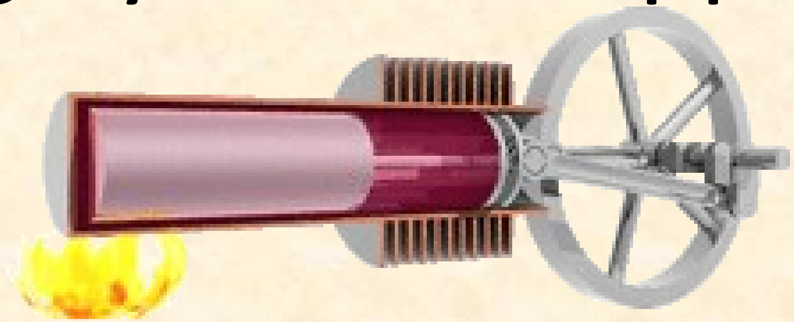
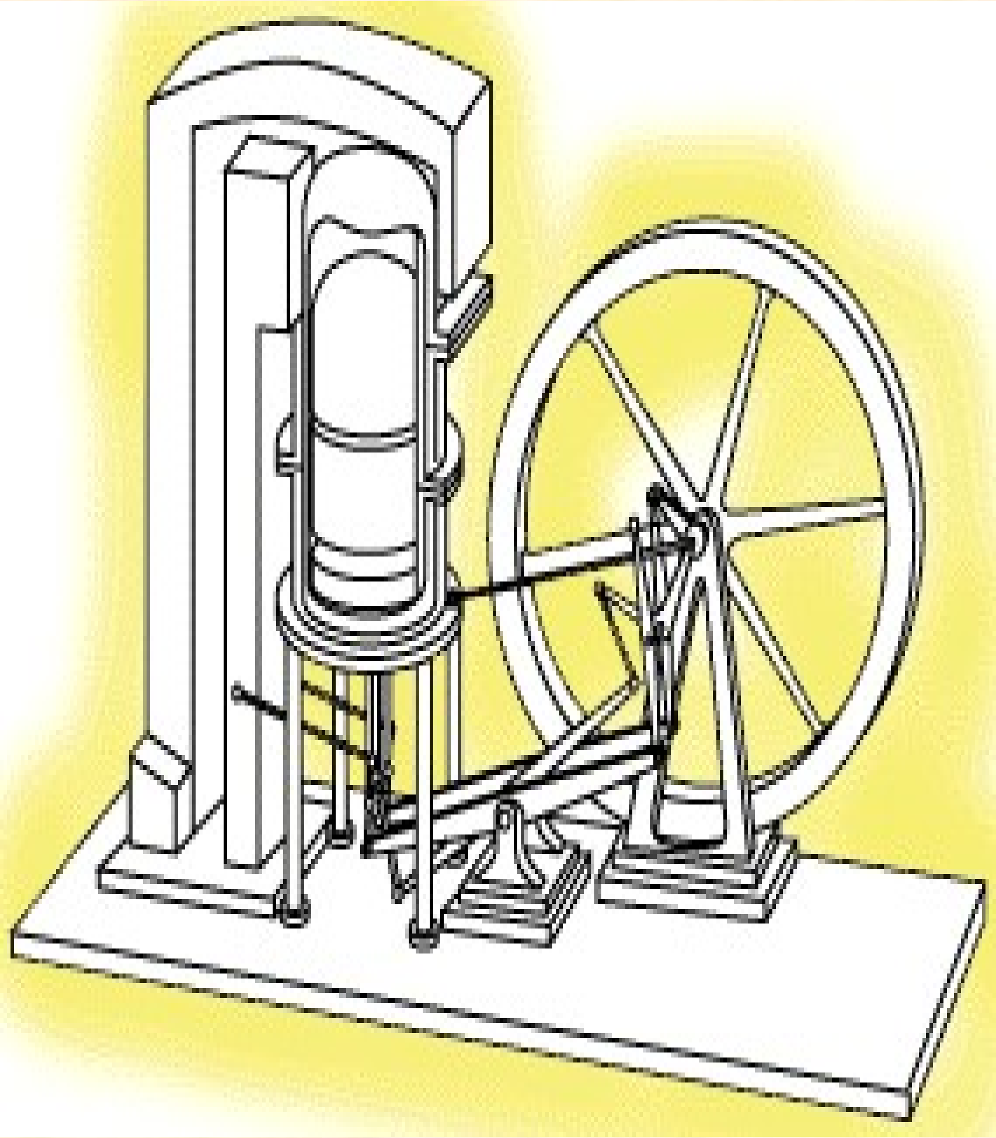
Stirling Cycle & its Applications



Sustainable Future Technology

History

- Inventor = Robert Stirling (1790 - 1878)
- Sought to replace the steam turbines of his days due to frequent explosion caused by unsustainable high pressure killing and injuring workers
- Invented Stirling engine in 1816 which could not explode and produce more power then the steam engine used.



Idealised Stirling Cycle

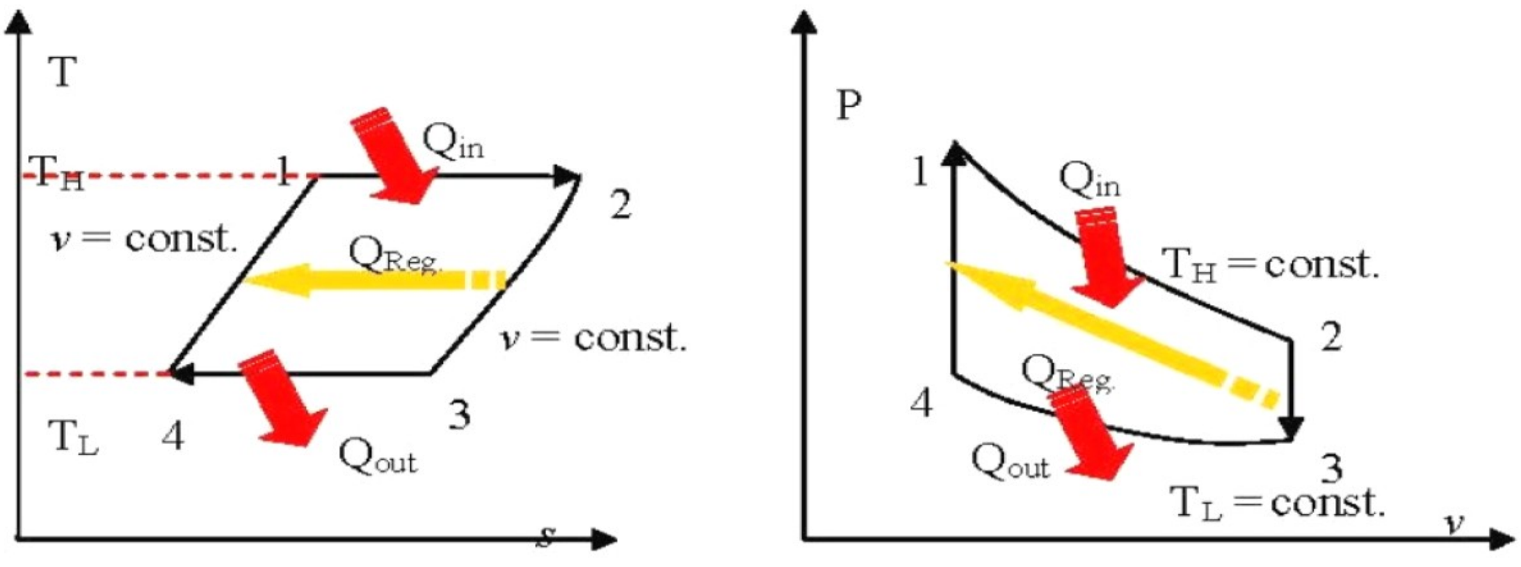
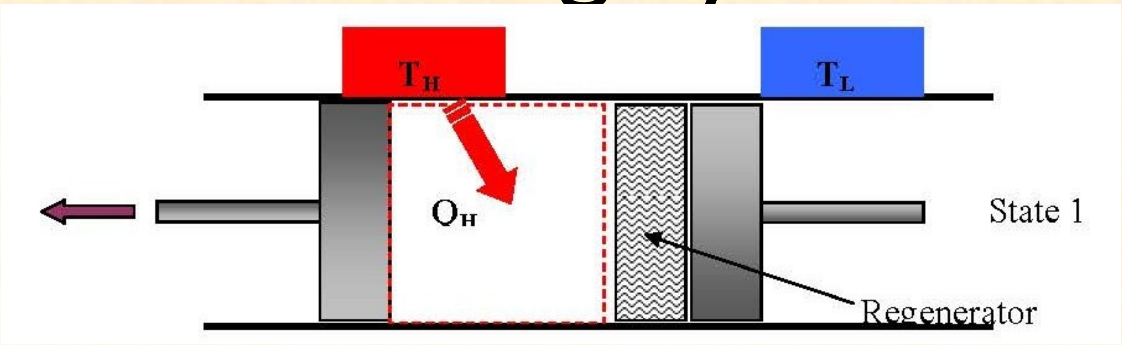


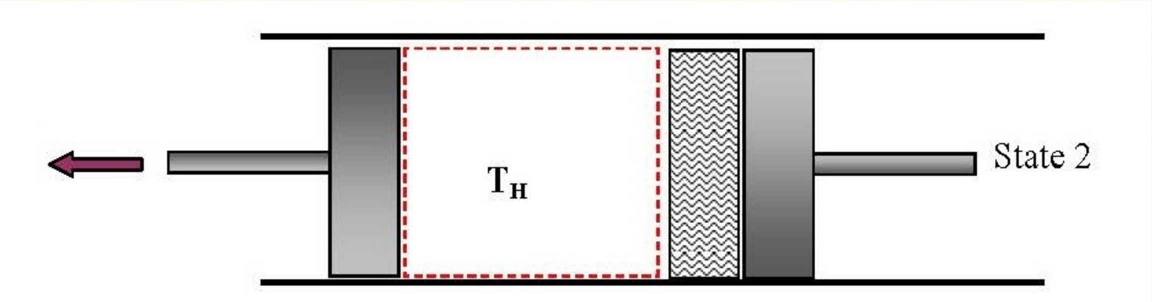
Fig. 3-2: T-s and P-v diagrams for Stirling cycle.

- 1-2 isothermal expansion heat addition from external source
- 2-3 const. vol. heat transfer internal heat transfer from the gas to the regenerator
- 3-4 isothermal compression heat rejection to the external sink
- 4-1 const. vol. heat transfer internal heat transfer from the regenerator to the gas

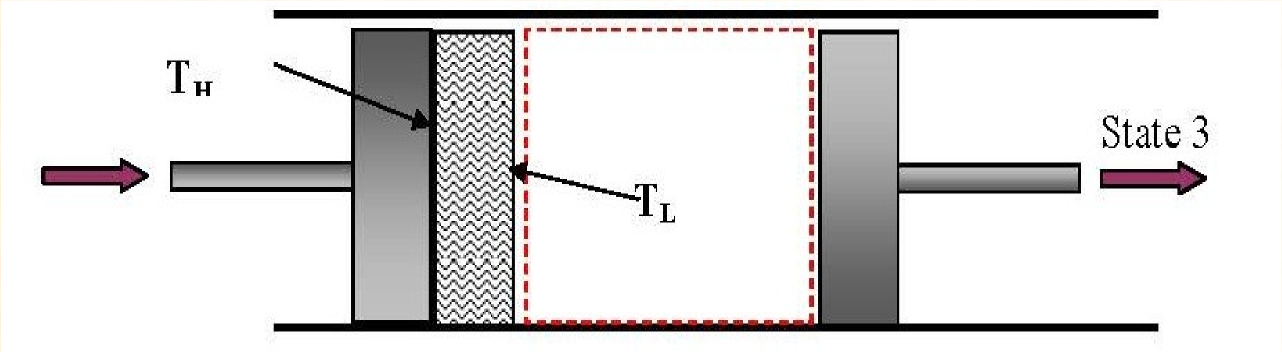
Working Principle of Idealized Stirling cycle



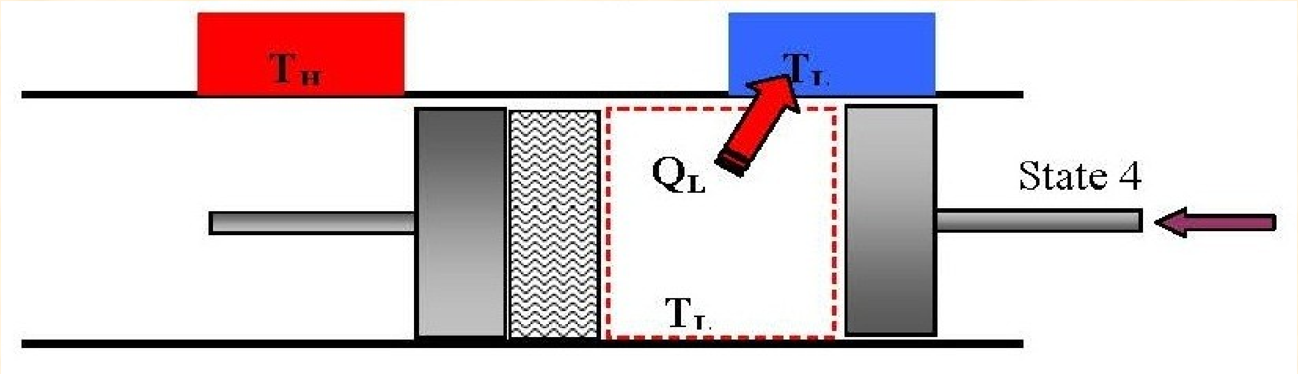
1-2, isothermal heat transfer to the gas at TH from external source. As gas expands isothermally, left piston moves outward, doing work and the gas pressure drops



2-3, both pistons move to the right at same rate, keeping const. volume, until the entire gas pushed to the right chamber (passing thru the regenerator). Heat is transferred to the regenerator and gas temperature drops to TL.



3-4, the right piston is moved to the left, compressing the gas. Heat transfers (isothermally) from the gas to the external heat source at TL, so the gas temperature remains at TL while the pressure rises.



Fi 4-1 both pistons are moved to the left at the same rate (keeping const volume) forcing the gas thought the regenerator into the left chamber. The gas temperature rises to TH and cycle completes.

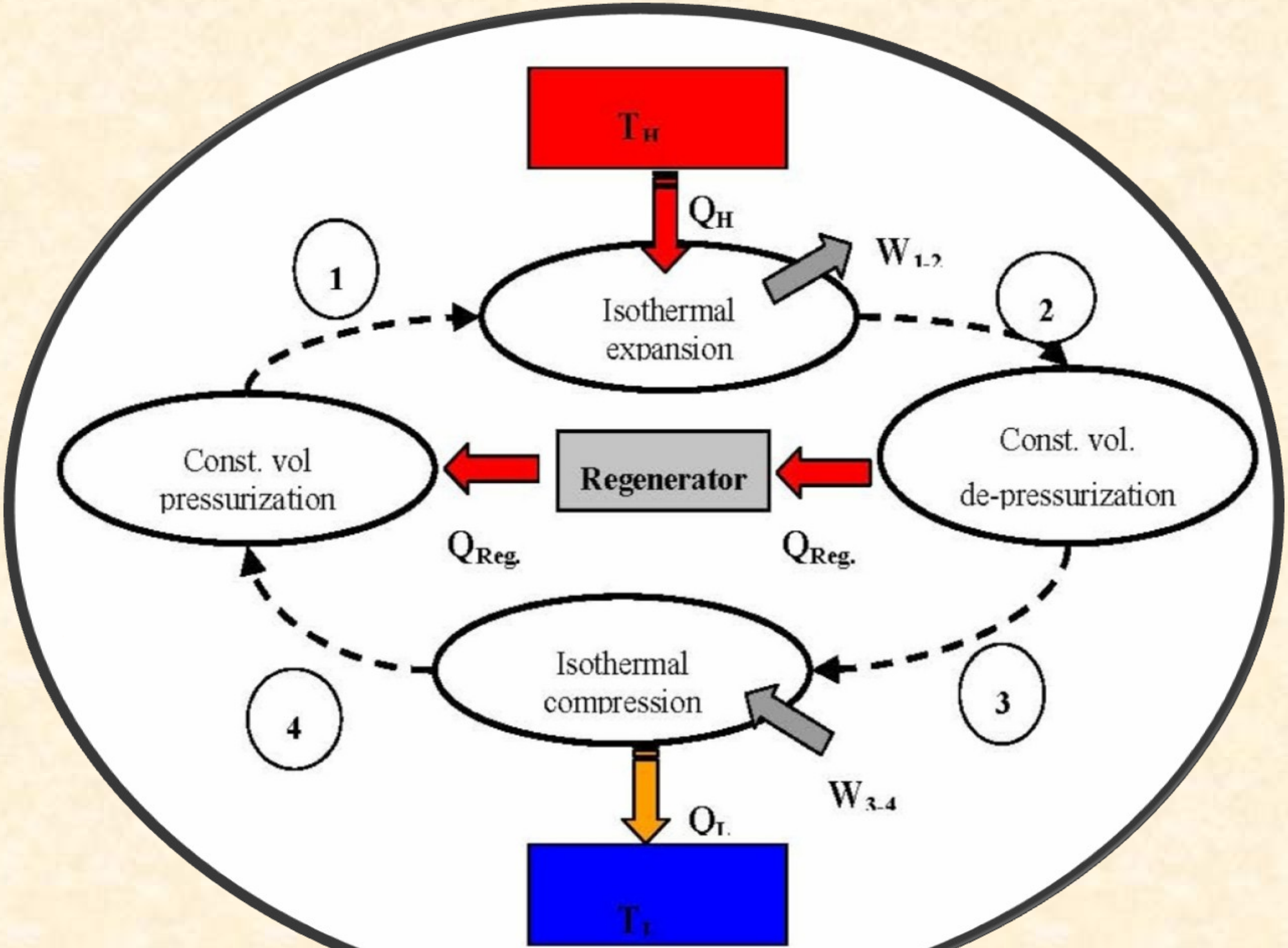
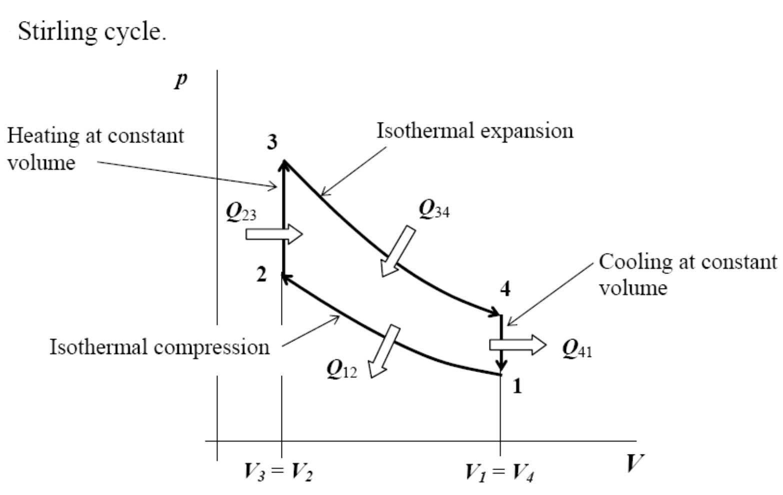
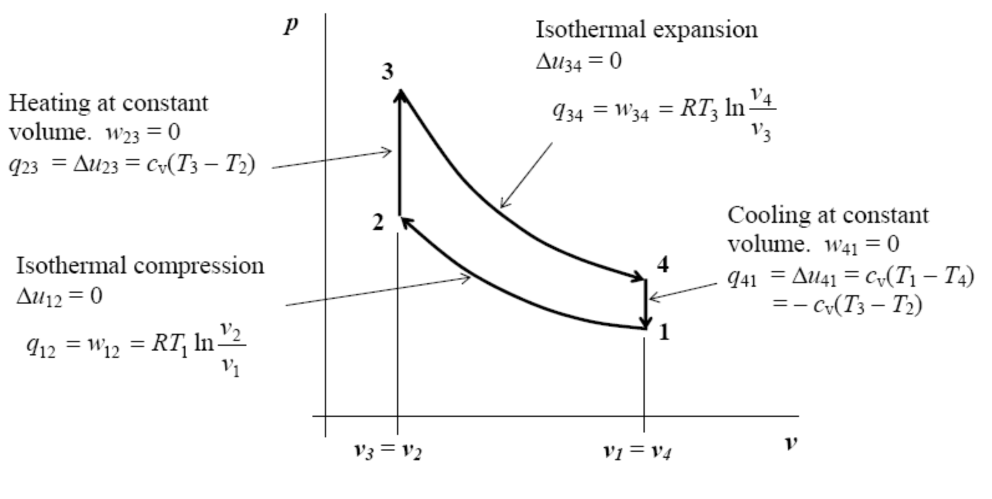


Fig. 3-4: Stirling cycle.

Thermodynamic relations for Stiriling Cycle





Recall that $v_3 = v_2$ and $v_4 = v_1$, also $v_1 > v_2$

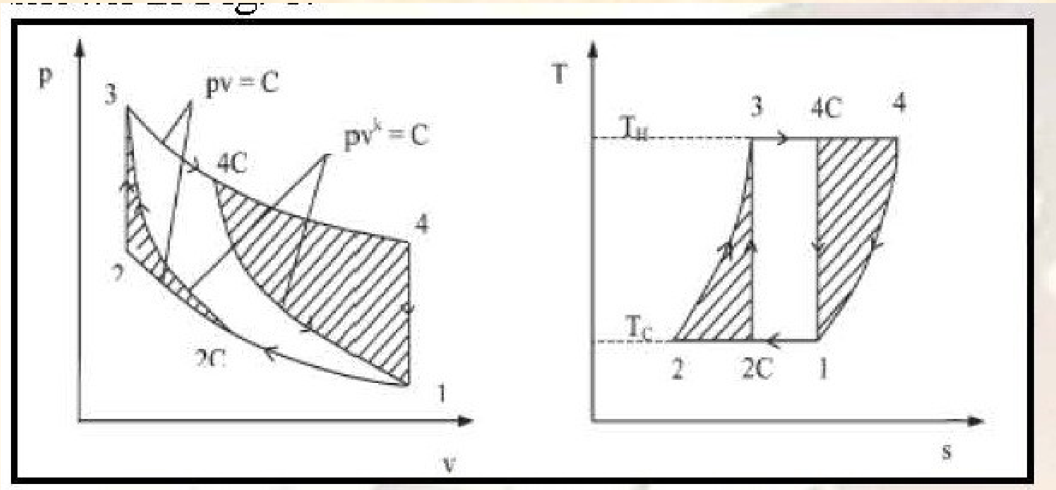
$$w_{net} = RT_1 \ln\frac{v_2}{v_1} + RT_3 \ln\frac{v_1}{v_2} = -RT_1 \ln\frac{v_1}{v_2} + RT_3 \ln\frac{v_1}{v_2}$$

$$w_{net} = R(T_3 - T_1)\ln\frac{v_1}{v_2}$$

For stirling engine with regeneration

$$\eta = \frac{W_{net}}{Q_{34}} = \frac{R(T_3 - T_2)\ln\frac{V_4}{V_3}}{RT_3 \ln\frac{V_4}{V_3}} = \frac{T_3 - T_2}{T_3} = 1 - \frac{T_1}{T_3} = 1 - \frac{T_C}{T_H}$$

Comparison of Carnot and Stiriling cycle[4]:-



The ideal Stirling cycle has three theoretical advantages

- The thermal efficiency of the cycle with ideal regeneration is equal to the Carnotcycle.

- The second advantage, over the Carnot cycle, is obtained by substitution of two isentropic processes with two constant-volume processes. This results in increasing the p–v diagram area

- Compared with all reciprocal piston heat engines working at the same temperature limits, the same volume ratios, the same mass of ideal working fluid, the same external pressure, and mechanism of the same overall effectiveness, the ideal Stirling engine has the maximum possible mechanical efficiency

What is a Stirling Engine

- **Device that converts heat energy to mechanical power by alternately compressing and expanding a fixed quantity of working fluid at different temperatures.**
- **External Combustion Engine**

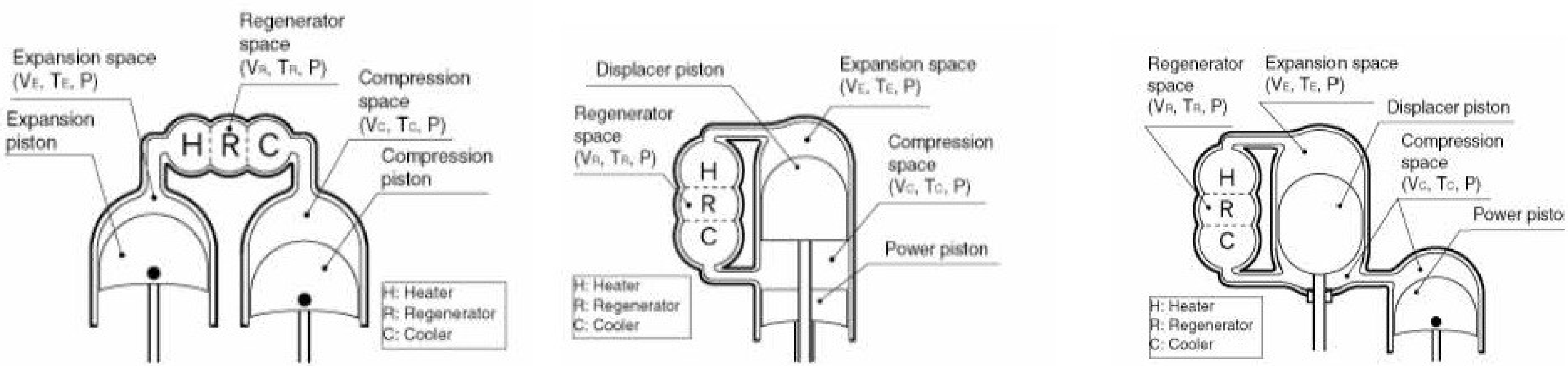
Why use Stiriling Engine

- The Stirling cycle engine is environmental harmless and high theoretical efficiency and almost silent operation.
- Plenty heat sources can be employed on Stirling engine including combustible materials, agricultural waste, biomass, biogas, solar energy and so on
- The fuel ,the combustion air and the products of combustion do not enter the engine cyclinder to become working gas
- It is closed cyclic system
- The cyclic flow of working fluid with in the engine is achieved soley through gometrical changes without intermediate closed valves or ports

Different Configuration of Stirling Engine

There are two major types of Stirling engines, that are distinguished by the way they move the air between the hot and cold sides of the cylinder

- Two Piston Alpha Type
- Displacement Beta and Gamma types



Alpha type Stirling Engine | **Beta type Stirling Engine** | **Gamma type Stirling Engine**

Stirling Engines and Different Forms of Cylinder Configurations (Alpha, Beta and Gamma)
Source: Thermodynamic Fundamentals for Energy Conversion Systems

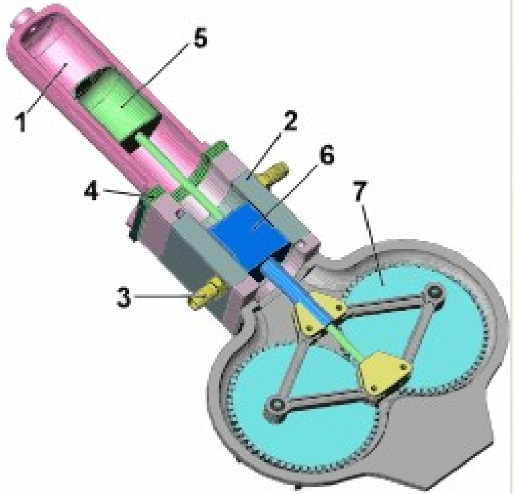
There are five main components in a Stirling-cycle machine

- ***Working gas*** –

  the Stirling Cycle is a closed cycle and the various thermodynamic processes are carried out on a working gas that is trapped within the system.
- ***Heat-exchangers*** –

  two heat exchangers are used to transfer heat across the system boundary.A *heat absorbing heat-exchanger* transfers heat from outside the system into the working gas,and a *heat rejecting heat-exchanger* transfers heat from the working gas to outside thesystem
- ***Displacer mechanism*** –

  this moves (or displaces) the working gas between the hot and cold ends of the machine (via the regenerator).



1.Pink – Hot cylinder wall
2.Dark grey – Cold cylinder wall
3.Yellow – Coolant inlet and outlet pipes
4.Dark green – Thermal insulation separating the two cylinder ends
5.Light green – Displacer piston
6.Dark blue – Power piston
7.Light blue – Linkage crank and flywheels

- ***Regenerator*** –

  this acts both as a thermal barrier between the hot and cold ends of themachine, and also as a “thermal store” for the cycle. Physically a regenerator usually consistsof a mesh material (household pot scrubbers have even been used in some engines), and heat is transferred as the working gas is forced through the regenerator mesh. When the working gas is displaced from the hot end of the machine (via the regenerator) to the cold end of themachine, heat is “deposited” in the regenerator, and the temperature of the working gas islowered. When the reverse displacement occurs, heat is “withdrawn” from the regenerator again, and the temperature of the working gas is raised.

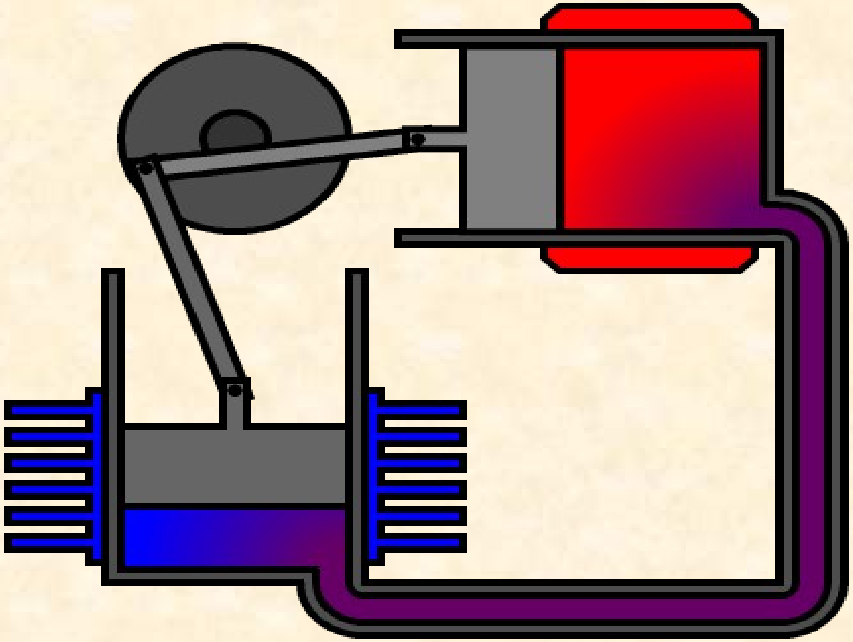
- ***Expansion/compression mechanism*** –

  this expands and/or compresses the working gas. In an engine this mechanism produces a net work output.

Alpha type Stirling engine

An Alpha Stirling contains two power pistons in separate cylinders, one hot and one cold. The hot cylinder is situated inside the high temperature heat exchanger and the cold cylinder is situated inside the low temperature heat exchanger

Action of an alpha type Stirling engine



Most of the working gas is in contact

with the hot cylinder

walls, it hasbeen heated and expansion has

pushed the

hot piston to the bottom of its travel

in the cylinder. The expansion continues

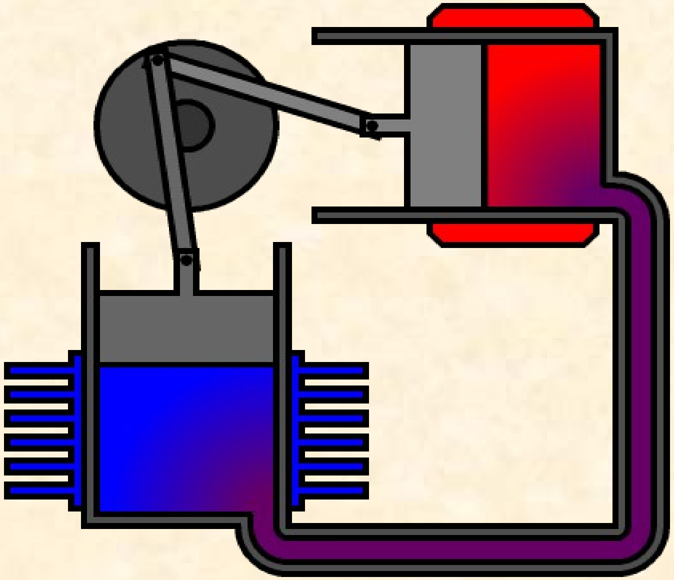
in

the cold cylinder, which is 90° behind the

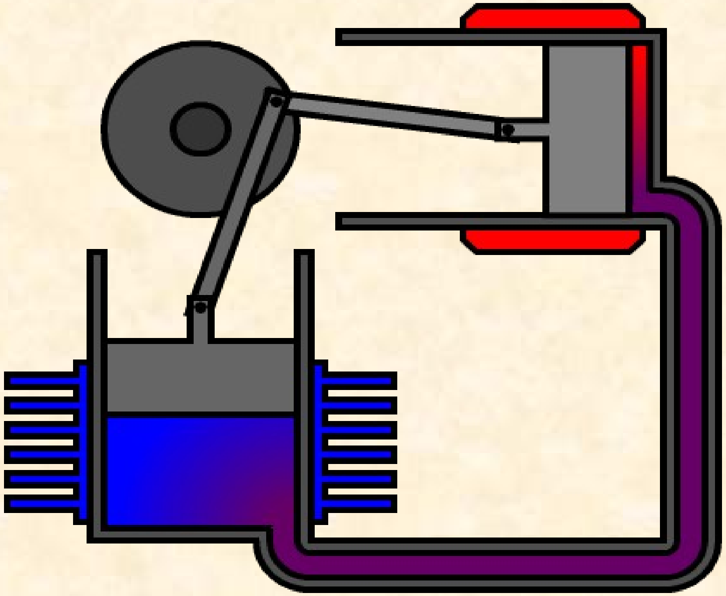
hot piston

in its cycle, extracting more work from the

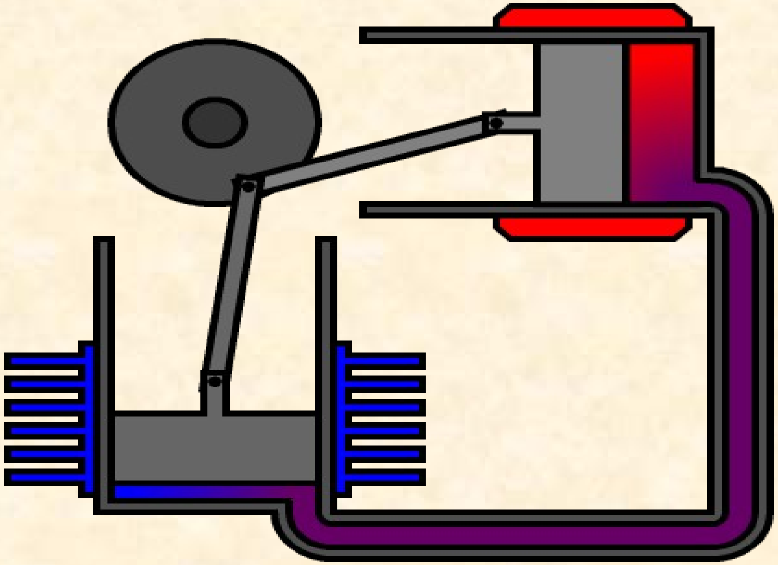
hot gas.



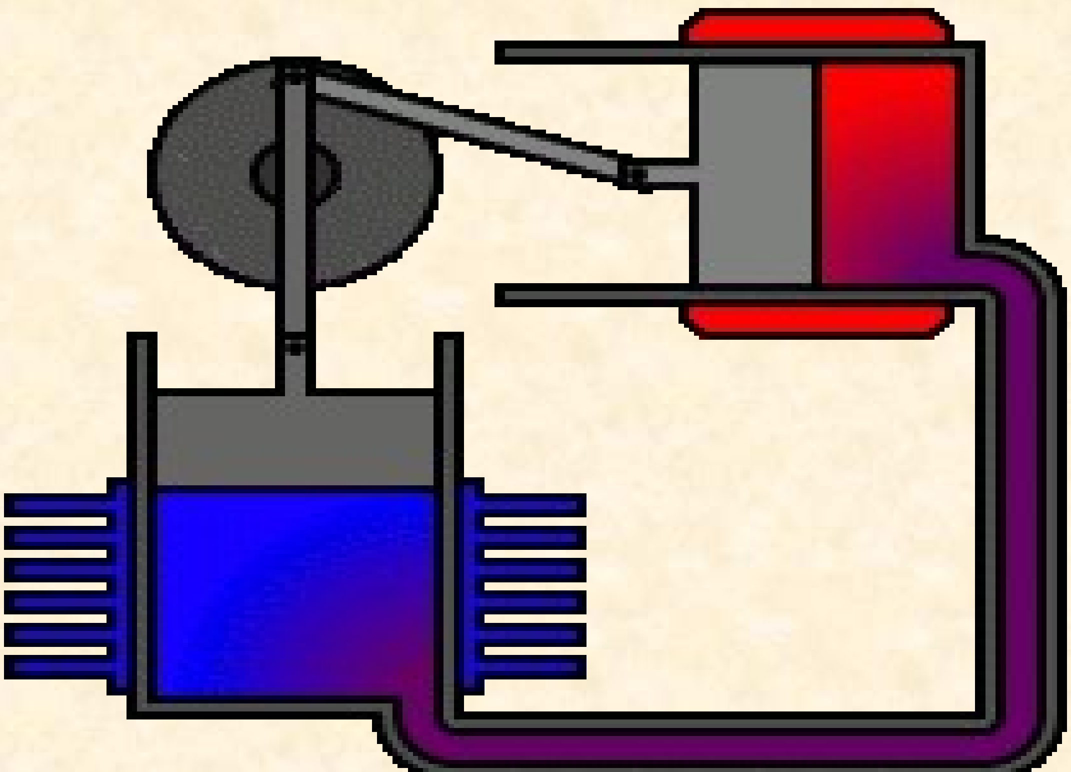
The gas is now at its maximum volume. The hot cylinder piston begins to move most of the gas into the cold cylinder, where it cools and the pressure drops



Almost all the gas is now in the cold cylinder and cooling continues. The cold piston, powered by flywheel momentum (or other piston pairs on the same shaft) compresses the remaining part of the gas



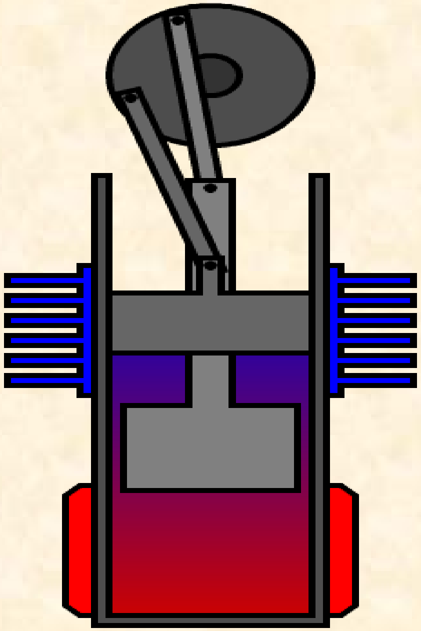
The gas reaches its minimum volume, and it will now expand in the hot cylinder where it will be heated once more, driving the hot piston in its power stroke



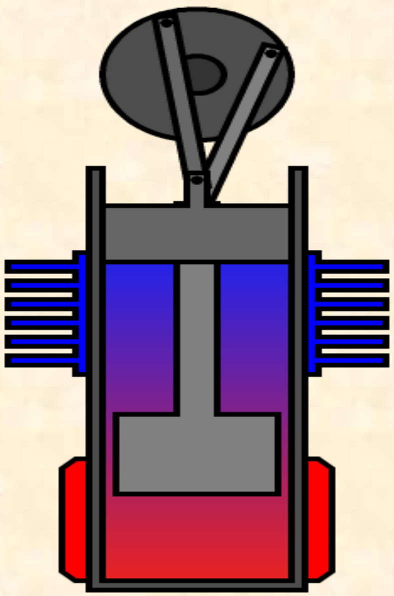
Beta type Stirling Engine

A beta Stirling has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas between the hot and cold heat exchangers

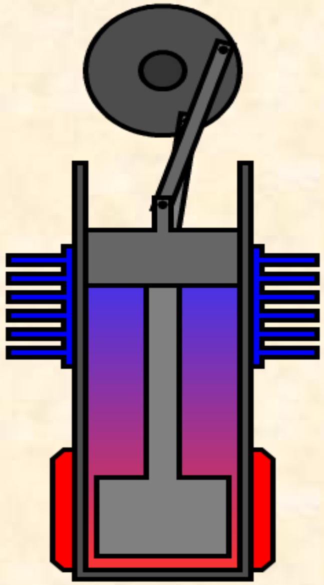
Action of a beta type Stirling engine



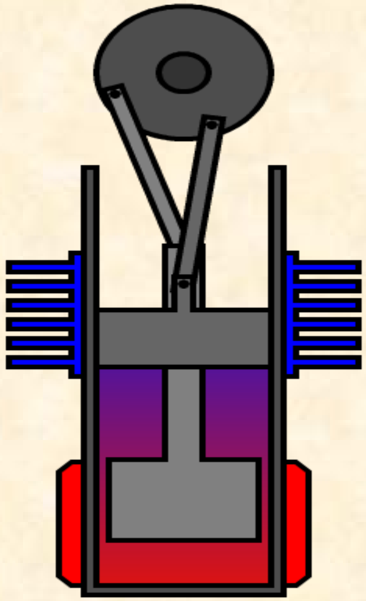
Power piston (dark grey) has compressed the gas, the displacer piston (light grey) has moved so that most of the gas is adjacent to the hot heat exchange



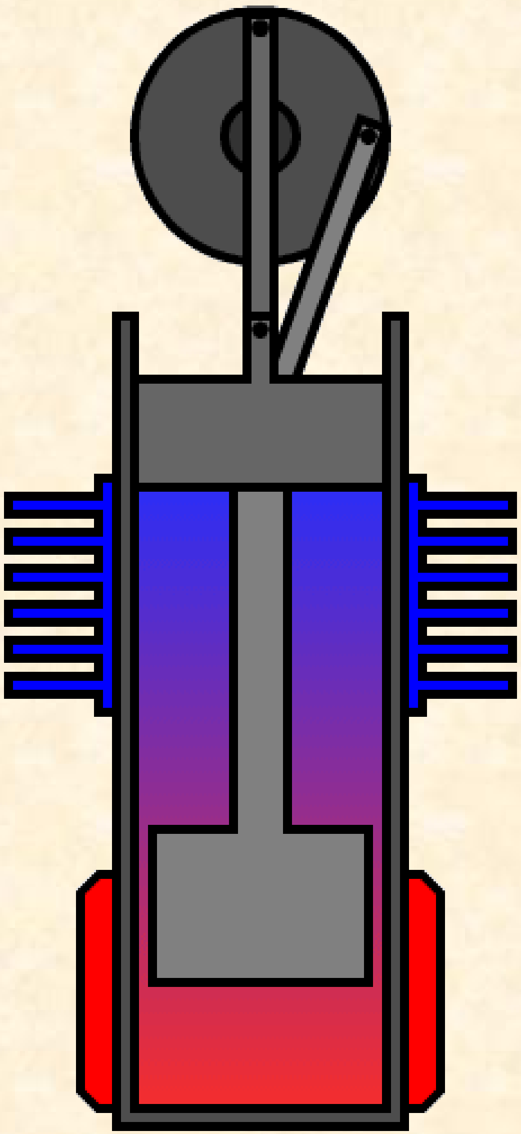
The heated gas increases in pressure and pushes the power piston to the farthest limit of the power stroke



The displacer piston now moves, shunting the gas to the cold end of the cylinder.



The cooled gas is now compressed by the flywheel momentum. This takes less energy, since its pressure drops when it is cooled



Design of a Stirling Engine

These are some of following design parameter:

i. length of displacer chamber L = 3 times its diameter.
ii. length of heater chamber = 2/3L
iii. length of cooler = 1/3L
iv. swept volume of displacer = 1.5 times swept volume of piston cylinder.
v. length of displacer = 2/3L and stroke = 1/3L.

Kolin describes a ‘rule of the thumb’ for approximating the ideal volume ratio which depends on the temperature difference of the engine in question. The formula states:

$$V_R = \left(1 + \frac{\Delta T}{1100}\right)$$

*Compression ratios selected:
1.5 ::: compression ratio of contemporary "Stirling" engines,
2.5 = improved ratio, arbitrary

Performance of stirling engine

- At initial testing conducted with ambient pressure and displacer cylinder having smooth inner surface, the engine started to run at a 93 C hot-end temperature(H. Karabulut et al. / Applied Energy 86 (2009) 68–73).

- Cooling water temperature was measured as 27 C

- All the other tests conducted with different charge pressures, running temperature of the engine varied up to 125 C

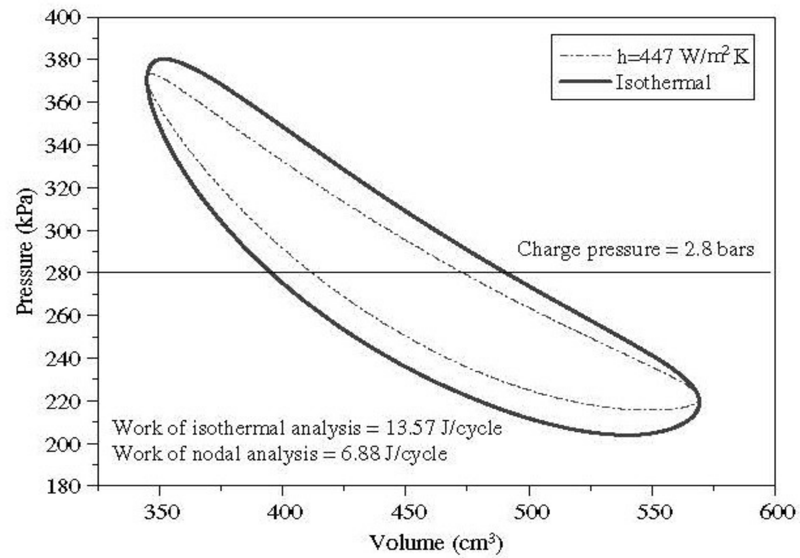
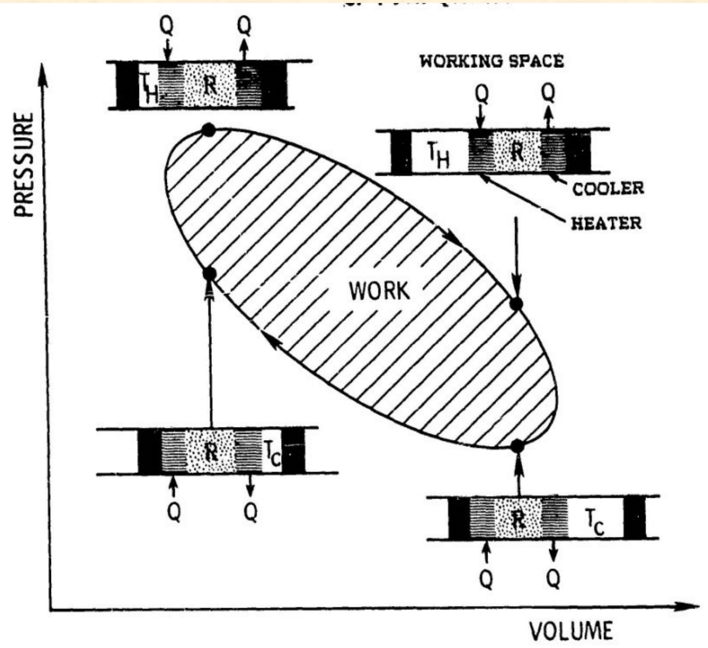


Fig. 7. p–V diagrams obtained with isothermal and nodal analysis.



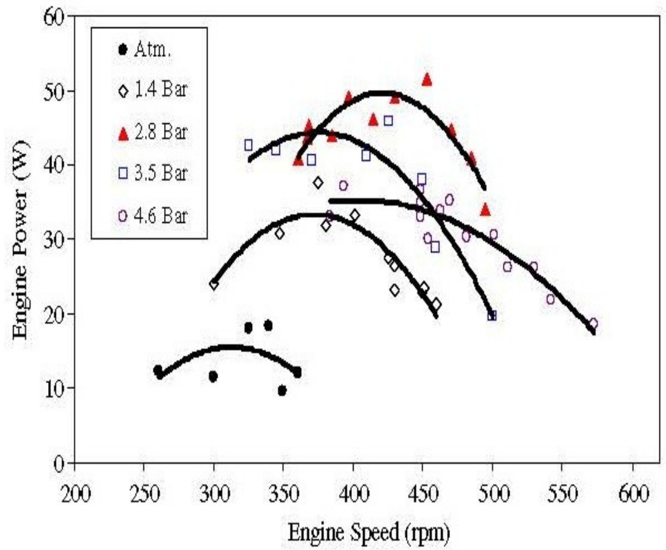


Fig. 5. Variation of brake power with engine speed.

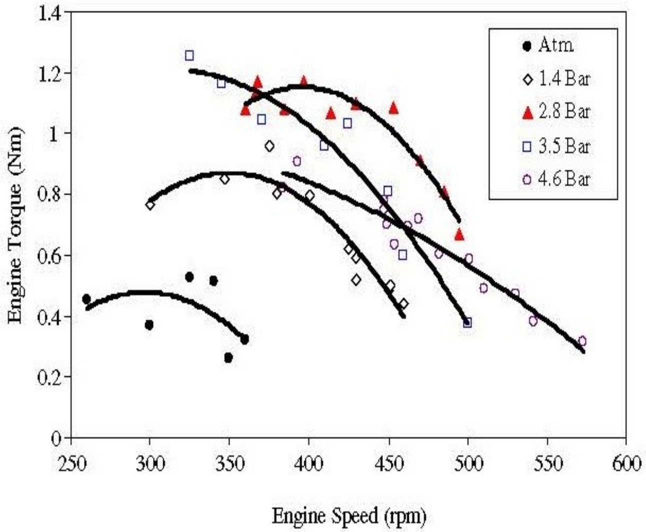


Fig. 6. Variation of engine torque with engine speed.

•Data used in Figs. 5 and 6 were obtained about 200 °C hot-end temperature and at different values of charge pressure.
•Up to a certain level of speed, the power increases with speed and then declines. Decrease of the power output after a certain speed is estimated due to inadequate heat transfer caused by limited heating and cooling time
•At 200 C hot-end temperature, the optimum charge pressure is estimated as 2.8 bars. Maximum power output obtained at 2.8 bars charge pressure is 51.93W and appears at 453 rpm engine speed.
•As seen in Fig. 6, the brake torque has also a maximum value at a certain value of speed. At higher and lower values of speed, the reasons causing the power output to decrease causes also the brake torque to decrease. The maximum values of power and torque correspond almost to the same speed

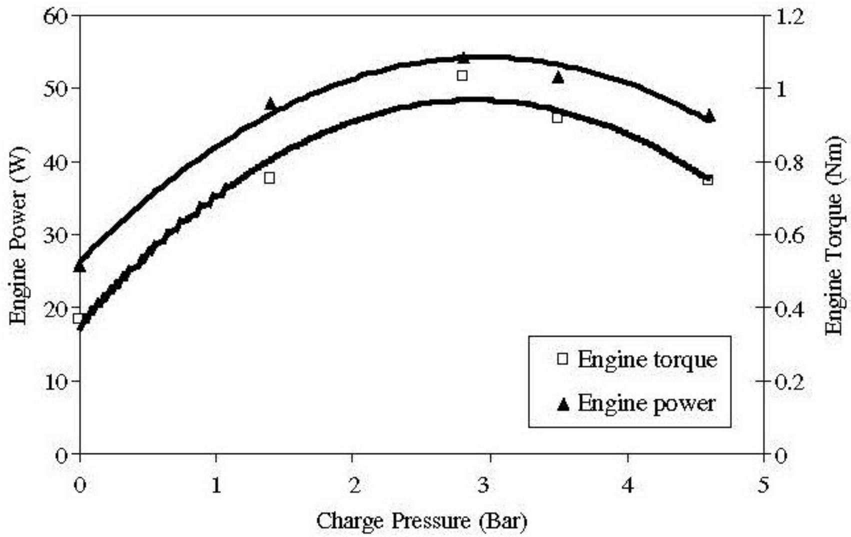


Fig. 8. Variation of brake power and engine torque with charge pressure.

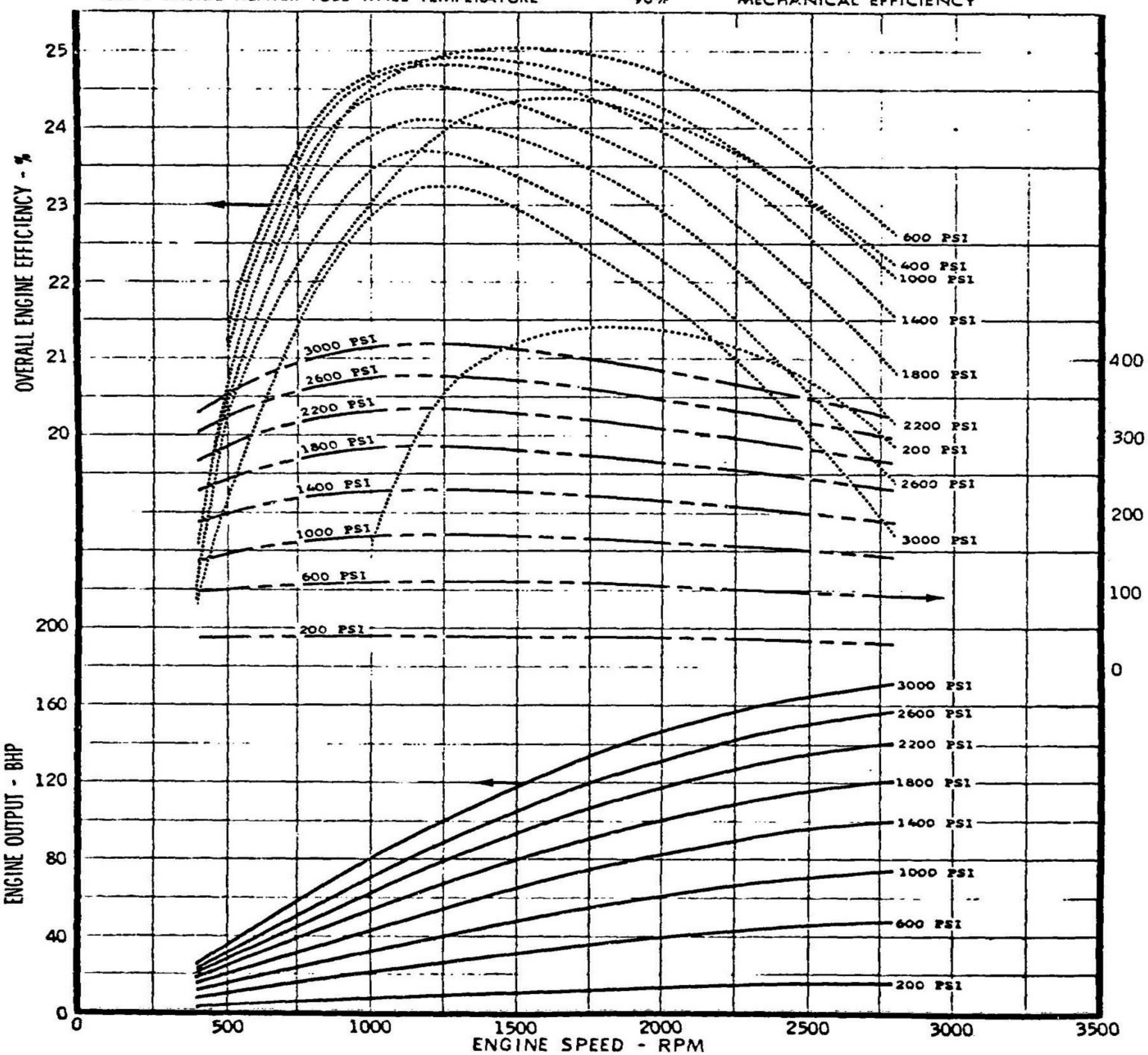
- Fig. 8 illustrates the variation of the power output and brake torque with charge pressure ranging from 0 to 4.6 bars. As the charge pressure increases, the output power and brake torque increase as well, and reaches to a maximum.
- Further increase of charge pressure over the optimum value causes output power and brake torque to decrease. It was also noted that, increasing the charge pressure resulted in increase of vibration.

4L23 CALCULATED PERFORMANCE

BHP, TORQUE AND EFFICIENCY VS. ENGINE SPEED
AT VARIOUS MEAN WORKING PRESSURES

100 GPM COOLING WATER FLOW (AT 2000 RPM)
135°F COOLING WATER INLET TEMPERATURE
80% FURNACE EFFICIENCY
90% MECHANICAL EFFICIENCY

1000°F INSIDE HEATER TUBE WALL TEMPERATURE



Indicated Efficiencies of a
1-98 Rhombic Drive Philips Engine
(Reference 76 e)

Working Fluid	Heater Temp. C	Cooler Temp. C	Indicated Power at Maximum Efficiency Kilowatts	Indicated Efficiency %	Percent of Carnot Efficiency
H_2	850	100	8	50	75
H_2	400	100	1	32	72
H_2	250	100	.35	18	63
He	850	100	6	50	75
He	400	100	1	30	67
He	250	100	.18	17	59
N_2	850	100	1.5	49	73
N_2	400	100	.35	31	70
N_2	250	100	Negative	--	--
H_2	850	0	10	57	75
H_2	400	0	2.8	45	76
H_2	250	0	1	34	71
He	850	0	8	58	77
He	400	0	2	42	71
He	250	0	.7	32	67
N_2	850	0	2	55	73
N_2	400	0	.48	42	71
N_2	250	0	.18	33	69

APPLICATIONS OF STIRILING ENGINE:-

1.Stirling Engines for Pumping Water using Solar Energy as a source of Power

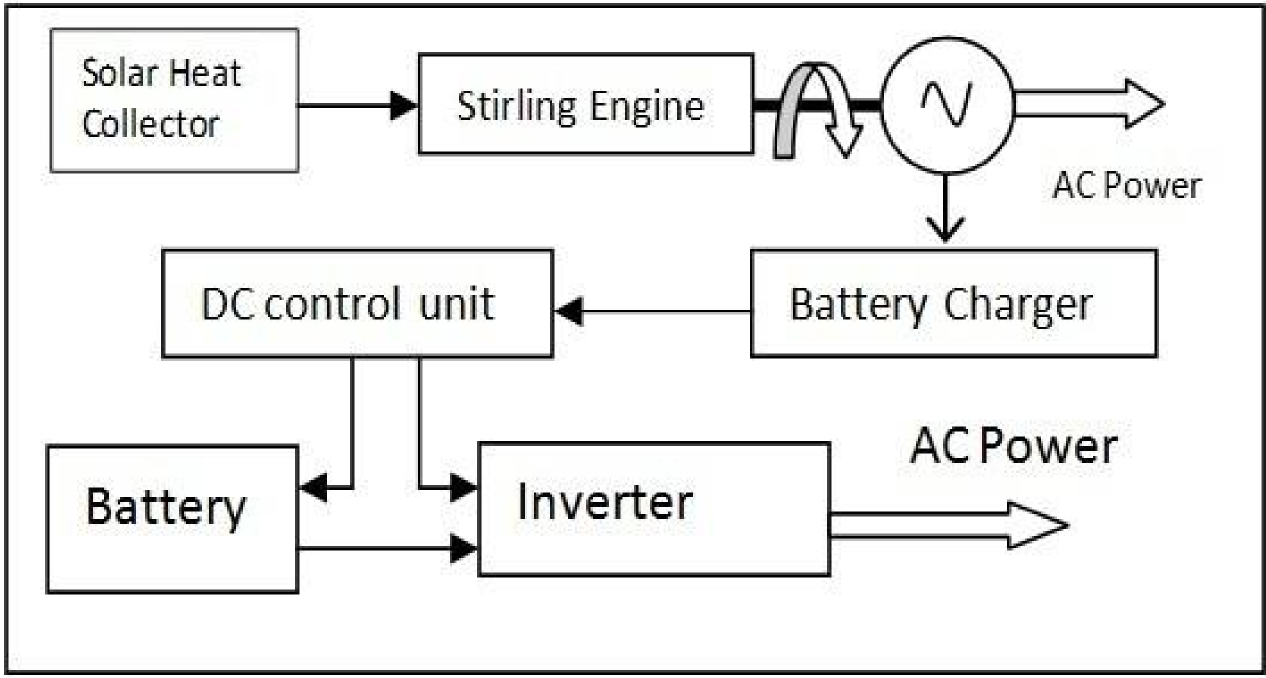
- Limited availability of petroleum product and electricity in rural areas and high demandable human need for water; make demand for searching another alternative for pumping water.

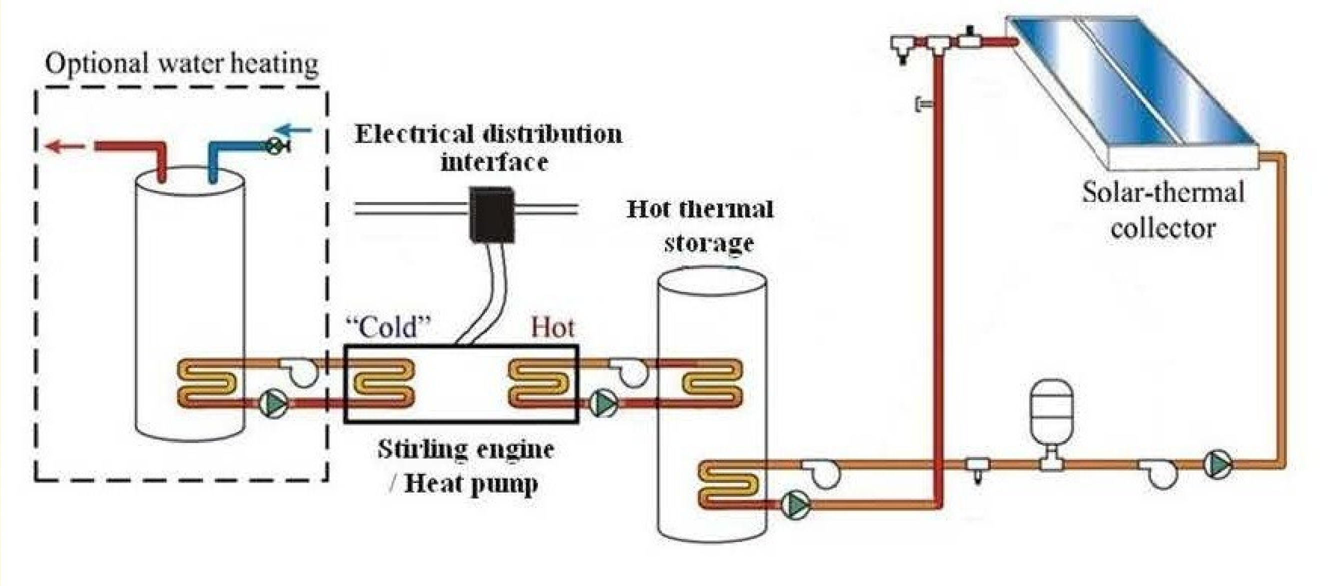
- One optional and potential engine solving this problem is the solar Stirling engine

- In this system, the solar heat collector provides heat for the solar Stirling engine which in turn provides AC power. The electrical power can be transferred to a battery charger, then to DC control unit which can either go into a battery or into an inverter. Efficiencies for this type of small scale system can range from 18% to 23%

- Cost of the equipment is low comparetively.

- ***Solar Stirling engine will give good hope and way for pumping water in rural areas.***





Schematic of the proposed Stirling engine system.

2. WASTE HEAT RECOVERY USING STIRLING ENGINE

For any developing country energy acts as a catalyst in the process of expansion and development of the country.

Different Energy Utilization Systems:-

a) *Thermal Power Plant*
b) ***Nuclear Power Plant***
c) ***Gas Turbine Power Plant***
d) ***Process Industries***
e) ***Automotive Applications***

Drawbacks of above Mentioned Energy Utilization Systems:-

All the systems use large amount of fossil fuels and reject large amount of energy to the atmosphere thus causing global warming,causing environmental degradation and wastage of fuel

Table 1- typical waste heat temperatures at high temperature range from various sources

Types of Device	Temperature, °C
Nickel refining furnace	1370 –1650
Aluminium refining furnace	650-760
Glass melting furnace	1000-1550
Solid waste incinerators	650-1000
Fume incinerators	650-1450

Table 2- typical waste heat temperature at medium temperature range from various sources

Type of Device	Temperature, °C
Steam boiler exhausts	230-480
Gas turbine exhausts	370-540
Reciprocating engine exhausts	315-600
Reciprocating engine exhausts (turbo charged)	230- 370
Heat treating furnaces	425 - 650
Drying and baking ovens	230 - 600
Catalytic crackers	425 - 650
Annealing furnace cooling systems	425 - 650

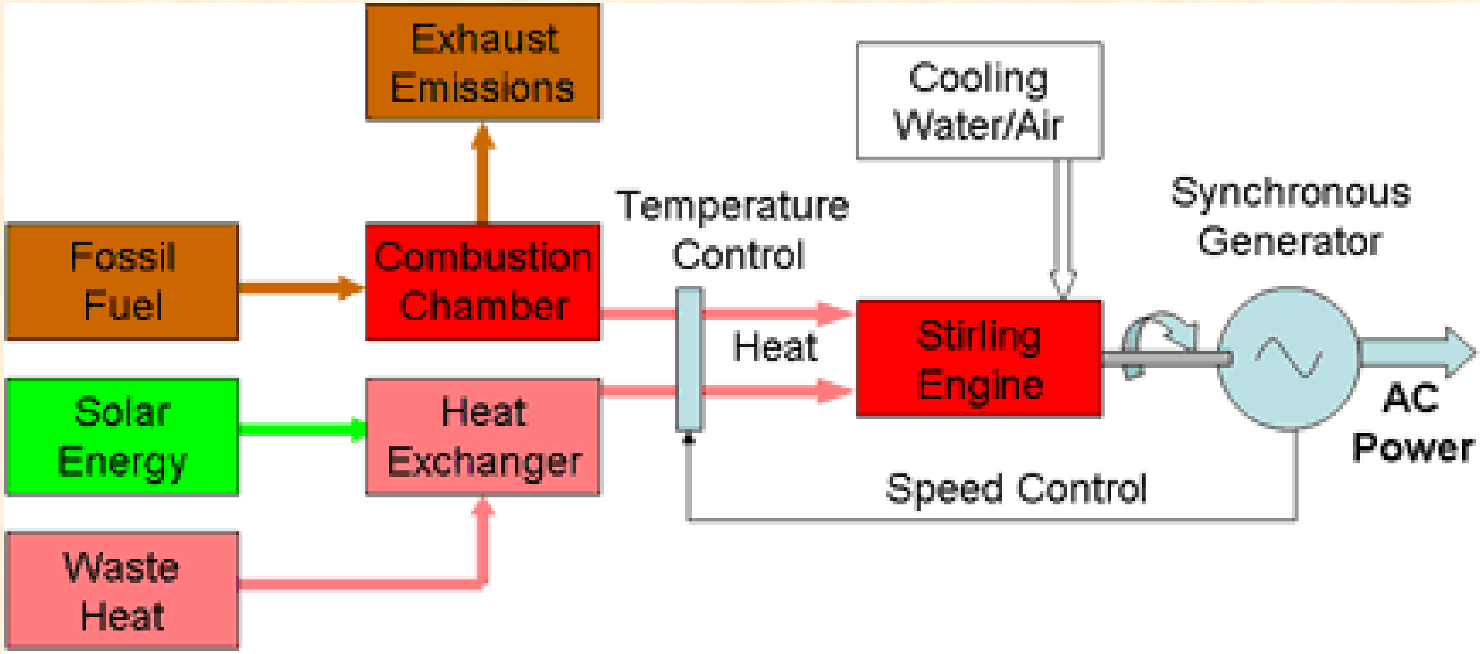
Table 3- typical waste heat temperature at low temperature range from various sources

Source	Temperature, °C
Cooling water from: Furnace	32-55
Forming dies	27-88
Air compressors	27-50
Liquid still condensers	32-88
Hot processed liquids	32-232

Types of waste heat recovery systems are;

1) **Recuperators,**
2) **regenerator,**
3) **heat wheels,**
4) **heat pipe.**

Above mentioned waste heat recovery systems can utilise high and medium temperature waste heat only. They cannot recover low temperature waste heat effectively. So if we want to recover low and very low temperature waste heat we can go for STIRLING ENGINE, which can recover any kind of low grade waste heat because it is external combustion engine and also its efficiency is very good



Electric Power Generation by External Combustion Engine

Stirling Engines in Aviation

- The main reasons these engines are needed in Aviation is because their motor is silent. Smooth torque and lack of vibrations.
- Aviation is the last major user of leaded fuel, Stirling Engines produce less pollution.
- Altitude performance is the strong reason why these engines are needed. If a plane could hold a constant power, it could cruise twice as fast at 40,000 ft as it can at sea level.

Disadvantages to using Stirling Engines in Vehicles

- In the past 25 years, Stirling Cycling Research Group has directed it interest towards the automotive field.
- They are a couple of key characteristics why Stirling Engines are impractical for many applications, including most cars and trucks.
- Since the heat source is external, it will take a longer time for the engine to respond to the changes in the amount of heat that is applied to the cylinder.

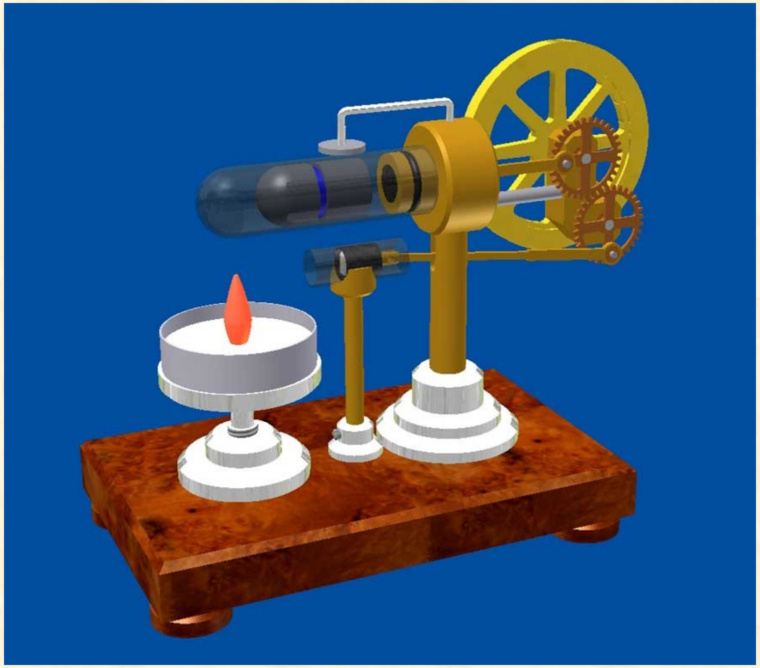
- In other words, the engine needs to warm up to obtain and produce the useful power.
- The engine can not change its power output quickly.

Advantages of Stiriling Engine:-

- Stirling engines can run directly on any available heat source
- A continuous combustion process can be used to supply heat, so those emissions associated with the intermittent combustion processes of a reciprocating internal combustion engine can be reduced.
- The engine mechanisms are in some ways simpler than other reciprocating engine types. No valves are needed,
- A Stirling engine uses a single-phase working fluid which maintains an internal pressure close to the design pressure, and thus for a properly designed system the risk of explosion is low. In comparison, a steam engine uses a two-phase gas/liquid working fluid, so a faulty overpressure relief valve can cause an explosion.
- Waste heat is easily harvested (compared to waste heat from an internal combustion engine) making Stirling engines useful for dual-output heat and power systems.

Disadvantages of Stiriling Engine:-

- The engine is complex due to use of heaters,regenerators,coolers
- The cost of the engine is high
- Stiriling engine requires a blower to force air through preheater and combustion chamber ,this reduces engine efficiency and noise



Stirling-Cycle Heat-Pumps and Refrigerators

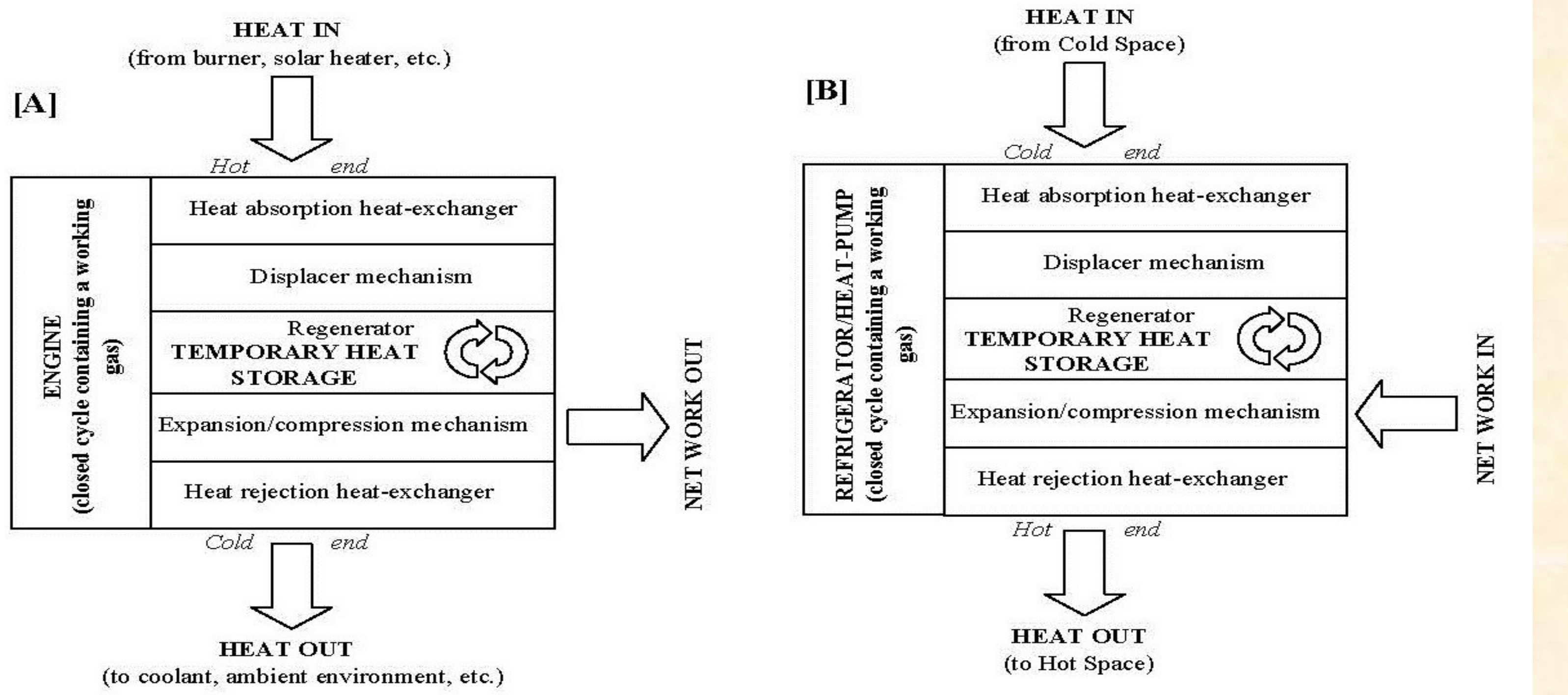
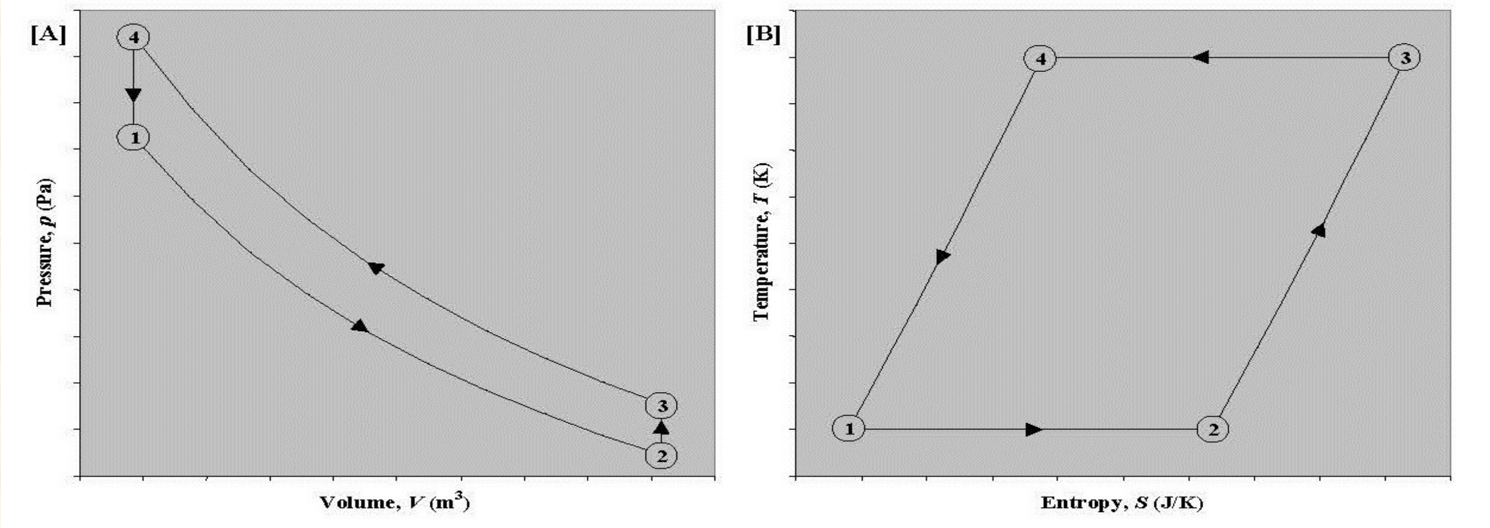


Figure 1. Stirling-cycle machine block diagrams: (A) Engine (B) Refrigerator or heat-pump.

Ideal reversed stiriling cycle



1 ⟹ 2 : *Isothermal expansion*

2 ⟹ 3 : *Isochoric displacement*

3 ⟹ 4 : *Isothermal compression*

4 ⟹ 1 : *Isochoric displacement*

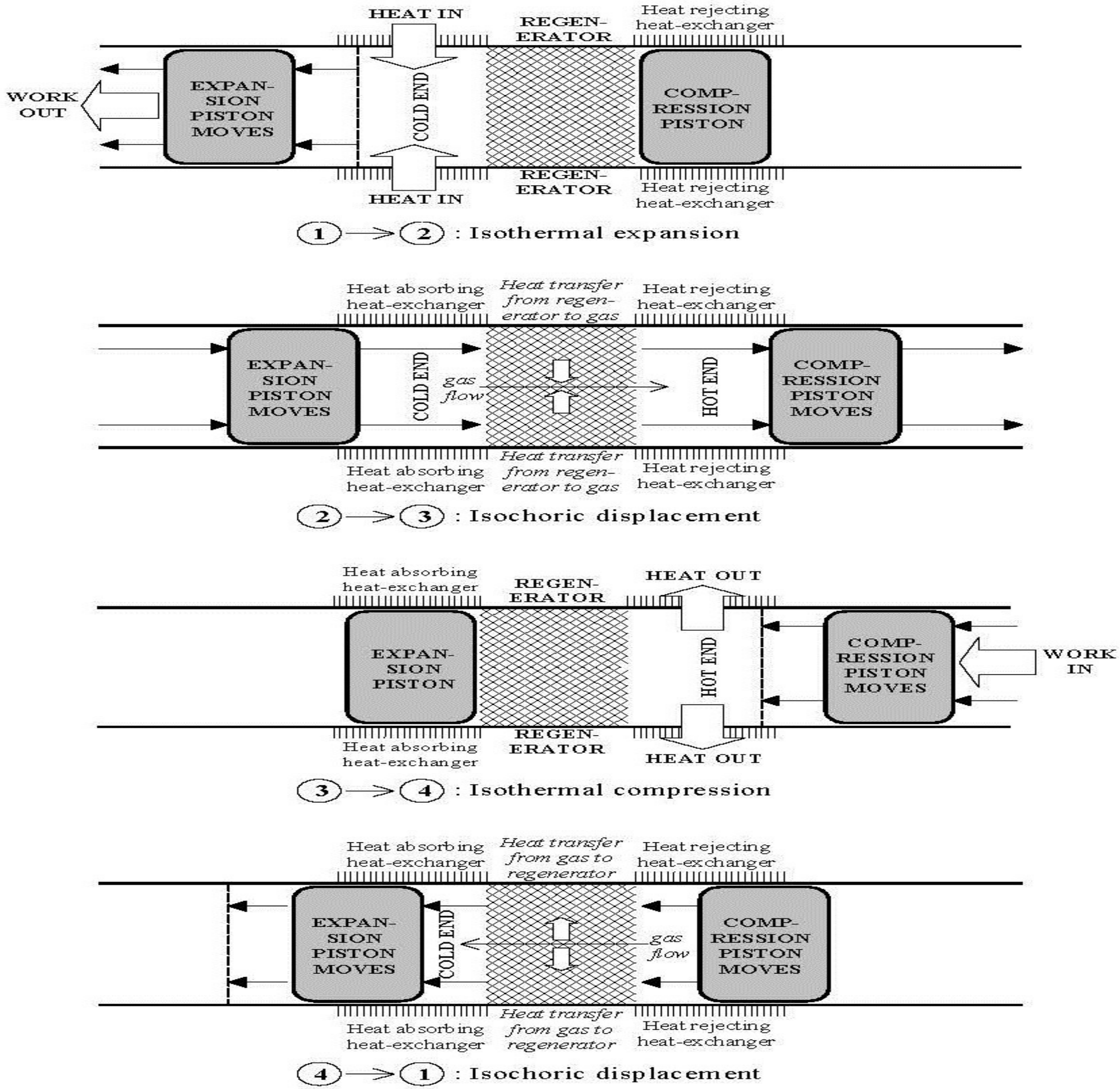


Figure 3. Thermodynamic processes in the ideal Stirling-cycle refrigerator or heat-pump as shown on a simplified α-configuration machine.

Working Substance in Stiriling Refrigeration Cycle:-

Crucial factors for high COP in Stiriling Cycle are:-
- High regenerator efficiency
- High heat transfer coefficients in compressor and expander spaces
- Low pressure drop in the system
- Low work of compression

This means we require a working substance which has high thermal conductivity simultaneously with temperatue conducticity simultaneously with high thermal diffusivity,it should have low value of γ (ratio of specific heats)

GAS	k(w/m.K)	μ*(10^5)(kg/m.s)	γ
Air	0.02624	1.983	1.4
Hydrogen	0.182	1.554	1.409
Helium	0.1491	2.012	1.667

Hydrogen is the prefered gas for stiriling cycle refrigeration as it has
- High thermal conductivity
- Lowest viscocity
- Thermal diffusivity is also high
- Ratio of specific heat is quite low

Comparison Between Striling Refrigeration and Vapour Compression Refrigeration Cycle:-

Criteria	STIRLING REFRIGERATION	VAPOUR COMPRESSION CYCLE
General	• No phase change in the refrigerant • Refrigerant contained with in stirling cooler(closed) • Constant high efficiencies for a large capacity range	• Gas-liquid phase change refrigerant • Refrigerant flows throughtout the system(open system) • Decreasing capacities for small capacities
Target COP	3.1 (approaches carnot value)	Lower than 2.1
Reliability	High	High
Cost	Lower	Higher
Starting Current	Low	High
Noise	Very low	Moderate
Refrigerant used	Helium,Hydrogen (Environment Friendly)	HFCs(R-134a)

Application of Stirling Cycle Refrigeration

***Stiriling Refrigeration can be applied to*:-**

1. *Cryocooler*

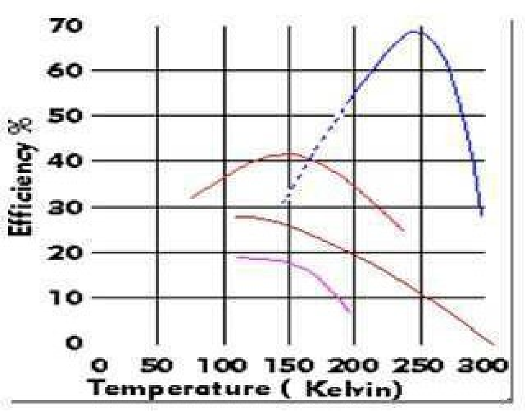
A Cryocooler is a standalone cooler, usually of table-top size. It is used to cool some particular application to cryogenic temperatures 65-250K

Different cycrocoolers available are:-

- Ideal heat exchangers and regenerators
- Stirling refrigerators
- Joule-Thomson cooler

Comparison of Stirling Cycle with other cycrocoolers:-

Generating sufficient cold to liquefy gases can be done in various ways. The choice is often determined by the temperature required to liquefy the gas, and the degree of efficiency within a given temperature range. Within the cryogenic range of 65 to 250 K, the least efficient process is the Joule-Thomson method. This is based on expansion of high-pressure gas by throttling. The compressor, heat exchanger and expander technology used in the Claude (turbine) process is only marginally more efficient,



The Stirling Cycle process is by far the most effective principle for cryogenic operations.Consequently, all Stirling cryogenerator feature this technique. It is a proven and tested concept that assures the highest level as the blue line in the figure indicates

Application of Stirling Cycle Refrigeration(cont.....)

- It can be applied to domestic,single-temperature refrigerator
- It can also be applied to all other types of refrigerators ranging from small coolers to fridge freezer combinations with 3 compartments
- It can be used in business market (hotels,retails.etc)
- Leisure market (coolboxes)
- Industrial market (for cooling measuring –instruments)
- Global cooling is developing a super-insulated solar powered cool box with Stiriling technology

Advantages of Stirling Cycle Refrigeration:-

- Stiriling cooling systems operate with very low noise emissons
- Absorption type refrigerators use lot of energy while compared to stiriling refrigeration
- Hydrogen is the working fluid which is environmental friendly compared to cfcs ,it can replace as an alternative
- With regenerator COP approaches carnot COP
- Components used in stiriling refrigeration can be easily reusable and recyclable

Disadvantages of Stirling Cycle Refrigeration:-

- This can be employed in small refrigeration capacity application as the surface area of heat transfer available is the area of expansion space only and heat transfer coefficients with the gas is very low

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