BASIC DESIGN OF
STIRLING ENGINE

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Chapter 1

INTRODUCTION

Stirling engines are external combustion heat engines that usually utilize air or other gases as working fuel. They are capable of operating on any source of heat such as sun, wood, coal, or field waste. The Stirling cycle lends itself to a wide variety of physical forms, and some of these are sufficiently simple to make effective and strong ways of power generation in developing countries, using any local fuel or solar energy as their heat source. Some other works had been made in liquid piston water pumps, free cylinder water pumps, low pressure air engines, diaphram engines, and cooling machines. Simple liquid piston water pumps of reasonable efficiency and reliability are in the late stages of prototype development. Free cylinder water pumps, in which a free piston Stirling engine is arranged so that it pumps by direct action of its hermetically sealed cylinder on the water, are now well proven. Both of these can use solar, solid fuel or biogas heat sources.

Now there is a new design of Stirling engine for produce 1 km of shaft power at 1200 rpm with a slightly pressurized, dry crankcase using permanently lubricated bearings. This machine is readily adaptable to biogas or solid fuels, rice husks, or bagasse and has universal applications as a result of its rotating shaft power output.

Stirling engines are also being developed for cooling tasks, driving either Rankine cycle compressors or Stirling cycle coolers. Both free piston and rotating shaft machines are being developed for food freezing and domestic heat pumps, for both heating and cooling. Possibly the simplest cooling engine is the duplex Stirling, free piston, heat driven heat pump. This machine contains both the heat engine and heat pump within the same hermetically sealed pressure enclosure, which is free of lubricants or any other fluid than the working gas. Applications of the duplex Stirling engine include food coolers or freezers, refrigerators, portable vaccine coolers, and living space air conditioning. These machines could probably best be driven by biogas, alcohol or other liquid or gaseous fuels, but could be adapted to operate on solids such as coal, wood, rice husks, bagasse, etc.

Another emerging technology of importance is the large stationary Stirling engine, ranging from 100 Kw to several megawatts of power output, and are under development for stationary power generation and cogeneration using solid fuels and would be useful for those purposes elsewhere.

Chapter 2

LITERATURE SURVEY

The first British working model of a hot air engine was introduced and patented by Sir George Cayley and later adopted by Mr. Buckett. This engine operated on an open cycle and consisted of two vertical pistons directly connected so as to make the compression stroke of one of the expansion stroke of the other. This engine was not equipped with a regenerator and had a thermal efficiency of 8 per cent. The Stirling brothers seem to have been the first to carry into practice the principle of a cycle heat engine. Their Stirling engine operated on a closed cycle and introduced a new feature, regeneration. Stirling made the heated air, which had already done work, pass through a wire gauge or this metal plates to take up heat from the gas. The heat momentarily stored is then transferred to the cold air coming from the cooler. This air then returns to the hot end to take up heat again thus completing the cycle. By this method the Stirling brothers were able to produce a reversible cycle. The actual engines operating between 350° and 65° F converted into work only 7 per cent of the heat supplied. Such an engine rated at 40 hp was used for three years to drive machinery in a foundry.

Most of the hot air engines which were developed later were based on the Stirling engine. Robinson built a compact engine with two pistons at right angles to each other operating on a closed cycle. The engine designed by British engineer Bailey resembles the Robinson engine. Most of the work described above was done in England and nothern Europe.

The hot air engines developed up to 1896 were slow, large and uneconomical; they offered little competition with the newly developed internal combustion engines and therefore temporarily disappeared from use. In 1946 the reseearch laboratories of N.V. Philips' Glueilampenfabrieken of Eindhoven, Holland, resumed work on hot air engines using modern concepts regarding to the air processes, flow resistance, heat transfer and properties of newly developed materials.

The engines developed by Philips operating on air cycle have two loaded pistons while the hot and the cold spaces can be either both in one cylinder or in two separate cylinders (v-construction). Most of the old air engines had one loaded and one transfer piston. For larger horsepowers, Philips developed the multi-cylinder air engine in which the nos of hot air cycles take place simultaneously. In this type of engine only one piston is needed per system and consequently no transfer piston is required. All the loaded pistons act on a common shaft. Fairly efficient engines of this type from 20 to 30 hp have been put into operation by Philips Laboratories.

David R. Gedeon of Sunpower Incorporated, Athens, Ohio, U.S.A., discussed the problem of numerical optimization with any computer simulation capable of modeling a Stirling cycle machine. A number of optimizations were done on free piston Stirling engines, each of them different from the others but evolving towards a software package of universal application.

Willia T. Beale of Sunpower Incorporated, Athens, Ohio 45701, U.S.A., designed a free cylinder Stirling engine for use as a solar water pump. The pumping action takes place as a result of the reciprocating motion of the cyclinder of the sealed free piston engine, this cylinder motion being used to directly drive a reciprocting water pump.

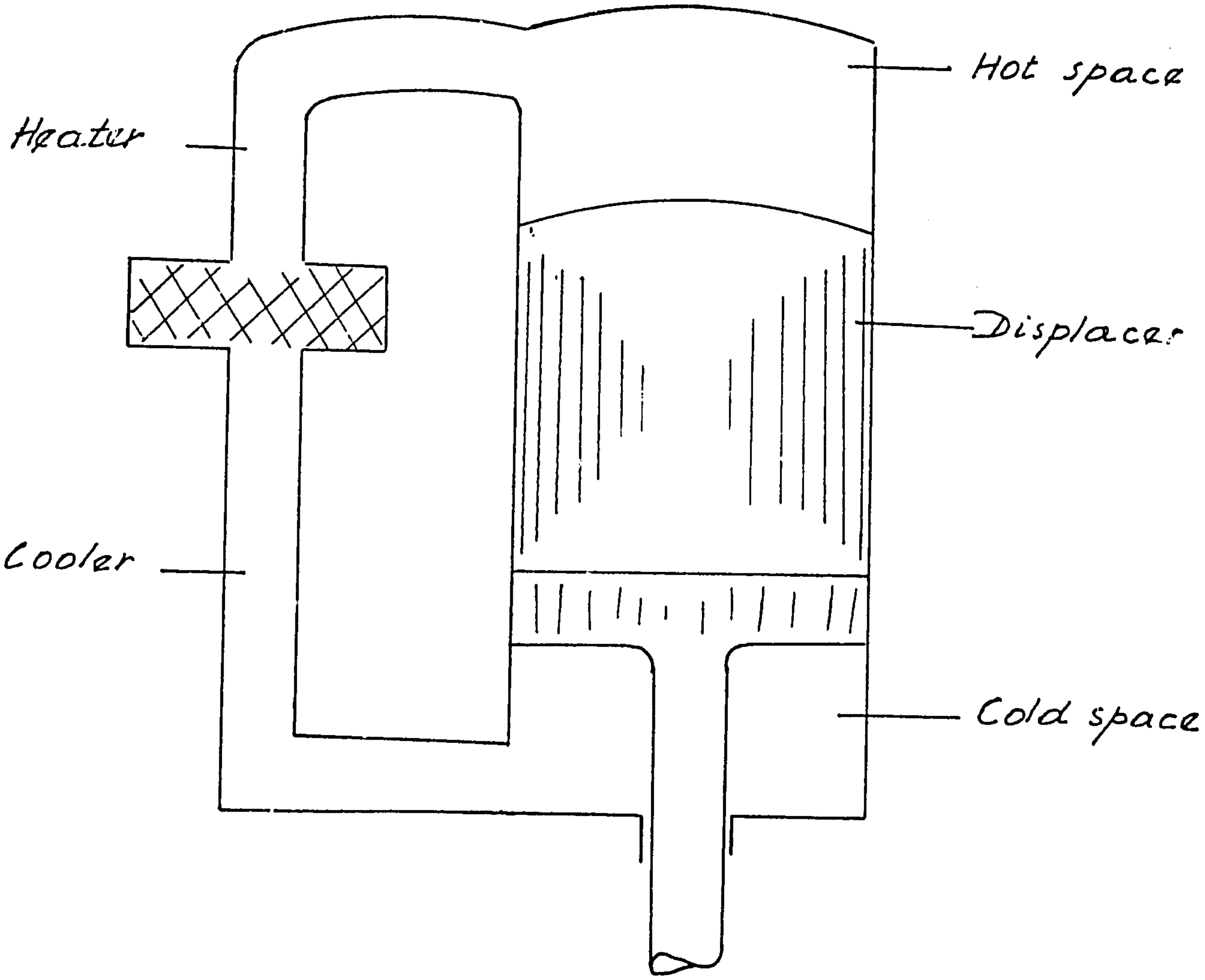
Chapter 3

THEORY OF STIRLING ENGINE

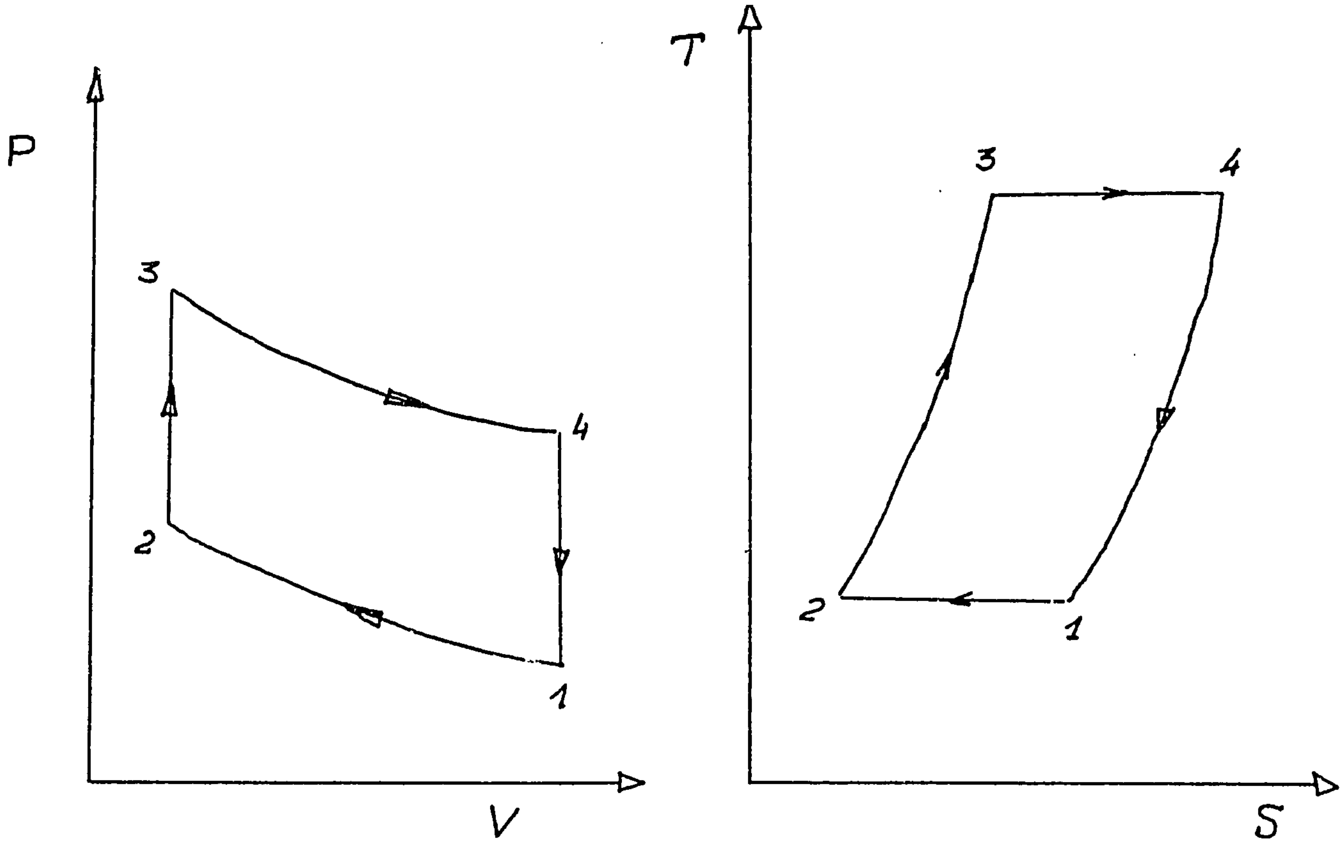
The basic operating principle on which the Stirling engine works is simply that the pressure of air or any gas, will increase if it is heated and decrease if it is cooled. The cylinder of a Stirling engine contains a certain amount of gas. In the early engines this gas was air, usually at normal atmospheric pressure, but in a modern engine it would more likely be helium or hydrogen. This working gas contained in the engine is alternately caused to be heated, then cooled, over and over again. When the gas is heated, its pressure rises and it "pushes" against and moves a piston thereby doing work. After the piston has been pushed as far as it will go, the gas is then cooled and its pressure drops, "sucking" the power piston back to its starting position, at which point the heating cycle begins again. The piston thus continues to go back and forth, reflecting the internal pressure changes of the working gas as it is alternately heated and cooled.

The Stirling Cycle

(a) Principle of the displacer system



(b) Thermodynamic cycle



1-2 Isothermal compression at the lower temperature

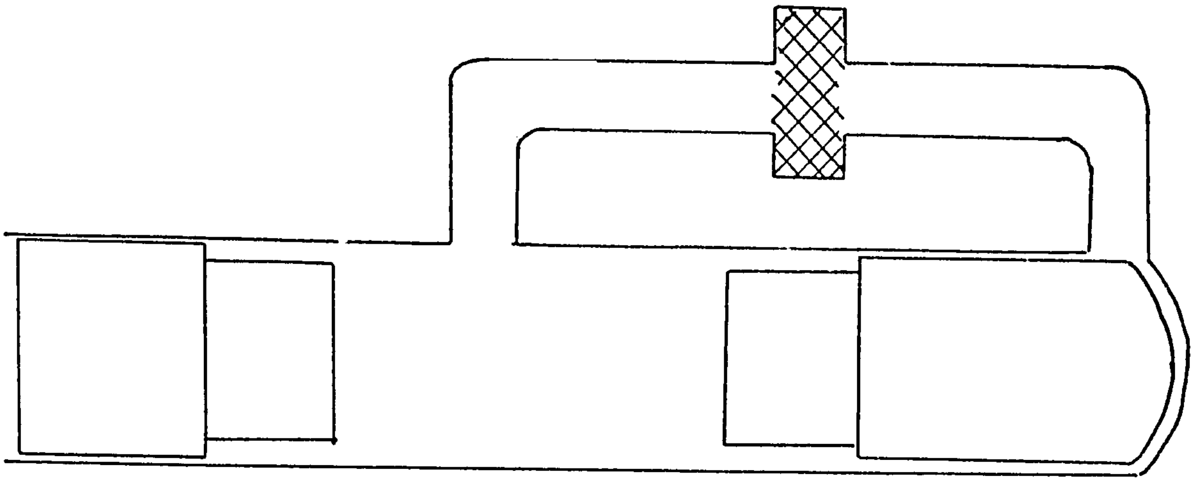
2-3 Heat input at constant volume, raising gas to upper temperature, increases pressure still further

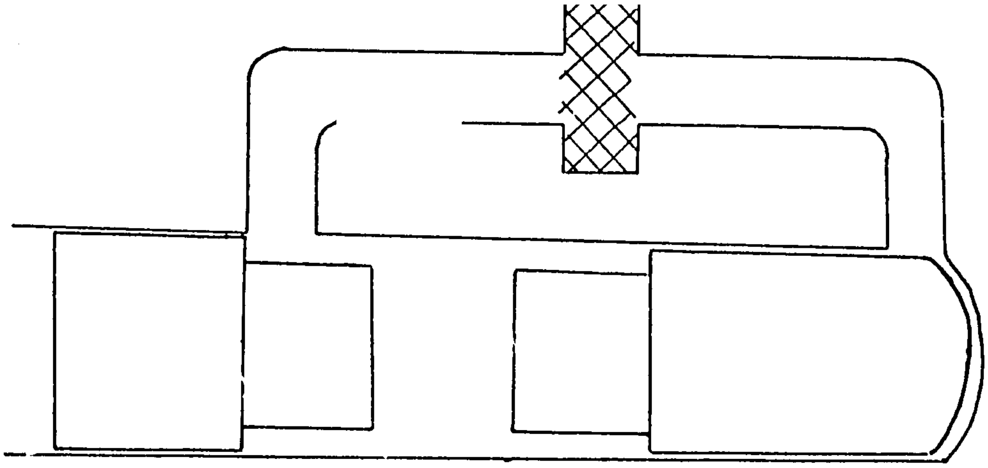
3-4 Isothermal expansion at upper temperature

4-1 Gas cooled to lower temperature at constant volume

(c) Diagram of the cycle

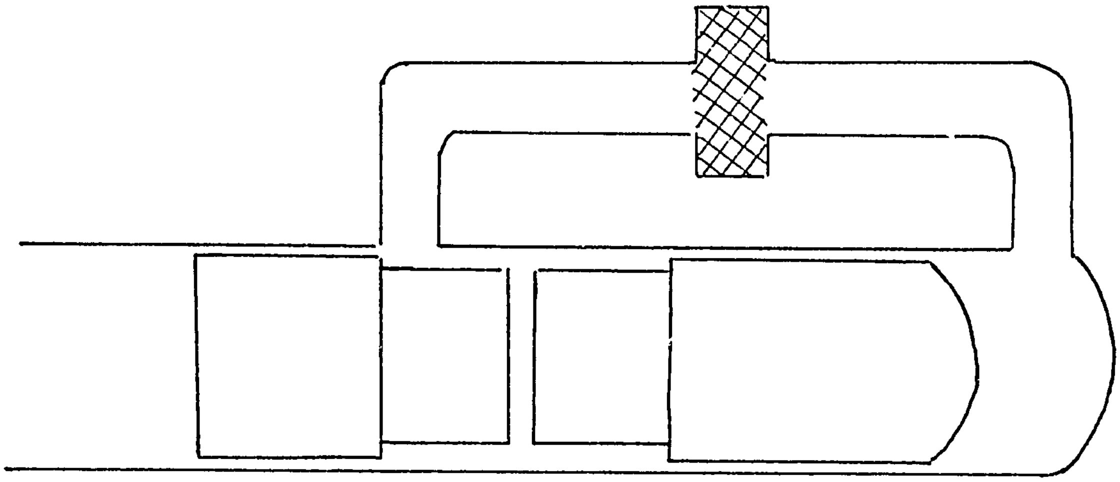
I Piston at bottom dead centre.
Displacer at top dead centre
All gas in cold space

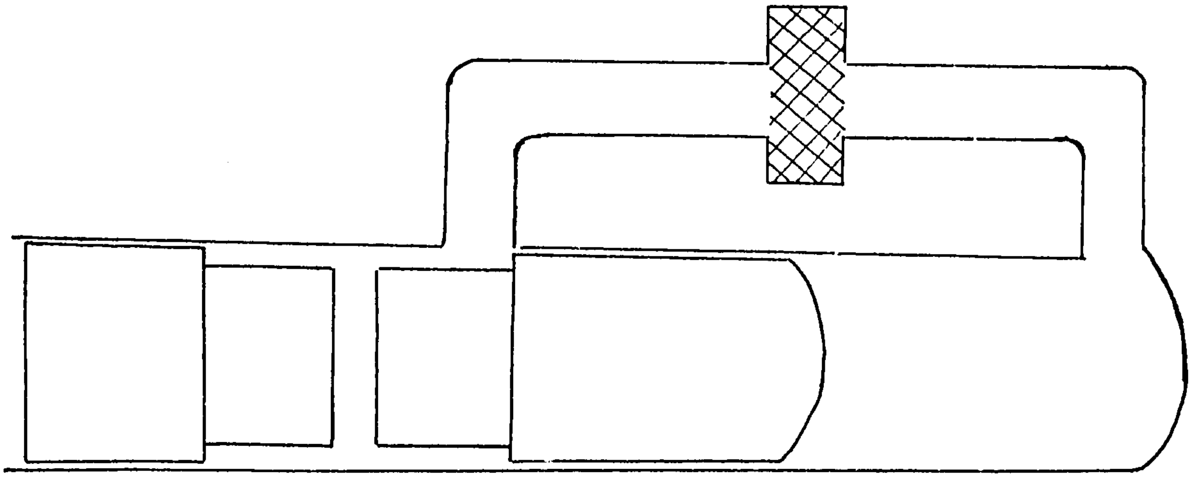




II. Displacer remaining at top dead centre,
piston has compressed gas at lower temperature.

III Piston remaining at top dead centre. Displacer has shifted gas through cooler, regenerator and heater into hot space.





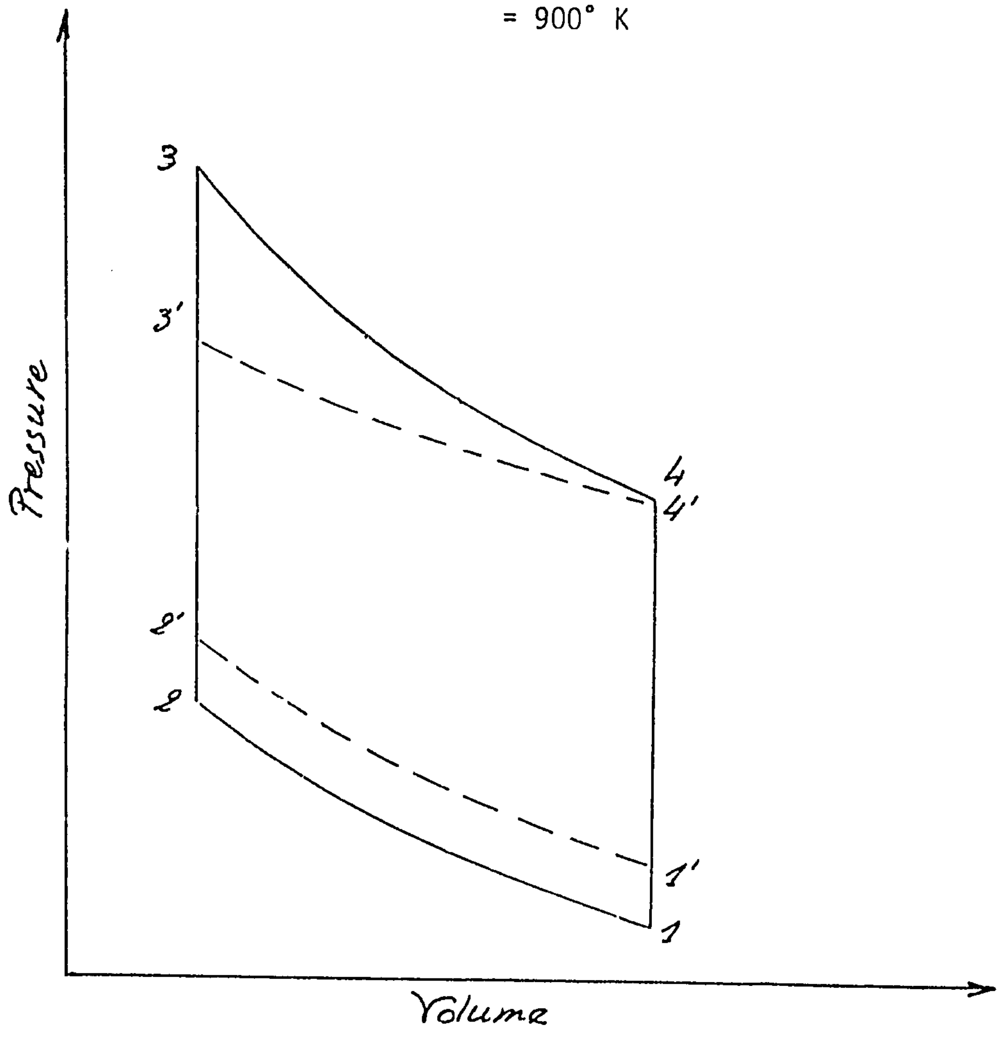
II Hot gas expanded. Displacer and piston have reached bottom dead centre together, with piston stationary, displacer now forces gas through heater, regenerator and cooler into cold space thus recreating situation -I-

Chapter 4

Design approach of 10 kW hydrogen fueled Stirling engine.

Design Conditions

Volume of hydrogen gas = 100 cm^3
Initial pressure = 100 atm i.e. 10M Pa
Compression ratio = 2
Tc = cold side temperature = 27° C
= 300° K
Th = hot side temperature = 627° C
= 900° K



-----Stirling cycle, no dead volume, isothermal compression and expansion

-----Stirling cycle, 33% dead volume, isothermal compression and expansion

$PV = 100 \times 10^5 \ N/M^2 \times 100 \times 10^{-6} \ m^3 = 1000$ Joules

$dW = PdV = PV \frac{dV}{V}, = \frac{1000}{v} dV$

$W = 1000 \ln (\frac{50}{100}) = -693.14$ Joules

-ve means work is supplied by perfect gas laws

$PV = mRT = m \frac{\overline{R}}{M} T$ or $PV = N\overline{R} \ TC$

where

P = gas pressure in N/M^2 or M Pa

P = gas pressure in N/M^2 or M Pa

V = gas volume, m^3 or cm^3

$\underline{n}$ = Nos. of moles of hydrogen

$\overline{R}$ = Universal gas constant = 8.134 Joule/K.mal

Tc = cold side temperature, °K

$100 \times 10^5 \ N/M^2 \times 100 \times 10^{-6} \ m^3 = n \times 8.314 \times 300$

$n = \frac{1000}{8.134 \times 300} = \frac{10}{8.134 \times 3} = 0.4009$ moles

$dW = PdV = PV\frac{dV}{V}$

$i.W = NRTC \int \frac{dV}{V} = -NRTc \ln (\frac{V_2}{V_1}) = -0.4 \times 8.314 \times 300 \ \ln (\frac{900}{50}) = 693.14$ Joules

Gas is heated from 300° K to 900° K
Let us assume 100% regenerative efficiency

Thus $q(r) = Nc_v \ (Th - Tc)$

cv = heat capacity of hydrogen at constant volume = 21.030 J/K.mal

hence $q \ (r) = 0.400o \times 21.030 \times (900 - 300) = 5059$ Joule

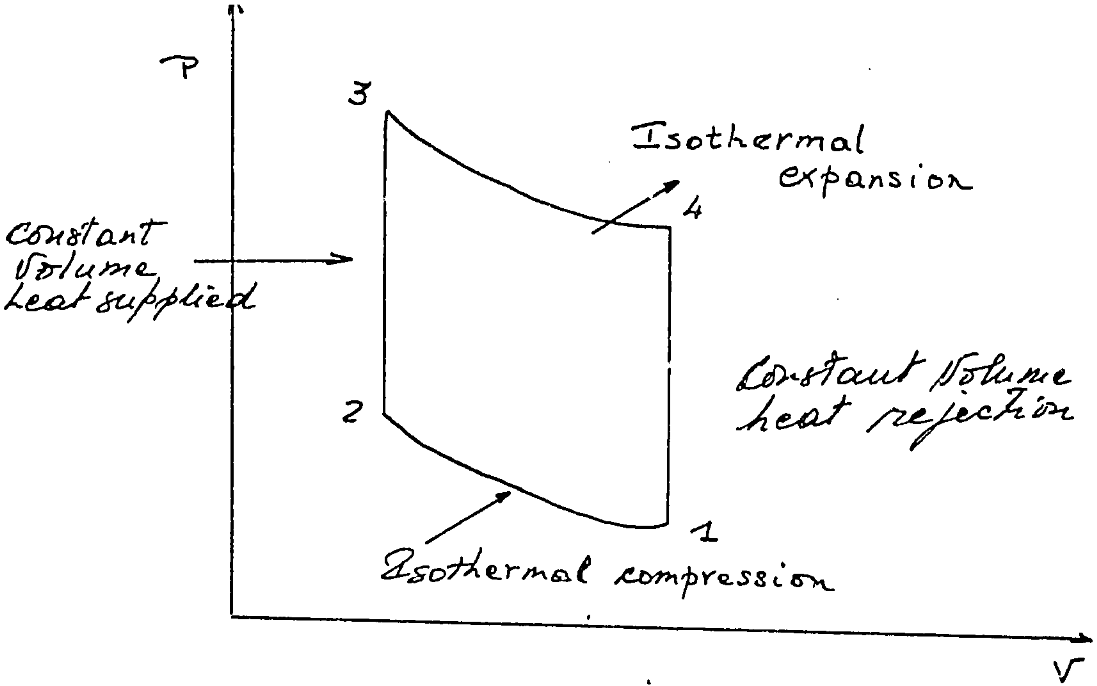
Process $\underline{1-2}$ $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$ as $T_1 = T_2$

$P_1 V_1 = P_2 V_2$ or $P_2 = \frac{P_1 V_1}{V_2} = \frac{100 \times 10^5 \times 100^2}{50} = 2 \times 10^7 \ N/M^2$

$V_2 = V_3 = 50 \ cm^3$

$P_3 V_3 = N\overline{R} \ Th_3$ or $P_3 = \frac{NR \ Th_3}{V_3} = \frac{0.4009 \times 8.314 \times 900}{50 \times 10^{-6}} = 60 \times 10^6 \ N/M^2$

$W_{(out)} = NR \ Th \ln \frac{V_1}{V_2} = 0.4009 \times 8.314 \times 900 \times \ln \frac{100}{50} = 2079.4$ Joules



$Q_{3-2} = Q_{4-1}$ for perfect regeneration.

The net work generated per cycle is $W_{net} = W_{(in)} + W_{(out)} = 693.14 + 2079.4$

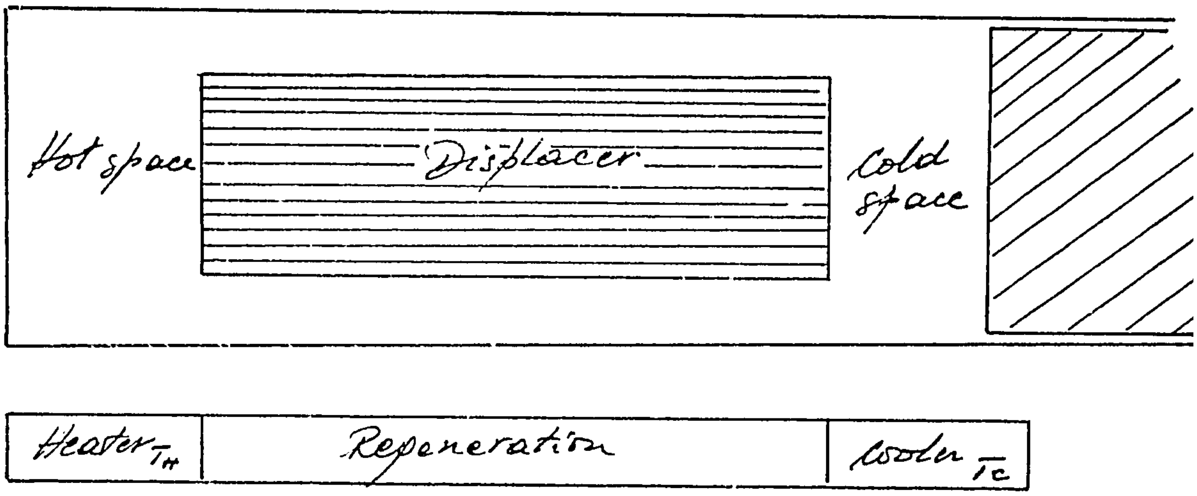
$= 1386.3$ Joules

$$\eta_{cycle} = \frac{W_{(net)}}{q_{(in)}} = \frac{1386.3}{2079.4} = 0.6667$$

In general the efficiency is $\eta = \dfrac{W_{(in)} + W_{(out)}}{q_{(in)}} = \dfrac{NR\ Tc\ \ln \frac{V_2}{V_1} + NR\ Th\ \ln \frac{V_1}{V_2}}{NR\ \ Th\ \ln \frac{V_1}{V_2}}$

$$\eta\ \text{carnot} = \frac{Th - Tc}{Th} = \frac{9w - 300}{900} = 0.667$$

Stirling cycle, zero dead volume, imperfect regeneration.



Regeneration efficiency = $\eta_R = \dfrac{T_R - T_c}{T_h - T_c}$

T_R = temperature of regenerator,

During heat transfer the heat from the regenerator = $q(r) = nc_v\ (T_R - T_C)$ and the heat from the has heater is $q(h) = nc_v\ (T_h - T_R)$

$$(\eta_R \text{ (imperfect)} = \frac{Wnel-}{Q(in)} = \frac{NR\,T_H \ln \frac{V_1}{V_2} - NRTc \ln \frac{V_1}{V_2}}{NR\,T_H \ln \frac{V_1}{V_2} + N\,C_v\,(T_H - T_R)}$$

$$= \frac{T_H - T_c}{T_H + \frac{C_v}{R}\,\frac{(T_H - T_R)}{\ln \frac{V_1}{V_2}}}$$

Now $\eta_R = \frac{T_R - T_c}{T_H - T_c}$

or $1 - \eta_R = 1 - \frac{T_R - T_c}{T_H - T_c}$

$$= \frac{T_H - T_R}{T_H - T_c}$$

or $T_H - T_R = (1 - \eta_R)\,(T_H - T_c)$

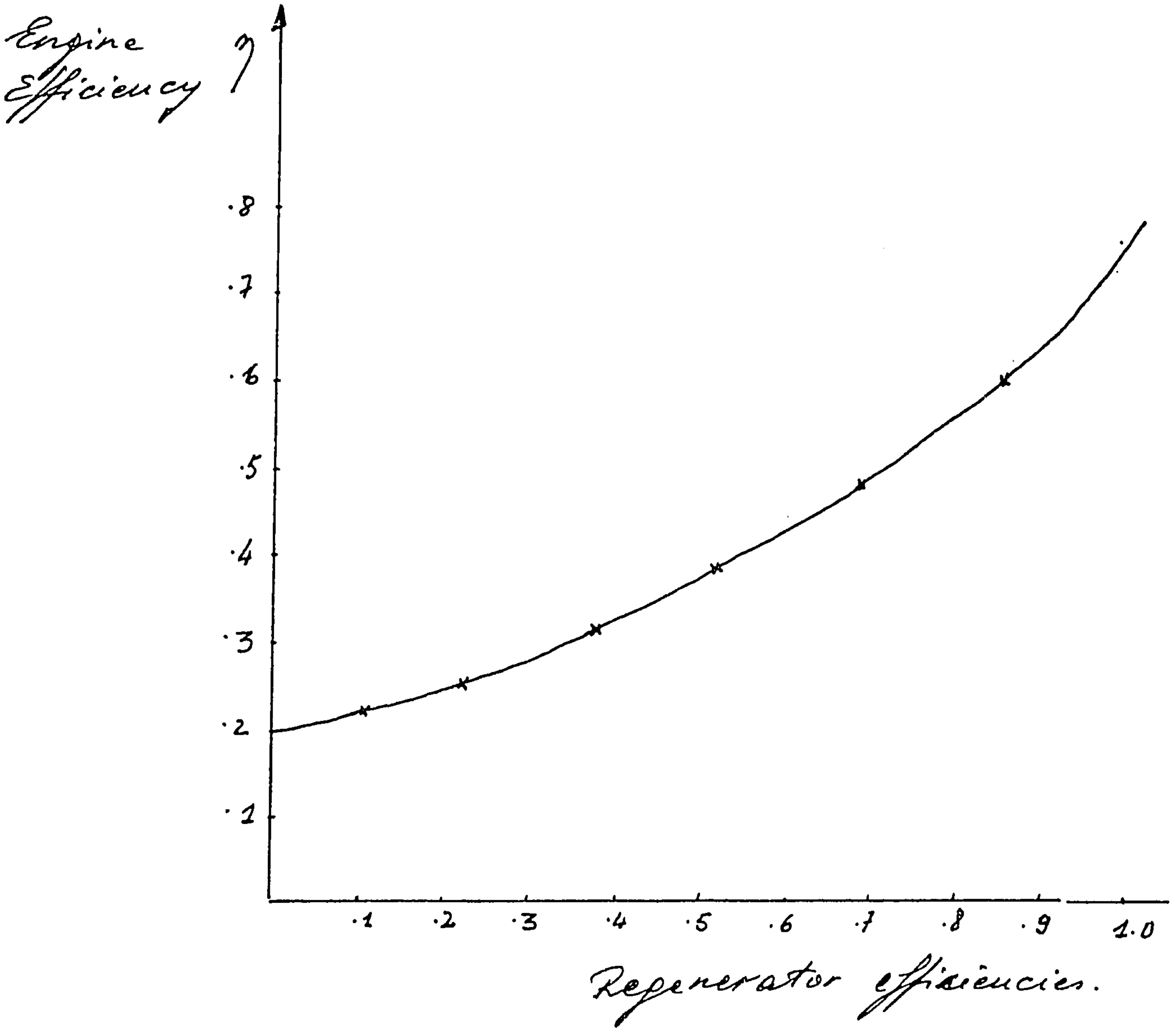
$$\eta_{cycle} = \frac{T_H - T_c}{T_H + \frac{C_v\,(T_H - T_c)(1 - \eta_R)}{\ln \frac{V_1}{V_2}}}$$

If $\eta_R = 1$, η_{cycle} reduces to $\frac{T_H - T_c}{T_H}$ carnot efficiency

substituting the numerical values

$$\eta_{cycle} = \frac{900 - 300}{900 + \frac{21.030 \times (900 - 300)\,(1 - \eta_R)}{8.314 \ln \frac{100}{50}}}$$

$$= \frac{600}{900 + 2189.5\ (1 - \eta_R)}$$



Effect of Regenerative Effectiveness on efficiency

Rallis derived the formula for the efficiency of a Stirling Engine with no dead volume but imperfect regeneration.

$$\eta \text{ cycle} = \frac{(\gamma - 1)(t - 1)\ l_n\ r}{(1 - \gamma_R)\ (t - 1) + t\ (\gamma - 1)\ l_n\ r}$$

where $\gamma = cp/cv$, $t = \frac{T_H}{T_c}$,

$r = \frac{V_1}{V_2}$ If $\eta_R = 1$

$$\eta \text{ cycle} = \frac{(\gamma - 1)(t - 1)\ l_n\ r}{t\ (\gamma - 1)\ l_n\ r} = \frac{(\frac{cp}{cv} - 1)\ (\frac{T_H}{T_c} - 1)\ l_n \frac{V_1}{V_2}}{\frac{T_H}{T_c}\ (\frac{cp}{cv} - 1)\ l_n \frac{V_1}{V_2}}$$

$$\frac{\frac{T_H - T_c}{T_{\cancel{c}}}}{T_H/T_{\cancel{c}}} = \frac{T_H - T_c}{T_H}$$

He dervied also a formula for work

$$\frac{W}{\Delta V X P_1} = \frac{r\ (t - 1)\ l_n\ r}{(r - 1)}$$

where $\Delta V = (V_1 - V_2)$, $r = \frac{V_1}{V_2}$, $t = \frac{T_H}{T_c}$

$$\text{or} \quad \frac{W}{\Delta V X P_1} = \frac{\frac{V_1}{V_2}\ (\frac{T_H}{T_c} - 1)\ l_n\ \frac{V_1}{V_2}}{(\frac{V_1}{V_2} - 1)}$$

or $$W = \frac{P_1 \times (V_1 - V_2) \times \frac{V_1}{V_2} (\frac{T_H}{T_c} - 1) \ln \frac{V_1}{V_2}}{(\frac{V_1}{V_2} - 1)}$$

Substituting the numerical values

$$W = \frac{50 \times 10^{-6} \times 10^{7} \times 2 \ (\frac{900}{300} - 1) \times \ln 2}{(2 - 1)} = 1386.3 \text{ Joules as before.}$$

Stirling cycle, variable dead volume, perfect or imperfect regeneration.

The addition of dead volume which is present in any real engine decreases the work available per cycle. Assume that the annulus between displacer and cylinder wall has some per centage of dead volume. The gas contained in this annulus is

$$\eta = \frac{P}{R} \int_{0}^{X} \frac{dV}{T_x}$$

where V = total volume of annulus

dV = Adx = differential volume of the annulus
CA = flow area of annulus
x = distance along annulus
X = total length of annulus

Let Tx = Ax + c, when x = o

$Tx = T_H = C$

when x = X

$$T_c - Ax + c = Ax + T_H \quad \text{or} \quad A = \frac{T_c - T_H}{X} \quad \text{or} \quad Tx = \frac{T_c - T_H}{X} x + T_H$$

substituting the value of T_x in equation

$$\eta = \frac{P}{R} \int_{0}^{X} \frac{dV}{T_x}$$

and integrating, we have

$$\eta = \frac{PV \ln ({}^{T}H/{}^{T}c)}{R\ (T_H - T_c)} = \frac{PV}{R(T_H - T_c)/\ln(\frac{T_H}{T_c})} = \frac{PV}{R\ T_R}$$

where $T_R = \frac{T_H - T_c}{\ln (\frac{T_H}{T_c})}$ = effective gas

temperature of the regenerator dead volume
Thus when T_H = 900°K and T_c = 300°K

$$T_R = \frac{900-300}{\ln\ 900} = 546.1°K$$

Now $\frac{TH + Tc}{2} = \frac{900 + 300}{2} = \begin{array}{l} 600°K \\ \approx 540.1°K \end{array}$

Hence it can be assumed $T_R = \frac{TH + Tc}{2}$

If P be the average pressure for expansion

$$n = \frac{P}{R}\left[\frac{VH}{TH} + \frac{VR}{TR}\right] = \frac{30 \times 10^6}{8.314}\left[\frac{100}{900} + \frac{5}{546.1}\right] = 0.7313 \text{ mol}$$

The equation for the gas expansion is

$$P = \frac{NR}{\frac{VH}{TH} + \frac{VR}{TR}} = \frac{0.7313 \times 8.314}{\frac{VH}{900} + \frac{50}{540.1}} = \frac{A}{VH + B} \quad \text{where } \begin{array}{l} A = 5472 \\ B = 82.4 \end{array}$$

the work output by expanding from $VH_1 = 50 \text{ cm}^3$ to $VH_2 = 100 \text{ cm}^3$

$$W(out) = \int_{VH_1}^{VH_2} P \, dV_H = \int_{VH_1}^{VH_2} \frac{A \, dV_H}{V_H + B}$$

$$= A \ln \left(\frac{VH_2 + B}{VH_1 + B}\right) = 5472 \ln \left(\frac{100 + 82.4}{50 + 82.4}\right) = 1753 \text{ Joule}$$

the equation for gas compression is

$$P = \frac{NR}{\frac{V_c}{Tc} + \frac{V_R}{T_R}} = \frac{0.7313 \times 8.314}{\frac{V_c}{300} + \frac{50}{546.1}} = \frac{C}{V_c + D} \quad \text{where } \begin{array}{l} C = 1824.02 \\ D = 27.4 \end{array}$$

hence:

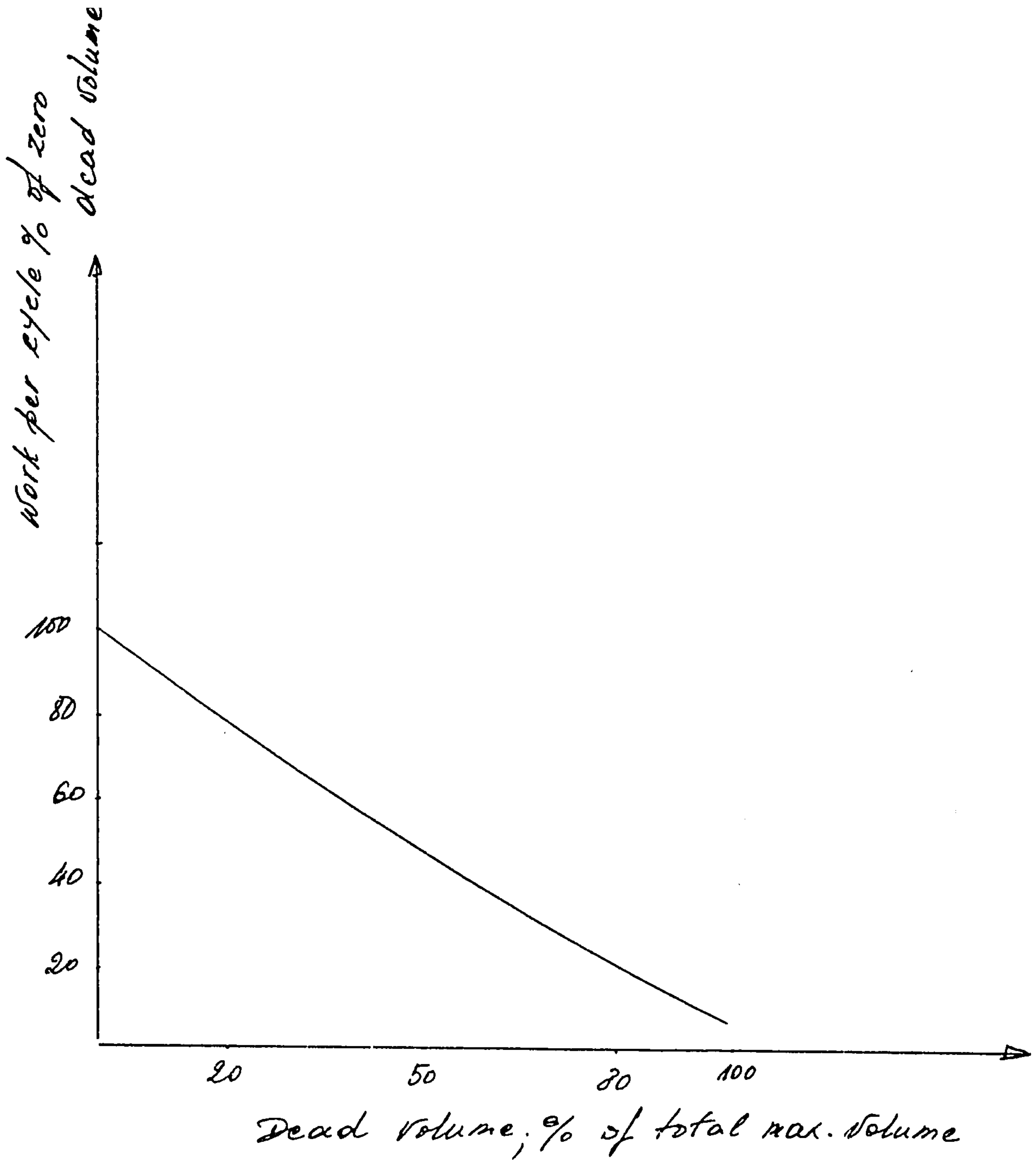
$$W(in) = C \ln \left(\frac{Vc_2 + D}{Vc_1 + D}\right) = 1824.02 \ln \left(\frac{50 + 27.4}{100 + 27.4}\right. = 908.37 \text{ Joule}$$

Therefore the net work is

$W \text{ (net)} = W \text{ (out)} + W \text{ (in)}$

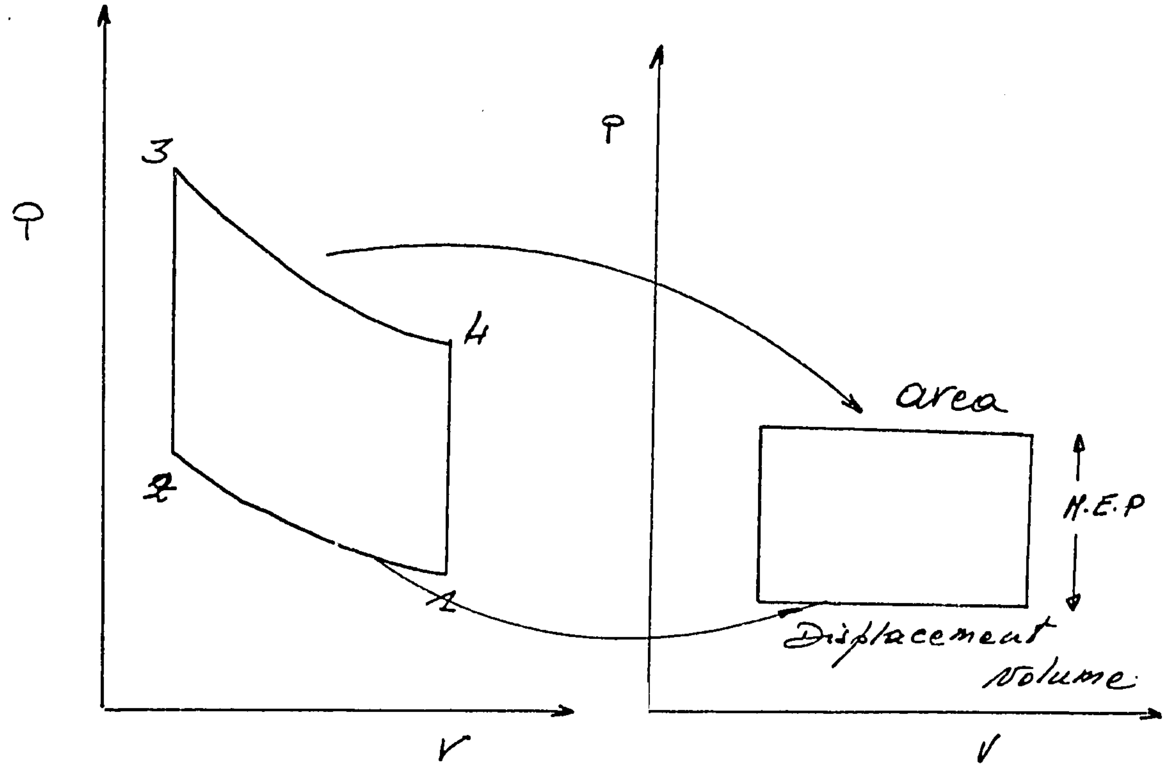
$= 1753.08 - 908.37$

$= 844.71$ joules



Ideal efficiency of Stirling engine = 0.607 (with perfect regeneration)

None with imperfect regeneration of 70% regeneration efficiency, η of the engine = 0.4 = $\frac{\text{output}}{\text{input}}$ or Input = $\frac{\text{output}}{0.4}$ = $\frac{10}{0.4}$ = 25 kW



$$\text{MEP} = \frac{\text{net work}}{V_1 - V_2} = \frac{844.71}{(100 - 50)} = \frac{844.71}{50 \times 10^{-6}} \text{ N/m}^2 = 16.89 \times 10^6 \text{ N/m}^2 = 16.89 \text{ MPa}$$

work done = MEP x stroke volume

$$\text{BHP} = \frac{\text{work done}}{\text{time}} = \frac{\text{MEP} \times \text{stroke volume} \times N}{w}$$

where N is R.P.M.

Let L/D = 1 where L = stroke length of power piston
B = bore of power piston

$$\text{Now BHP} = \frac{\text{MEP} \times V_s \times N}{2} = \frac{\text{PLAN}}{2} = \frac{P \times L \times \frac{\pi}{4} D^2 \times N}{2} = \frac{P \times \frac{\pi}{4} L^3 \times N}{2}$$

Substituting the values of P, L and N in this equation:

$$\frac{16.89 \times 10^6 \times P/4 \times L^3 \times 10^{-6} \times 1000}{60 \times 2 \times 1000} = 10$$

or $L^3 = \frac{10 \times 60 \times 2 \times 4}{16.89 \times \pi} = 91\ cm^3$ or L = D = 4.5 cm = 4.5 cm

Stroke of power piston = 4.5 cm
Diameter of power piston = 4.5 cm

$$\text{Compression ratio} = \frac{\text{displacer stroke volume + piston stroke volume}}{\text{displacer stroke volume}}$$

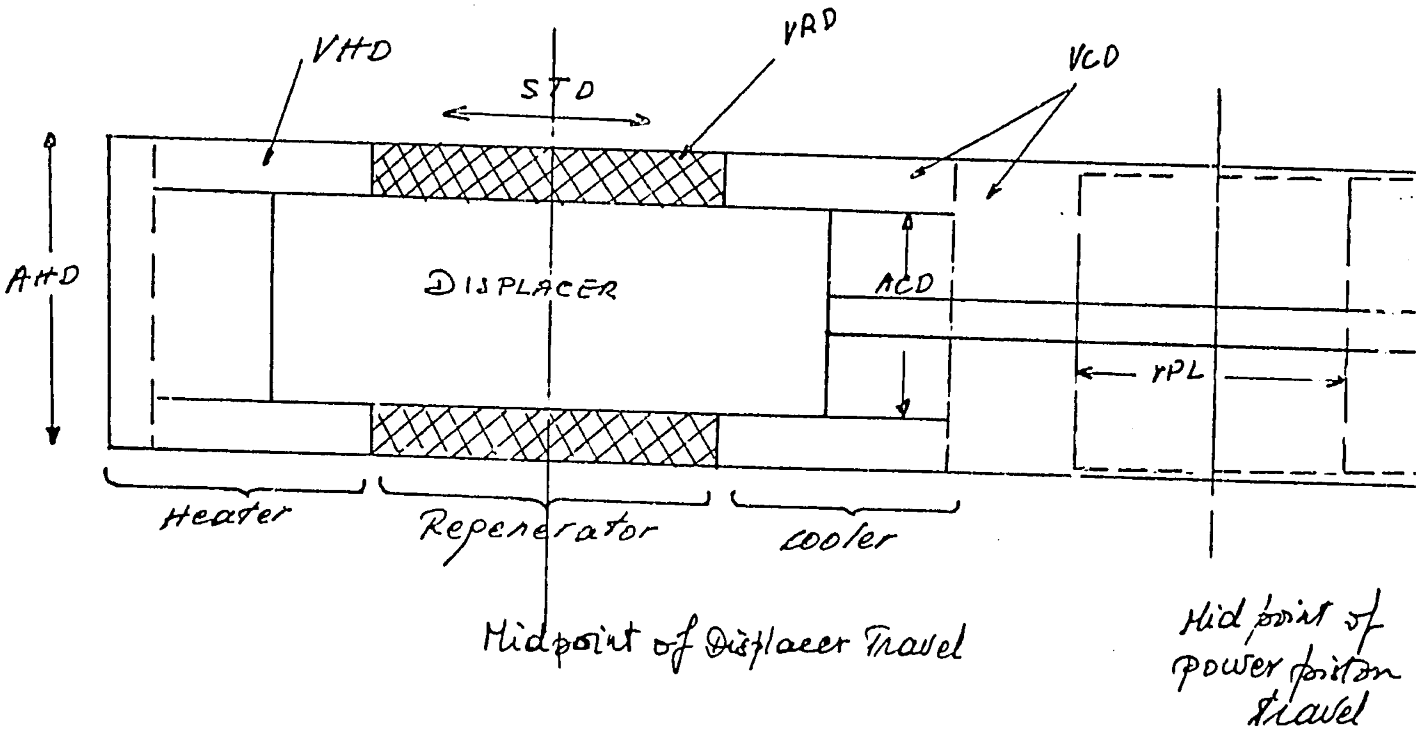
$$= Y + \frac{\text{piston stroke volume}}{Y}$$

where Y = displacer stroke volume

piston stroke volume = $P/4\ L^2 \times L = \frac{Q}{U} \int \pi/4\ L^3 = \frac{\pi}{4} \times (4.5)^3 = 71.5\ cm^3$

Then $\frac{Y + 71.5}{Y} = 2$ or $Y + 71.5 = 2Y$ or $Y = 71.5$

Hence Displacer stroke = 4.2 cm
Diameter = 4.2 cm

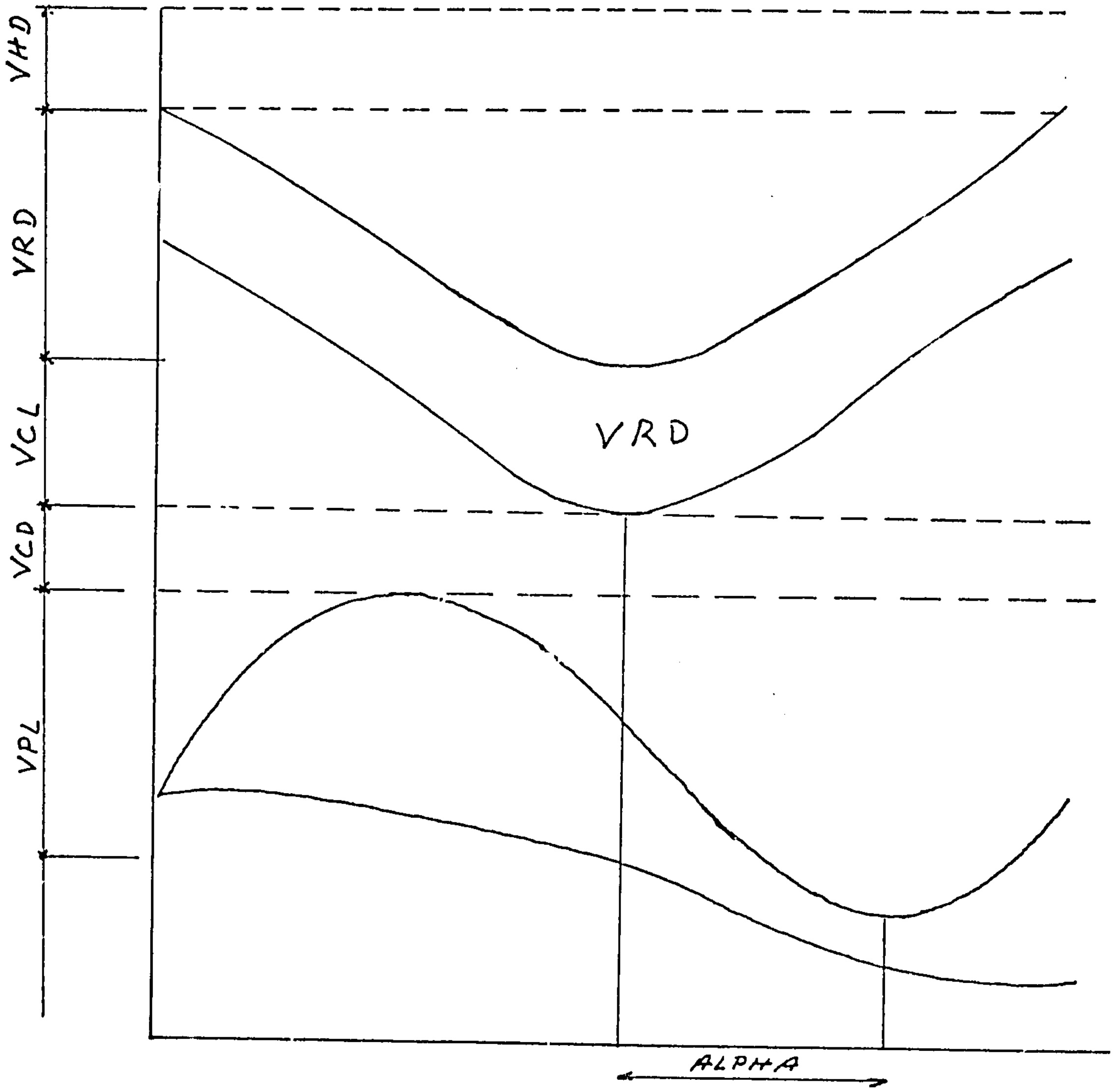


AHD = area of hot face of displacer, cm^2
VHD = hot dead volume, cm^3
STD = stroke of displacer, cm
VRD = regenerator dead volume, cm^3
VCD = cold dead volume, cm^3
ACD = area of cold face of displacer, cm^2
VPL = power piston volume, cm^3
TH = effective hot gas temperature ok
TC = effective cold gas temperature ok
PHI = crank angle, degrees
ALPH= phase angle, degrees

VHL = AHD (STD) - volume of hot chamber]
VCL = ACD (STD) - volume of cold chamber

Hot volume, $VH = \frac{VHL}{2} [1 - \cos (PHI)] + VHD$

Cold volume, $VC = \frac{VCL}{2} [1 + \cos (PHI)] + VCD + \frac{VPL}{2} [1 - \cos (PHI - ALPH)]$


VHD
VRD
VCL
VCD
VPL
VRD
ALPHA

Chapter 5

Potential use of Stirling engines.

Commercial production of stirling engines have not yet started but appears to be imminent for several uses, first of which is water pumping. Simple liquid piston water pumps of reasonable efficiency and reliability are in the late stages of prototype development. Free cylinder water pumps, in which a free piston stirling engine is arranged so that it pumps by direct action of its hermetically sealed cylinder (premiere enclosure) on the water are now well proven and may attract investment from manufacturers if they see a significant commercial market in the near future. Both the liquid piston and the free cylinder stirling engines can use solar, solid fuel on biogas heat sources. The machine is readily adapted to biogas or solid fuels, rice husks or bagasse and has universal application as a result of its rotating shaft power output. It is quite simple mechanically and can be designed to be fabricated in shops.

Varieties of Stirling Engines

(a) Low Pressure Air Engines

This type of engine operating at an average pressure of 1.5 bar, speed of 900 r.p.m. and a piston displacement of about 3 litres was found capable of about 1KW shaft power. Its design criteria are simplicity, repairability, low maintenance.

(b) Free Cylinder Engines.

These are extremely simple mechanisms having only a piston, a displacer and a cylinder which move to produce work. In their simplest form they use only an annular gap around the displacer to serve the heat exchange and regenerative function. They are hermetically sealed and can use hydrogen or helium without danger of leakage.

Free Piston Alternator Engines

These machines can be sealed up to much larger sizes on the order of looker/cylinder and gauged together to form large stationary power plants producing power in the megawatt range. They promise long life, low maintenance and high thermal eficiency while using solid fuels as their heat source.

In developing countries, simplified designs of the linear alternator engine could be built to provide electric power for lighting.

Free Piston Stirling Heat Pump

One of the simplest yet most effective arrangements of Stirling machines is the duplex Stirling heat driven heat pump. This machine exists at the moment in small sizes and low temperature (-70°C) design but is readily adaptable to refrigeration, for freezing, space cooling and similar tasks. It requires no higher level of manufacturing skill than the free cylinder engine or alternator engine and is no more complex mechanically than the simple free cylinder engine.

Chapter 6

Economic Feasibility

Though the capital cost of the Stirling engine is high but as the conventional fuels are getting exhausted, the Stirling engines will gradually capture its popularity because these can be used by unconventional fuels. Especially in the rural areas where the rice husks, coconut shells, and biomass are abundant, there Stirling engines can be run by these cheap fuels.

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