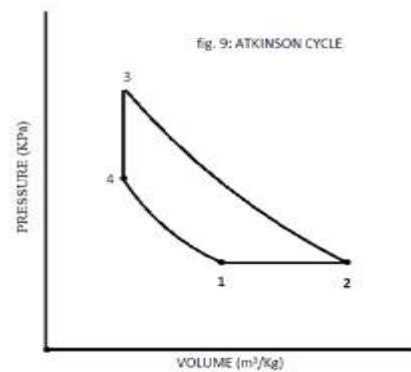


Fig. 9: Atkinson cycle

CALCULATION:

ATKINSON ENGINE [10]

GIVEN:

Engine RPM = 6000

Air Fuel Ratio (A/F) = $m_a/m_f = 15.1$ [15]

Consumption:

Fuel/hr. = 2.25 Kg

Fuel/sec = 0.625 g

Fuel/cycle = 0.0125 g

$R = 0.287 \text{ KJ/Kg K}$

$\gamma_{\text{air}} = 1.4$

$C_{p \text{ air}} = 1.005 \text{ KJ/Kg}$

$C_{v \text{ air}} = 0.718 \text{ KJ/Kg}$

Compression Ratio $r_c = v_1/v_4 = 7.5$

Expansion Ratio $r_e = v_2/v_3 = 13$

Air enters at point 1 at STP.

So,

$$P_1 = P_2 = 1 \text{ bar} = 101.325 \text{ KPa}$$

$$P_3 = r_c^\gamma \cdot P_2 = 3674.83 \text{ KPa}$$

$$T_1 = 300 \text{ K}$$

$$v_1 = RT_1/P_1 = 0.85 \text{ m}^3/\text{Kg}$$

For Process 1-4,

$$v_4 = v_1/r_c = 0.1133 \text{ m}^3/\text{Kg}$$

$$P_1 v_1^\gamma = P_4 v_4^\gamma$$

$$P_4 = r_c^\gamma \cdot P_1$$

$$P_4 = 1701.25 \text{ KPa}$$

Also,

$$P_1^{1-\gamma} T_1^\gamma = P_4^{1-\gamma} T_4^\gamma$$

Therefore,

$$T_4 = 671.64 \text{ K}$$

For Process 4-3,

$$v_3 = v_4 = 0.1133 \text{ m}^3/\text{Kg}$$

$$T_3/P_3 = T_4/P_4$$

$$T_3 = 1460.09 \text{ K}$$

For Process 2-1,

$$P_1 = P_2 = 101.325 \text{ KPa}$$

$$v_2 = r_e v_3 = 1.473 \text{ m}^3/\text{Kg}$$

$$T_1/v_1 = T_2/v_2$$

$$T_2 = 520 \text{ K}$$

$$\text{Work in (Absolute Value)} = W_{14} + W_{12}$$

$$= (P_1 v_1 - P_4 v_4) / (\gamma - 1) + P_1 (v_2 - v_1)$$

$$= 266.56 + 63.14 = 329.7 \text{ KJ/Kg of air}$$

$$\text{Work Out (Absolute Value)} = (P_3 v_3 - P_2 v_2) / (\gamma - 1)$$

$$= 674.51 \text{ KJ/Kg of air}$$

$$\text{Net work done} = W_{out} - W_{in} = 344.81 \text{ KJ/Kg of air}$$

$$\text{Net work done/hr.} = (A/F) \cdot \text{Fuel consumed per hr.} \cdot \text{Net Work Done per Kg of Air}$$

$$= 11715 \text{ KJ}$$

Thermal Efficiency of Atkinson engine,

$$\eta_{th} = 1 - \gamma (T_1 - T_2) / (T_3 - T_4)$$

$$= 60.94\%$$

VAPOUR COMPRESSION CYCLE:

GIVEN:

$$\gamma_r = C_p / C_v$$

$$\gamma_r = 1.14, C_p = 1.02 \text{ KJ/Kg-K}, C_v = 0.89 \text{ KJ/Kg-K}$$

Let, working temperature and pressure limits (from R-12 thermodynamic table) are [12]:

$$T_8 = T_5 = 293 \text{ K}$$

$$P_8 = P_5 = 566.4 \text{ KPa}$$

$$T_7 = T_6 = 343 \text{ K}$$

$$P_7 = P_6 = P_6 = 1880 \text{ KPa}$$

NOTE: Temperature and Pressure limits of Vapour Compression Cycle and Stirling engine will always change with respective change in working conditions of Atkinson engine. So that highest efficiency can be attained by Stirling engine

THEREFORE,

$$S_5 = S_6 = 1.552 \text{ KJ/Kg-K}$$

$$h_5 = 361.4 \text{ KJ/Kg}$$

$$v_5 = 0.0311 \text{ m}^3/\text{Kg}$$

$$v_6 = 0.0091 \text{ m}^3/\text{Kg}$$

In process 7-8', R-12 undergoes sub-cooling till it reaches 300K

$$h_8 = h_{8'} = 226 \text{ KJ/Kg}$$

$$P_{8'} = 686.5 \text{ KPa}$$

$$h_{85} = h_5 - h_8$$

$$h_{85} = 135.4 \text{ KJ/Kg}$$

Superheated temperature,

$$T_6 \text{ (from table)} = 348 \text{ K (approx.)}$$

$$h_{76'} = h_6 - h_7$$

$$h_{76'} = 105.3 \text{ KJ/Kg}$$

$$\text{Superheated heat} = C_v (T_6 - T_{6'}) = 4.45 \text{ KJ/Kg}$$

$$\text{Sub-cooled heat} = C_v (T_7 - T_{8'}) = 38.27 \text{ KJ/Kg}$$

Now the residual heat from the exhaust is transferred to evaporator (E) by heat exchangers till R-12 reaches its saturated stage (i.e. process 8-5)

Temperature of exhaust after heat transfer process 8-5, X: $h_{85} = C_{v \text{ air}}(T_2 - X)$

$$135.4 = 1.005 (520 - X)$$

$$X = 385.27 \text{ K}$$

Compression work for process 5-6,

$$W_{56} (\text{absolute}): (P_6 v_6 - P_5 v_5) / (\gamma_r - 1)$$

$$W_{56} = 3.62 \text{ KJ/Kg per cycle}$$

STIRLING CYCLE:

Because Stirling engine needs a constant temperature heat source, only latent heat of vaporization (h_{76}) will be transferred from condenser to its hot side (such that $T_{12} = T_6$) and rest of the condenser heat will be exchanged through atmosphere. Heat transfer from cold side of Stirling engine is also through atmosphere.

Also, the exhaust after heat transfer with evaporator is connected with the hot side of Stirling engine by heat exchangers, so that if there is any requirement of heat more than is supplied by condenser. By this arrangement, desired higher temperature limit (T_{12}) can be achieved by Stirling engine.

GIVEN:

$$C_{v \text{ He}} = 3.12 \text{ KJ/Kg-K}, R_{\text{He}} = 2.08 \text{ KJ/Kg-K}$$

T_{atm} is temperature at which exhaust is emitted in atmosphere.

$$T_{11} = T_{12} = T_6 = 343 \text{ K}, T_{10} = T_9 = 273 \text{ K}$$

By taking 1 Kg of helium. [6]

$$\text{Volume Ratio: } v_{12}/v_{11} = v_9/v_{10} = 1 + (T_{12} - T_9)/1100 \quad [13]$$

$$v_{12}/v_{11} = v_9/v_{10} = 1.04$$

In heat addition process, at constant volume:

$$Q_{12-9} = C_v (T_{12} - T_9); W_{12-9} = 0$$

$$Q_{10-11} = -C_v (T_{12} - T_9); W_{10-11} = 0$$

$$Q_{12-9} = -Q_{10-11} = C_v (T_{12} - T_9) = 134.16 \text{ KJ/Kg}$$

Major fraction Q_{12-9} is supplied by condenser heat (h_{67})

$$\text{Rest heat required, } Z = Q_{12-9} - h_{67} = 28.86 \text{ KJ/Kg}$$

$$\text{Heat supplied by exhaust, } Z = C_{v \text{ air}} (X - T_{\text{atm}})$$

$$T_{\text{atm}} = 356.55 \text{ K}$$

For adiabatic processes,

$$Q_{9-10} = W_{9-10} = -RT_9 \ln (v_9/v_{10}) = 22.27 \text{ KJ/Kg per revolution}$$

$$Q_{11-12} = W_{11-12} = RT_{11} \ln (v_{12}/v_{11}) = 27.98 \text{ KJ/Kg per revolution}$$

$$\text{Net work} = W_{11-12} - W_{9-10} = 5.71 \text{ KJ/Kg per revolution}$$

$$\eta_{\text{stirling}} = 1 - T_9/T_{12}$$

$$\eta_{\text{stirling}} = 20.41 \%$$

Efficiency of rest of the system other than Atkinson, η_s :

[Net Stirling work - compressor work (W_{56})] / heat input at Stirling

$$\eta_s = 7.47 \%$$

This net work ($W_{11-12} - W_{9-10}$) is sent through Stirling engine shaft to couple with shaft of Atkinson engine or shaft of generator (whichever may be the case).

CONCLUSION:

Now, if the individual cycles of Atkinson and Stirling engine are combined through vapour compression to form a cascade series of cycles. The output of Atkinson engine is utilized as a major fraction of the input of Stirling engine. This in turn increases the efficiency of the Atkinson cycle. Also, the extra power of Stirling engine will reduce the petrol consumption of Atkinson engine, thus making this as a better solution to mitigate the demands of fuel and consequently leading to a greener environment.

APPLICATIONS:

- Implementation in automobile sector.
- Utilization for power generation.
- Implementation in aircrafts.
- Realization in marine engines.
- Application in agricultural practices.

FURTHER SCOPE OF RESEARCH:

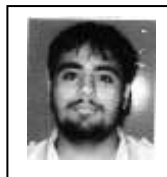
Elementary calculations have shown that such a concept is possible. Practical feasibility of this concept needs to be proved. Another horizon of this research could be a combination to implement and work on other types of engines, for example integrating Stirling engine with diesel engine. Another possibility would be of having the vapour compression to work on different refrigerants better than R-12 because R-12 is a CFC. Optimization of system temperature for better efficiency needs to be done. Also, the further analysis of Stirling Engine needs to be done so that its working parameters can be more accurately known.

ASSUMPTIONS:

- The heat transfer in all the heat exchangers occurs at 100% efficiency.
- No heat loss is occurring in any part of the system.
- In practical use of the Stirling cycle, isotherms are impossible to occur so they are treated as adiabatic.
- S.T.P. is 300 K, 1bar
- The refrigerant entering the compressor is in pure saturated vapour stage.
- C_p & C_v are independent of temperatures.
- Mass of fuel per Kg of air is very less, so it is neglected.
- Frictional losses of transmission are not considered.

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Paritosh Rustogi was born in 1991 in Delhi, graduated in Mechanical and Automation Engineering from Guru Gobind Singh Indraprastha University, Delhi (India) in 2009-2013. He has high interest in mechanisms and Thermodynamics, also quite proficient in CAD/CAE. He is also a lead author of three other research papers.



Shivang Batra was born in 1991 in Delhi, graduated in Mechanical and Automation Engineering from Guru Gobind Singh Indraprastha University, Delhi (India) in 2009-2013. He has a flair for technologies in automobiles and have passion in CAD/CAM. He has worked for two months in Sonalika International Tractors