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BASIC STUDY ON ENGINE WITH SCROLL COMPRESSOR AND EXPANDER

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ABSTRACT

Scroll compressors are becoming popular in air conditioning and refrigeration. This is primarily due to their higher efficiency and low noise/vibration characteristics. The scroll principle can be applied also to the steam expander and the Brayton cycle engine, as shown in the past literature. The Otto cycle spark-ignition engine with a scroll compressor and expander is studied in this report. The principle and basic structure of the scroll engine are explained, and the engine characteristics are calculated based on the idealized cycles and processes. A prototype model has been proposed and constructed. The rotary type engine has always had a problem with sealing. The scroll engine might overcome this shortcoming with its much lower rubbing speed compared to its previous counterparts, and is therefore worth investigating.

NOMENCLATURE

a : radius of a base circle
Cv: specific heat at constant volume
F : force
h : scroll height
N : number of scroll turns - 1/4
p : scroll pitch
P : pressure
q : heat addition per unit mass
r : crank radius
R_c: pressure ratio (after ignition/ before ignition)
t : scroll wrap thickness
T : torque
V : volume
W : work per revolution

α : involute initial angle on the base circle
γ : specific heat ratio
ϵ : volumetric ratio
ζ : efficiency
θ : rotating angle
ρ : pressure ratio
Φ : Involute extension angle

suffixes

a : axial
av: average
c : compressor
d : discharge
e : expander
i : i-th chamber (increase outward)
s : compressor suction
θ : tangential
* : end of compressor discharge process

INTRODUCTION

Scroll compressors have a smooth torque variation. Their lower rubbing speed enables them to realize a higher efficiency, because mechanical sealing can be effectively employed. The theory and the art of the scroll compressor have already been studied[(1),(2)] and production is now in progress. This theory and experience with the scroll compressor may be easily extended to an engine with a scroll compressor and a scroll expander. The scroll compressor compresses the air-fuel mixture, and the scroll expander is used to get power from the heat of the combustion. The flow is continuous and uni-directional, which is different from that of the reciprocating engine. Although the Brayton cycle engine is possible with a scroll compressor and a scroll expander, the temperature of the scroll expander could be extremely high due to the continuous combustion. The requirement of the scroll expander material may become very severe. The spark-ignition scroll engine is therefore studied in this report, based on the air-standard Otto cycle. The thermal problems of the scroll expander can be eased by the fresh air-fuel mixture charged into the combustion chamber, although the temperature of the air-fuel mixture is already high due to the compression. Although the displacement volume of the scroll engine is halved compared to the reciprocating engine, we need two pairs of scrolls. Many concepts of the scroll engine structure will be developed. A structure of the scroll engine is proposed, to cancel part of the axial forces of the scroll expander.

PRINCIPLE

The operating principle of the scroll engine is shown in Fig.1. The scroll engine consists of two components, the scroll compressor and the scroll expander. The elements are assumed to have the same geometric dimensions and to be synchronized via a proper mechanism.

Fig.1a) shows the seal-off position of the scroll compressor. The air-fuel mixture is taken into the compressor from the periphery. This corresponds to the suction process.

After several degrees of rotation, the compressed air-fuel mixture discharge is to commence at $\theta_{c,d}$ as shown in Fig.1b). The volume of the combustion chamber (innermost) of the scroll expander is minimum at this angle. The volume is actually zero when the scroll shape shown in Fig.1 is employed. The discharge port of the scroll compressor and the combustion chamber of the scroll expander are connected via a discharge valve. The compressed air-fuel mixture is transferred to the combustion chamber of the scroll expander. This is shown in Fig.1c). The volume change rate of the two connected chambers is the same during the transfer process. The discharge from the scroll compressor to the scroll expander ends at θ_c^* and the volume of the combustion chamber of the scroll at this angle is exactly the same as that of the innermost chamber of the scroll compressor at $\theta_{c,d}$. The discharge valve is then closed. This corresponds to the end of the compression process.

The air-fuel mixture is ignited in the combustion chamber of the scroll expander. This is shown in Fig.1d). The combustion is assumed to take place instantly. This process corresponds to the constant-volume addition of heat in the idealized air-standard cycle, and the pressure of the combustion chamber of the scroll expander increases suddenly. The orbiting scroll of the expander is therefore driven by the high pressure of the combustion gas. The gas pressure decreases during expansion. This corresponds to the expansion process. The expansion ends when the gas reaches the outermost chamber as shown in Fig.1e). The gas is then exhausted from the expander. This corresponds to the exhaust process. Fig.1e) is the same as Fig.1a) and the same process is repeated.

In the scroll engine, the suction, compression, expansion and exhaust processes take place continuously, while combustion occurs once per revolution. A carburetor is employed to vaporize the fuel in the suction process. The pressure after-expansion may be higher than the ambient pressure when the scroll expander has the same volumetric ratio as the scroll compressor and part of the energy is not used. The number of scroll turns of the expander may be increased in this case. The complete expansion cycle is realized relatively easily in theory.

The intake, compression, combustion, expansion and exhaust processes occur in the same cylinder in the 4-stroke cycle reciprocating engine. In the scroll engine, the intake and compression are by the scroll compressor and the combustion, expansion and exhaust are by the scroll expander. The scroll engine is different from the Wankel rotary engine in this regard and much closer to the conventional gas turbine engine as far as the system is concerned. The Brayton cycle scroll engine is possible, like the gas turbine as mentioned earlier, but the high temperature will cause many problems in the scroll expander and make it less likely to be realized. The spark-ignition scroll engine is thus preferred. The temperature of the scroll expander, however, can be higher than the reciprocating counterpart because the fresh air-fuel mixture is already compressed. The temperature of the scroll expander is still much lower than in the Brayton cycle. The torque can be zero in the reciprocating and Wankel rotary engine when they are used in a single cylinder. The torque of the scroll engine will always be higher than zero when the proper pressure is employed. This is because the scroll is a kind of multi-stage machine in a single structure, as is well known in scroll compressor technology.

The scroll diesel engine is also theoretically possible when a higher compression ratio is used and fuel is injected into the combustion chamber, although at present interest is in the Otto cycle engine. The design requirements, however, will become more severe in the diesel engine due to the high pressure level.

SCROLL ENGINE THEORY IN IDEALIZED CYCLES AND PROCESSES

The scroll engine consists of a scroll compressor and a scroll expander, and therefore the characteristics of the two components can be handled independently. The scroll compressor is analyzed in the same way as before(1). The scroll expander is a machine which rotates in the opposite direction and the theory of the scroll compressor is modified easily. An involute of a base circle with radius a is employed for the scroll wrap geometry for mathematical simplicity. This does not necessarily mean that the actual machine is designed in this way. The geometric shape shown in Fig.1 will be used in the actual design, primarily because the dead volume can be minimized, i.e., effectively zero. This sort of shape makes the equations unnecessarily complicated and is not considered here. We have studied a scroll engine of N=3 ($\Phi=6.5\pi$), and this is the maximum number of chambers in the scroll compressor and the scroll expander.

Volume of Chambers

The volumes of each chamber of the scroll compressor have already been obtained, and the result has been applied to the scroll expander keeping in mind that the rotating direction is opposite. The following relation is used to obtain the volumes of chambers in the scroll expander from the scroll compressor results.

$$\theta_c=2\pi-\theta_e \tag{1}$$

The equations for the scroll expander are expressed as a function of θ_e. The displacement volumes of each chamber of the scroll expander are calculated form $V_{c,i}(\theta_c)$ of the scroll compressor as follows:

$$V_{e,i}(\theta_e)=V_{c,i}(2\pi-\theta_e) \qquad 1\leqq i\leqq N \tag{2}$$

The exact expressions for $V_{c,i}(\theta_c)$ are known and are shown in Appendix A, although slight modifications have been made from reference (1). To build a scroll engine, we need a proper phase difference between the compressor and the expander rotating angles. This is given by

$$\theta_c = MOD\,(\theta_e+\theta_{c,d}+\theta_c{}^{*}-2\pi,\ 2\pi) \qquad (3)$$

Eq.(3) shows that the volume of the combustion chamber (i=1) of the scroll expander takes a minimum value when the air-fuel mixture discharge commences from the scroll compressor.

The volume of chambers is shown in Fig.2 when Eq.(3) is applied to the scroll engine, where $\theta_{c,d}=\pi/2$ ($\theta_{e,d}=3\pi/2$), $\theta_c{}^{*}=3\pi/2$ ($\theta_e{}^{*}=\pi/2$), $\alpha=\pi/5$ and ϵ = 8.90. The same conditions are applied to the following calculations and figures. The overlapping zone of the minimum chambers of the scroll compressor and expander correspond to the air-fuel mixture transfer process from the compressor to the expander. This process is assumed to occur at a constant pressure in the ideal treatment. There appears a discontinuity in volume change, which is due to the dead volume of the innermost chamber. The dead volume exists when the involute of a circle is used for the wrap shape. It can be avoided when the shape shown in Fig.1 is employed.

Pressure

The pressure of each chamber is obtained assuming the proper thermodynamic process, and the isentropic process is considered. The pressure ratio of each chamber of the scroll compressor is given by

$$\rho_{c,i}=\rho_{c,i}\,(\theta_c) \qquad 1\leq i\leq N+1 \qquad (4)$$

Eq.(4) is based on the compressor suction pressure P_S($=P_{N+1}$). The pressure ratio of the scroll expander is given by

$$\rho_{e,i}=\rho_{e,i}\,(\theta_e) \qquad 1\leq i\leq N+1 \qquad (5)$$

Eq.(5) is also based on the compressor suction pressure P_S. The exact expressions for Eqs.(4) and (5) are given in Appendix B. Eq.(5) actually contains R_C. This is given by

$$R_c = \frac{\rho_{e,1}\,(\theta_{e,d})_{\ after\ S.I.}}{\rho_{e,1}\,(\theta_{e,d})_{\ before\ S.I.}} \qquad (6)$$

and indicates the pressure ratio in the combustion chamber before and after the spark-ignition.

Fig.3 shows the pressure of the scroll engine vs the rotating angle for R_C=3.

P-V Diagram

The P-V diagram in the idealized cycle and processes is obtained for the scroll engine by combining the results of Fig.2 and Fig.3, and is shown in Fig.4 in non-dimensional form for R_C= 3. The kinks in the P-V diagram are due to the dead volume in the innermost chambers. The area covered by the P-V diagram is the theoretical output work of the scroll engine. The theoretical output work is zero when R_C=1 because the output of the scroll expander is the same as the power to drive the scroll compressor. The theoretical output work per revolution is also calculated from the Otto cycle theory, and this is given as follows for the Otto cycle scroll engine:

$$\frac{W}{P_s\,p\,r\,h}=2\pi\ (2N-1)\ \frac{(R_c-1)}{(\gamma-1)}\ (\varepsilon^{\gamma-1}-1) \qquad (7)$$

where

$$\varepsilon=\frac{V_{c,N}\,(0)}{V_{c,1}\,(\theta_{c,d})} \qquad (8)$$

This is called built-in volume ratio in the field of compressor technology. This is also termed as the compression ratio and the expansion ratio in the engine field. It corresponds to the volume ratio at the bottom dead center and at the top dead center in the reciprocating engine. Eq.(7) simply tells us that the scroll engine theoretical output work is proportional to the number of scroll turns, i.e., the displacement volume.

The T-V diagram is also obtained from P-V diagrams and, is shown in Fig. 5 for R_C=3.

The combustion process is handled as the heat addition process at a constant volume in the idealized cycle. The heat q added per unit mass of the cycle gas, i.e., air, is estimated from the following equation:

$$R_c = 1 + \frac{q/(C_v T_s)}{\varepsilon^{\gamma-1}} \qquad (9)$$

R_C is used as a parameter in this report, although R_C is estimated from the lower heat of combustion of the fuel in the real engine. The relation of Eq.(9) is shown in Fig.6 for ϵ = 8.90.

Efficiency of Otto Cycle Scroll Engine

The efficiency of the Otto cycle scroll engine is exactly the same as that of the conventional Otto cycle engine(3), and is given as follows:

$$\eta = 1 - \frac{1}{\varepsilon^{\gamma-1}} \qquad (10)$$

The compression ratio ϵ is a function of $V_{c,1}(\theta_{c,d})$, i.e., $\theta_{c,d}$. This relation is shown in Fig.7. ϵ is varied by changing the discharge timing from the compressor into the expander.

Torque

The theoretical output work of the scroll engine is given by Eq.(7), and therefore the average torque T_{av} of the scroll engine is derived from the relation $W=2\pi T_{av}$ together with Eq.(7),

$$\frac{T_{av}}{P_s p r h} = (2N-1)\frac{(R_c-1)}{(\gamma-1)}(\varepsilon^{\gamma-1}-1) \qquad (11)$$

The average torque T_{av} is also proportional to the number of scroll turns like the engine output.

The torque variation during a rotation is calculated as the difference between the scroll expander and the scroll compressor torque, and is

$$T(\theta_e) = T_e(\theta_e) - T_c(\theta_c) \qquad (12)$$

The scroll compressor theory is applied to calculate Eq.(12), and Eq.(3) is used for θ_c. The torque of the scroll expander is obtained by reversing the rotation of the scroll compressor. The result is obtained as follows, by using Eq.(1):

$$\frac{T_e(\theta_e)}{P_s p r h} = \sum_{i=1}^{N}\left(2i-2+\frac{\theta_e}{\pi}\right)\{\rho_{e,i}(\theta_e) - \rho_{e,i+1}(\theta_e)\} \qquad (13)$$

The torque of the scroll compressor is given by (1)

$$\frac{T_c(\theta_c)}{P_s p r h} = \sum_{i=1}^{N}\left(2i-\frac{\theta_c}{\pi}\right)\{\rho_{c,i}(\theta_c) - \rho_{c,i+1}(\theta_c)\} \qquad (14)$$

where

$$0 \leq \theta_e\ (\theta_c) < 2\pi.$$

The torque of the scroll engine is shown in Fig.7 for R_C=3. As mentioned earlier, the torque of the scroll compressor is always positive when R_C is large enough. This feature makes it different from other engines with a single cylinder. There are three discontinuities in the engine torque curve. They are caused by combustion, underexpansion in the scroll expander and dead volume. The latter two can be changed by design.

Tangential Force on Crank Shaft

Tangential force $F_\theta(\theta_e)$ is exerted on the crank shaft due to the engine output torque, and this is calculated directly from Eq.(13) as follows:

$$F_e(\theta_e) = \frac{T(\theta_e)}{r} \qquad (15)$$

Axial Force

One difficulty experienced during the development of the scroll compressor was the large axial force exerted on the orbiting scroll due to the flat shape of the scroll. This is a very difficult problem for the sliding type bearing because the relative speed is extremely low. The situation is exactly the same in the scroll engine. A tandem structure is proposed, to cancel part of the axial force of the scroll expander by that of the scroll compressor. The axial force is then calculated as

$$F_a(\theta_e) = F_{a,e}(\theta_e) - F_{a,c}(\theta_c) \qquad (16)$$

where

$$\frac{F_{a,e}(\theta_e)}{\pi P_s p^2} = A_{e,j}(\theta_e)\ \{\rho_{e,j}(\theta_e) - 1\} + \sum_{i=j+1}^{N} \left(2i - 3 + \frac{\theta_e}{\pi}\right) \qquad (17)$$

and

$$\frac{F_{a,c}(\theta_c)}{\pi P_s p^2} = A_{c,j}(\theta_c)\ \{\rho_{c,j}(\theta_c) - 1\} + \sum_{i=j+1}^{N} \left(2i - 1 - \frac{\theta_c}{\pi}\right) \qquad (18)$$

$A_{c,j}(\theta_c)$ and $A_{e,j}(\theta_e)$ are shown in Appendix C.

The axial forces of the scroll engine are shown in Fig.9 using Eqs.(16),(17) and (18) for R_C=3.

SCROLL ENGINE PROTOTYPE

A typical structure of the scroll engine is shown in Fig.10. The tandem structure is employed to cancel part of the axial force due to gas pressure. The orbiting scrolls of the compressor and the expander are driven by the two synchronized crank shafts. The air-fuel mixture is taken into the scroll compressor and transferred to the scroll expander via the discharge valve after compression. The air-fuel mixture is ignited by the plug in the combustion chamber of the expander, and the pressure is suddenly increased. This energy is converted into mechanical work by the scroll expander and is made available through the synchronous mechanism. Part of the energy is used to drive the scroll compressor, and the rest of it is theoretically usable energy. A prototype similar to Fig.10 has been made, with a D.C. motor used as a starter. The ethyl alcohol is injected manually as a fuel, and the combustion takes place in the scroll expander. The engine is, however, running on the D.C. motor at the moment because of insufficient sealing in the chambers. This can definitely be improved.

CONCLUDING REMARKS

1. The principle of an engine with a scroll compressor and a scroll expander has been studied and the basic structure has been investigated. The scroll engine can be driven in any cycle known in engineering thermodynamics. The spark-ignition Otto cycle scroll engine is the focus of this report because it seems to be more promising than the others.

2. The volume, pressure, P-V/T-V diagrams, output work, torque and forces have been obtained analytically for the scroll engine in the idealized air-standard Otto cycle. The torque of the scroll engine can be made positive during a rotation, even though it is a single cylinder equivalent of other engines.

REFERENCES

1) Morishita, E. et al., Scroll Compressor Analytical Model, Proc. 1984 ICEC at Purdue, July 1984, pp.487-495.
2) Inaba, T., A Scroll Compressor with Sealing Means and Low Pressure Side Shell, 1986 ICEC at Purdue, Aug. 1986, pp.887-900.
3) Obert,E.F., Internal Combustion Engine (3rd Ed.), International Text Book Company, Scranton, Penn., 1968, pp.166-190.

APPENDIX A

$$V_{c,i} = S_i h \qquad i=1 \quad 0 \leqq \theta_c < \theta_c^{*}, \quad i=2 \quad \theta_c^{*} \leqq \theta_c < 2\pi \tag{A1}$$

$$V_{c,i} = 2\pi p r h\,(2i-1-\theta/\pi) \qquad i=2 \quad 0 \leqq \theta < \theta_c^{*}, \; i=3 \quad 0 \leqq \theta_c < 2\pi \tag{A2}$$

where

$$S_i = \frac{a^2}{3}\{([2i+.5]\pi-\alpha-\theta_c)^3-([2i-.5]\pi-\alpha-\theta_c)^3\}-S_i' \tag{A3}$$

$$S_i' = 2a^2\alpha([2i-.5]\pi-\theta_c)^2+(2/3)a^2+a^2(\pi-4\alpha) \tag{A4}$$

APPENDIX B

$$\rho_{c,1}(\theta_c) = (V_{c,N}(0)/V_{c,1}(\theta_c))^{\gamma} \qquad 0 \leqq \theta_c < \theta_{c,d} \tag{B1}$$

$$\rho_{c,1}(\theta_c) = (V_{c,N}(0)/V_{c,1}(\theta_{c,d}))^{\gamma} \qquad \theta_{c,d} \leqq \theta_c < \theta_c^{*} \tag{B2}$$

$$\rho_{c,i}(\theta_c) = (V_{c,N}(0)/V_{c,i}(\theta_c))^{\gamma} \qquad i=2,3, \quad 0 \leqq \theta_c < 2\pi \tag{B3}$$

$$\rho_{c,i+1}(\theta_c) = 1 \qquad i=N\,(=3). \quad 0 \leqq \theta_c < 2\pi \tag{B4}$$

$$\rho_{e,1}(\theta_e) = (V_{c,N}(0)/V_{c,1}(\theta_{c,d}))^{\gamma} \qquad \theta_e^{*} \leqq \theta_e < \theta_{e,d} \tag{B5}$$

$$\rho_{e,1}(\theta_e) = R_c(\epsilon V_{e,1}(\theta_{e,d})/V_{e,1}(\theta_e))^{\gamma} \qquad \theta_{e,d} \leqq \theta_e < 2\pi \tag{B6}$$

$$\rho_{e,i}(\theta_e) = R_c(\epsilon V_{e,1}(\theta_{e,d})/V_{e,i}(\theta_e))^{\gamma} \qquad i=2,3, \quad 0 \leqq \theta_e < 2\pi \tag{B7}$$

$$\rho_{e,i+1}(\theta_e) = 1 \qquad i=N\,(=3). \quad 0 \leqq \theta_e < 2\pi \tag{B8}$$

APPENDIX C

$$A_{c,j}(\theta_c) = \frac{1}{\pi p^2}\left[\frac{a^2}{3}\{([2j+.5]-\theta_c)^3-([2j-.5]-\theta_c)^3\} - a^2(\pi-4\alpha)\right] \qquad j=1 \quad 0 \leqq \theta_c < \theta_c^{*}, \quad j=2 \quad \theta_c^{*} \leqq \theta < 2\pi \tag{C1}$$

$$A_{e,j}(\theta_e) = A_{c,j}(2\pi-\theta_e) \qquad j=1 \quad \theta_e^{*} \leqq \theta_e < 2\pi, \quad j=2 \quad 0 \leqq \theta_e < \theta_e^{*} \tag{C2}$$

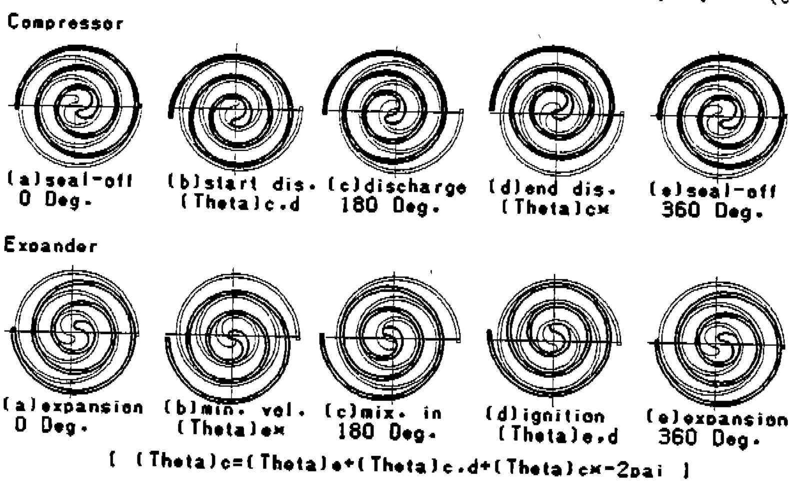

Fig.1 Processes of the Scroll Engine

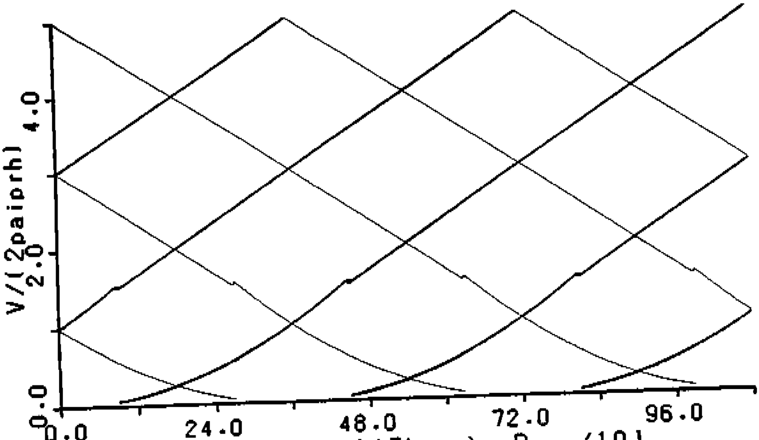

Fig.2 Volume [(Theta)e Deg./10]

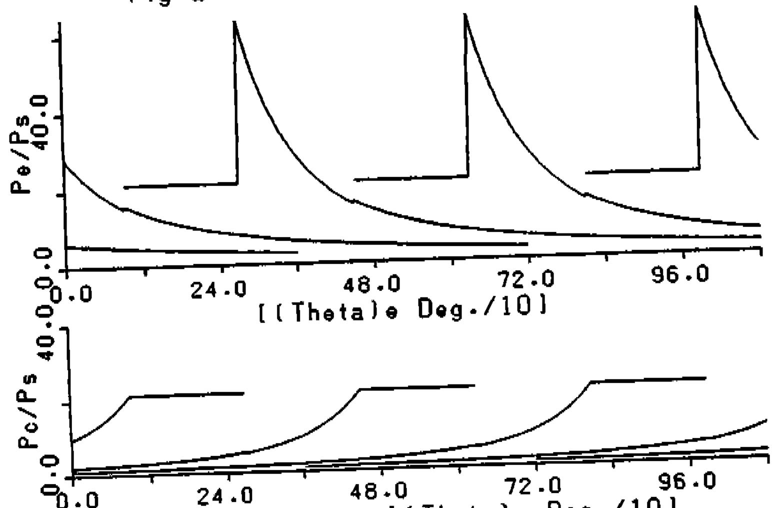

Fig.3 Pressure [(Theta)e Deg./10]

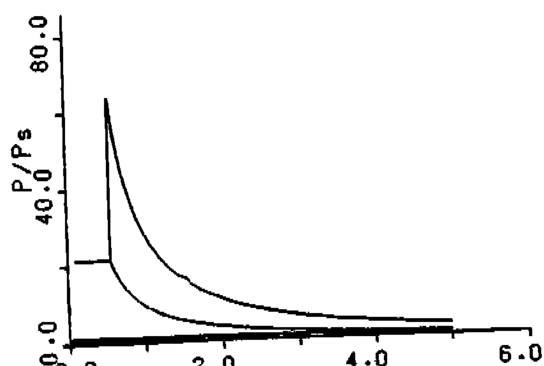

Fig.4 P-V Diagram [V/(2paiprh)]

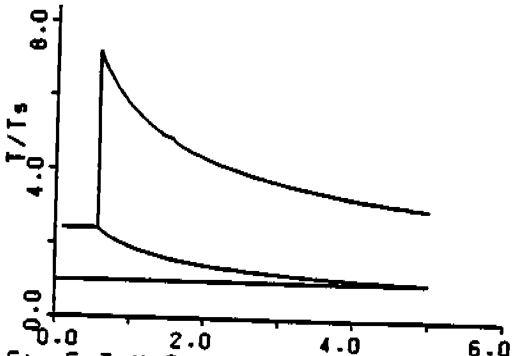

Fig.5 T-V Diagram [V/(2paiprh)]

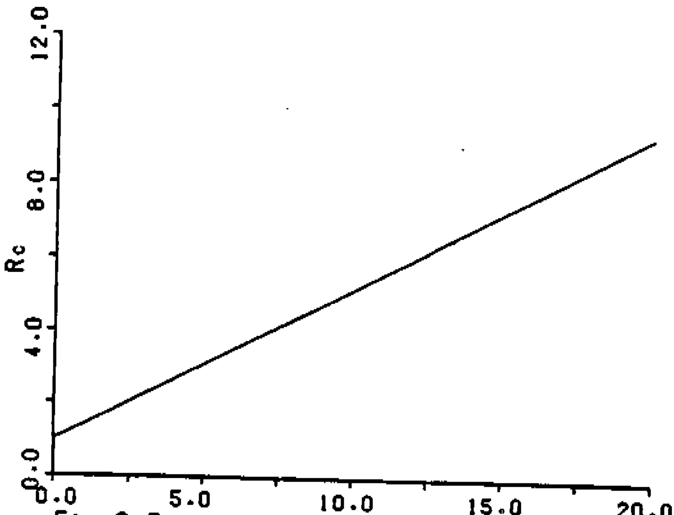

Fig.6 Pressure Ratio Rc [q/(CvTs)]

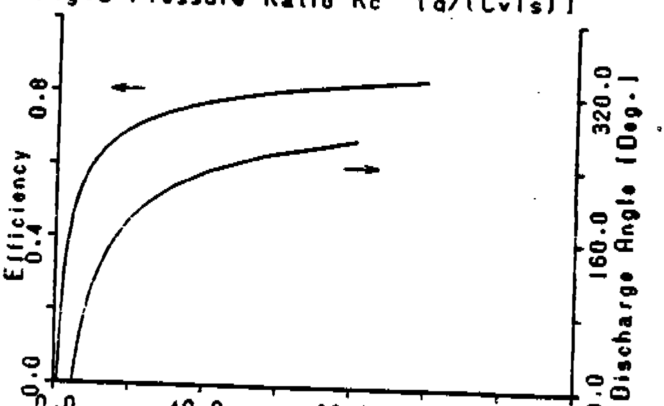

Fig.7 Efficiency [Volume Ratio]

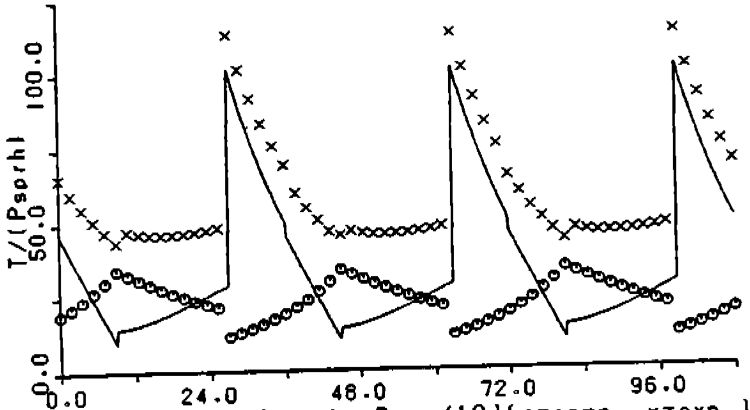

Fig.8 Torque ((Theta)e Deg./10)(o-comp. x-exp.)

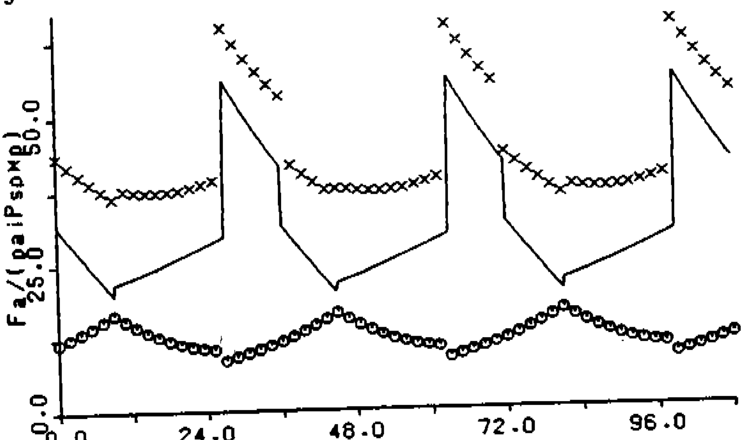

Fig.9 Axial Force ((Theta)e Deg./10)(o comp. e-exp.)

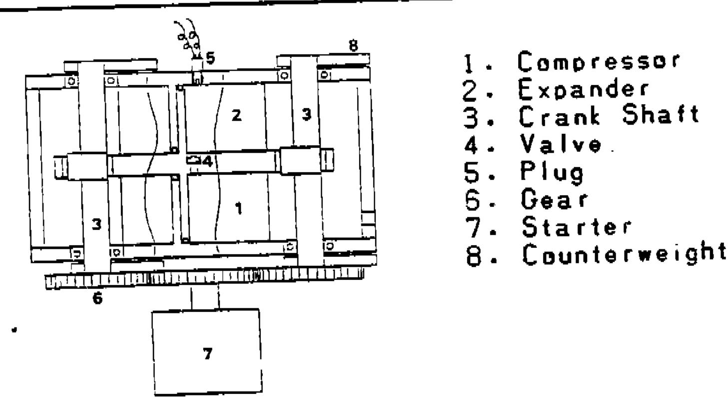

Fig.10 Scroll Engine