Impact Of Swept Volume Ratio In Designing A Beta Type Stirling Engine

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Abstract-A Stirling engine is an external combustion engine operating on a closed regenerative cycle. The working relies on cyclic expansion and compression. The displacer which is meant for shuttling the hot gases from the displacer space may share a part of volume with the piston known as overlap volume. In this paper, an appropriate model for beta type Stirling engine is developed for optimizing its efficiency based on the swept volume ratio (SVR), i.e., the ratio of swept volume of piston space to that of the displacer space. The analysis of impact of SVR on other parameters like phase angle and overlap volume has also been the part of this research. Based on the achieved results, it is observed that an optimum combination of swept volume of displacer and the piston space ensures the efficient working of the beta type Stirling engine and its efficiency increases with the increase of SVR but its impact lessens gradually as the SVR value increases by unity. The influence of phase angle and overlap volume on swept volume ratio is also investigated. The results are represented graphically. From this study, it is concluded that the required efficiency of the beta Stirling engine can be achieved by suitable combination of the discussed parameters.

Keywords-Beta Stirling Engine, Swept Volume Ratio, Work Done, Overlap Volume, Phase Angle

I. INTRODUCTION

Many attempts [i-ii] have been made on renewable energy resources in order to bring the power generating engines according to the needful specifications of input and output limits. Due to continuous increasing demand of energy and the pollution effects, the researchers are much focussed towards the environment friendly techniques [iii-iv] to decrease the gap between demand and supply of energy. Although a lot of studies have been done on existing thermodynamic models of Stirling engines little focus has been given towards parameters designing for targeting the optimum efficiency. In a recent research, discussed in. al. [v] used third order thermodynamic analysis by Fuzzy decision-making method to analyse the efficiency, output power and the pressure drop of a Stirling engine. "The use of regenerative displacer has been proposed in[vi]for replacing solid displacer and stationary regenerator in beta type Stirling engine" and expected about 20% more power per cubic centimetre. Similarly, development of a theoretical thermodynamic simulation model has been discussed in [vii] for beta Stirling engine with rhombic drive mechanism for improving its performance through periodic parametric variations. These research based developments indicate demand for directing the research towards the optimal design parameters of the Stirling engine. A Stirling engine is operated on cyclic expansion and compression of working fluid such as air or any other gas. Robert Stirling invented the first hot air engine of such kind in 1816. Due to non-breathing nature, Stirling engines are feasible to use in space and machinery working under sea. The energy sources vary and these engines can be operated by any kind of external heat source including coal, solar or waste heat energy from industries. A specific kind of heat exchanger is mounted inside the Stirling engine which acts as a thermal store; a reason for the use of term 'regenerative' for Stirling engine cycle. Out of three types (alpha, beta and gamma)of Stirling engines, the beta type Stirling engine is unique in a sense that both of the displacer and piston are confined to a same cylinder [viii] and normally, both shares the space i.e., the overlap volume. Recently, promising results have been achieved by various researchers for optimizing the engine's design.

For analysing the working of a Stirling engine, the research is still under progress. A dimensionless quantity (power parameter) has been introduced in [ix] for optimizing the Stirling engine performance. However, much of the research on Stirling engine performance is widely based on the classical Schmidt analysis given by x] in 1871. Out of many parameters effecting the performance of a Stirling engine, the ratio of swept volume of piston space and the displacer space is taken as a standard by many researchers[xi-xv].This research highlights the optimal designing of beta type Stirling engine with a special reference to a suitable combination of swept volumes of displacer and piston space respectively. The beta Stirling engine is shown in Fig. 1. As illustrated, the displacer and the power piston are mounted in the same cylinder. For the hot space,

there is a clearance between the displacer and the cylinder walls as the displacer is meant for shuttling the air between hot and cold space. The heat is supplied to the displacer space (hot cylinder) through external source and the displacer pushes the heated air to the piston space (cold cylinder) during the expansion of the working gas as the displacer moves from top dead centre (TDC) to the bottom dead centre (BDC). The work done at this stage is at the cost of heat supplied by the external source and hence the displacer moves to BDC. It is to be noted that small force is required to move the displacer because there is no seal with the wall and a result a small pressure drop across the heat exchanger and the regenerator will be observed. Since the internal energy of the system remains unaffected while the entropy of the gas increase for an ideal Stirling cycle. In result of the inertial force, the displacer moves up and then pushes the gas towards the

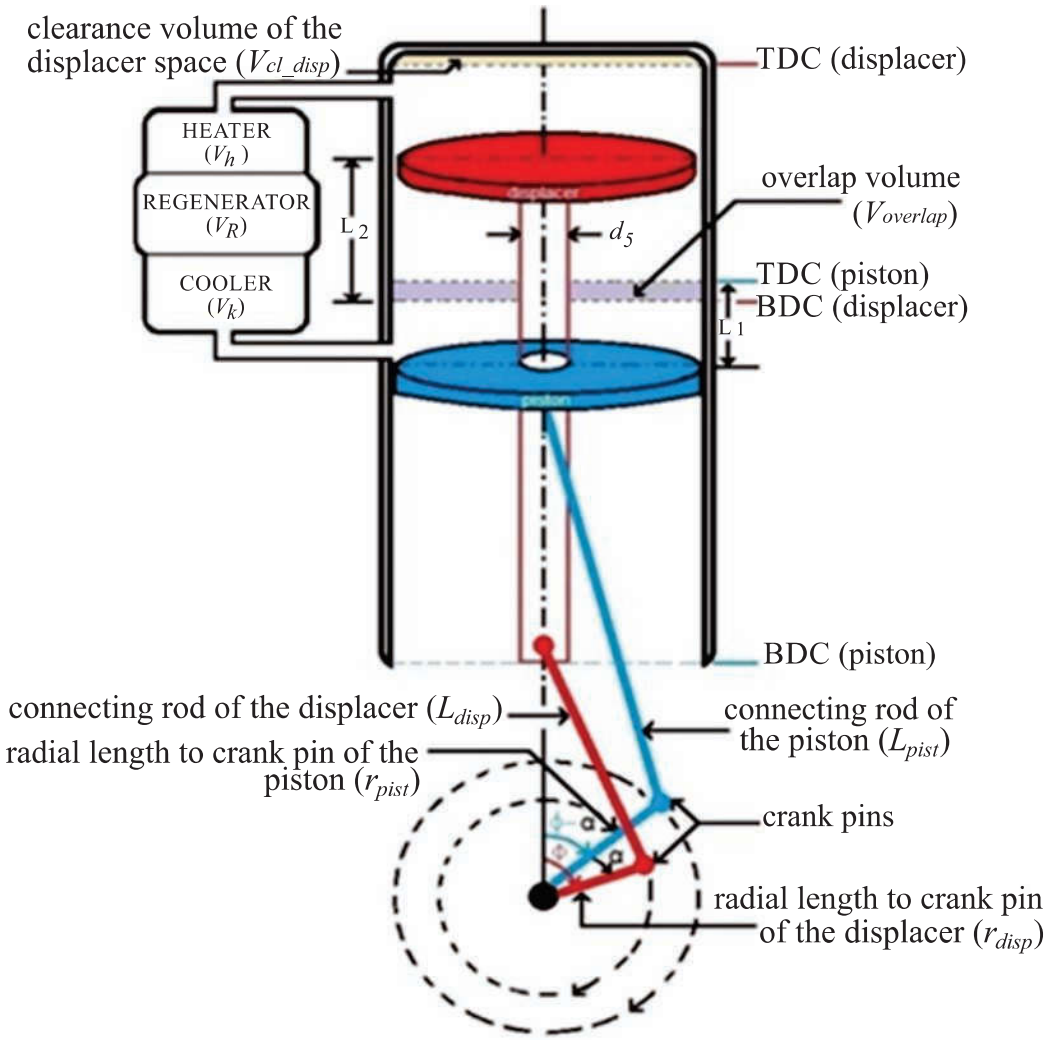

Fig. 1. Schematic volumetric configuration of the beta type Stirling engine

the piston space passing through theregenerator where the heat is abstracted. In cold cylinder, the air is compressed by the piston and the heat is rejected. The work done is equal to the magnitude of rejected heat from the system. There is a decrease in entropy for an ideal Stirling engine cycle; however, no change in internal energy can be seen. A pseudo model of a Stirling engine along with the temperature profile is depicted in Fig. 2.

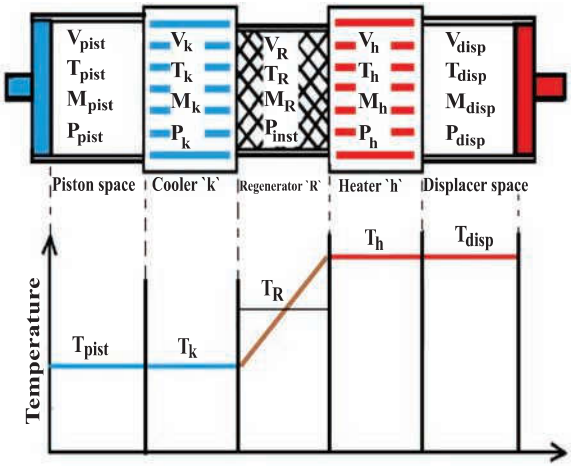

Fig. 2. Pseudo model of a Stirling engine

The work has been done through modelling and simulations by developing a programme on *matlab* software. The results are useful for the further designing of the engine on laboratory as well as on industrial scale.

II. Mathematical Analysis

A. *Calculations for the instantaneous pressure for the working cycle*

Based on the model illustrated in Fig. 2, the total mass of the working gas (M_T) for the closed cycle at any instant can be expressed as the sum of the gas components present in all constituent areas.

$$M_T = M_{pist} + M_K + M_R + M_h + M_{disp} \quad (1)$$

By Universal gas law,

$$M_T = \frac{P_{pist} V_{inst_pist}}{R\,T_{pist}} + \frac{P_K V_K}{R\,T_K} + \frac{P_R V_R}{R\,T_R} + \frac{P_h V_h}{R\,T_h} + \frac{P_{disp} V_{inst_disp}}{R\,T_{disp}}$$

Where, T_{pist}, T_K, T_R, T_h and T_{disp} represent the respective instantaneous temperature values in piston space, cooler, regenerator, heater, regenerator and displacer space, respectively while R is the universal gas constant. The instantaneous pressure (P_{inst}) is considered to be similar in all spaces. Therefore,

$$M_T = \frac{P_{inst}}{R}\left(\frac{V_{inst_pist}}{T_{pist}} + \frac{V_K}{T_K} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{inst_disp}}{T_{disp}}\right)$$

$$P_{inst} = \frac{M_T\,R}{\frac{V_{inst_pist}}{T_{pist}} + \frac{V_K}{T_K} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{inst_disp}}{T_{disp}}}$$

The temperature in the displacer and the piston space is similar to that in the heater and cooler, respectively. So, T_{disp} and T_{pist} can be replaced with T_h and T_k like wise.

$$P_{inst} = \frac{M_T\,R}{\frac{V_{inst_pist}}{T_K} + \frac{V_K}{T_K} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{inst_disp}}{T_h}} \quad (2)$$

Let 'Lr' be the regenerator's length and 'x' be the distance of a particular point from the cooler. The temperature profile of the regenerator can be given in Fig.3:

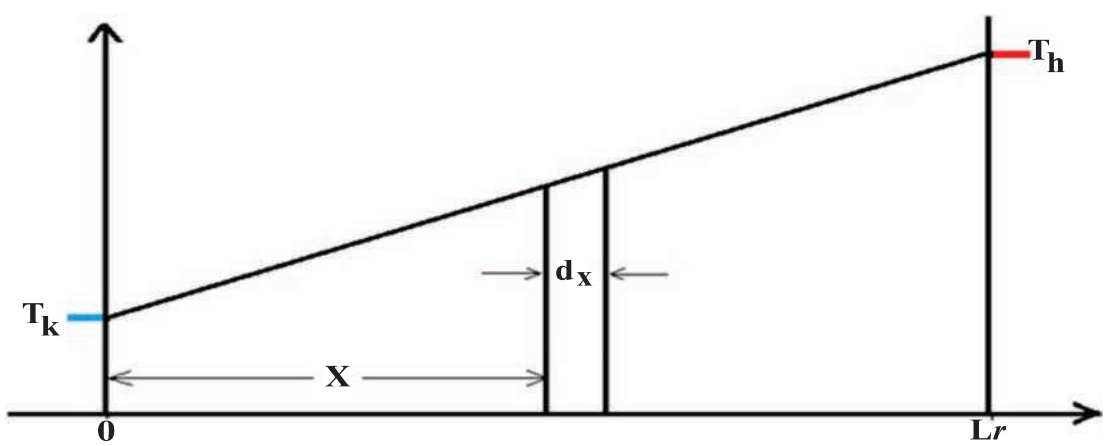

Fig. 3. Linear profile of the regenerator

Through calculations, the temperature profile of the regenerator in Eq. 2 takes the form as given in Eq 3.

$$P_{inst} = \frac{M_T\,R}{\frac{V_{inst_pist}}{T_K} + \frac{V_K}{T_K} + \frac{V_R \ln\left(\frac{T_h}{T_k}\right)}{(T_h - T_k)} + \frac{V_h}{T_h} + \frac{V_{inst_disp}}{T_h}} \quad (3)$$

B. *Volumetric analysis*

Fig. 2 illustrates the division of the volume of the engine based on its five major components. At any instance, the volume of the working gas present in any of the components of the engine can be analysed. The volume of the displacer space at any instance (V_{inst_disp}) is

given by the Schmidt analysis as (Eq.4),

$$V_{inst_disp} = (A_{disp}) [(r_{disp}) (1 - \cos\phi) + L_{disp} (1 - \sqrt{1 - \left(\frac{r_{disp}}{L_{disp}} \sin\phi\right)^2})] + V_{Ddisp} + V_{cldisp} \quad (4)$$

"Where, A_{disp} and V_{Ddisp} represent the displacer space area and the dead volume of the displacer space, respectively. Dead volume is the total void volume of working fluid (Helium in the present case) enclosed in the overall dead space of the Stirling engine [xvi]." Volumetric configuration in the Fig. 1 is mainly based on the displacer and piston space of the beta type Stirling engine along with other major components. The volume enclosed between the displacer and the piston at any instance is regarded as the instantaneous volume of the piston space (given as V_{inst_pist}). It is to be noted from Fig. 1 that the area of the displacer at the top side is greater than the area at the bottom side. This is due to the displacer rod (with diameter *ds*, Fig. 1) attached at the bottom centre of the displacer. Considering $A_{_disp}$ as the area of the displacer rod with radius of '$r_{_disp_rod}$', then the area is given by:

$$A_{_disp_rod} = (r_{_disp_rod})^2$$

The volume enclosed between the piston and its top dead centre (*V_pist_tdc*) at any instant is given as:

$$V_pist_tdc = (A_{pist}) \{ (r_{pist}) [1 - \cos(\phi - \alpha)] + L_{pist}[1 - \sqrt{1 - \frac{r_{pist}^2}{L_{pist}^2} \sin^2(\phi - \alpha)}]\}$$

The volume '*V_pist_tdc*' is represented as L_1 as the part of stroke length in Fig. 1. Similarly, the volume enclosed between the displacer and its bottom dead centre (*V_disp_bdc*) at any instant is given as:

$$V_disp_bdc = (A_{disp} - A_{disp\ rod}) [(r_{disp}) (1 + \cos\phi) - L_{disp} (1 - \sqrt{1 - \frac{r_{disp}^2}{L_{disp}^2} \sin^2\phi})]$$

'*V_disp_bdc*' is indicated as L_2 as part of stroke length in Fig. 1. It is notable that the volume of the piston space (V_{inst_pist}) at any particular moment is determined by calculating the volume between displacer and piston. Keeping clearance and dead volumes in account, the overlap volume ($V_{overlap}$) is subtracted from the sum of following two volume spaces:

(I) the volume between piston and its top dead centre (TDC). The part of its stroke length is represented as L_1 in Fig.1.

(ii) the volume between displacer and its bottom dead centre (BDC). The part of its stroke length is represented as L_2 in Fig.1.

Mathematically, it is expressed as:

$$V_{inst\ pist} = (A_{pist}) (r_{pist}) \{[1 - \cos(\phi - \alpha)] - L_{pist}[1 - \sqrt{1 - \frac{r_{pist}^2}{L_{pist}^2} \sin^2(\phi - \alpha)}]\} (A_{disp} - A_{disp\ rod}) [(r_{disp}) (1 + \cos\phi) - L_{disp}(1 - \sqrt{1 - \frac{r_{disp}^2}{L_{disp}^2} \sin^2\phi})] - V_{_overlap} - V_{cl\text{-}pist} - V_{D\ pist} \quad (5)$$

In Eq. (5), $V_{cl\text{-}pist}$ and V_{D_pist} represent the clearance volume of the piston with reference to displacer motion and the dead volume in the piston space respectively. Considering Fig. 2, the total volume (*V*) of the engine at any moment is:

$$V = V_{inst_pist} + V_K + V_R + V_h + V_{inst_disp}$$

Where, V_{inst_pist} , V_K, V_R, V_h and V_{inst_disp} indicate the instantaneous volume of the piston space, volume of the cooler, regenerator's volume, volume of the heater and the instantaneous volume of the displacer space, respectively.

TABLE I
SPECIFICATIONS OF THE BETA TYPE STIRLING ENGINE

Parameters	Specifications
Volume of the cooler	26.43 cm^3
Volume of the regenerator	7.48 cm^3
Volume of the heater	9.75 cm^3
Volume of min. clearance of piston and displacer	23.09 cm^3
Clearance volume of the displacer space	16.97 cm^3
Dead volume of the displacer space	33.83 cm^3
Output mean pressure	50 bar
Temperature of the hot space	900 K
Temperature of the cold space	300 K
Swept volume ratio	0.5, 1, 2, 3, 4, 5
Swept volume of the piston space	Different combinations
Swept volume of the displacer space	Different combinations
Volume of overlap region	Different combinations
Phase angle	Different combinations

$$V = (A_{pist})\,(r_{pist})\,\{[1-\cos(\phi-\alpha)] + L_{pist}[1-\sqrt{1-\frac{r_{pist}^2}{L_{pist}^2}\sin^2(\phi-\alpha)}]\} + (A_{disp}-A_{disp_rod})\,[(r_{disp})\,(1+\cos\phi) - L_{disp}(1-\sqrt{1-\frac{r_{disp}^2}{L_{disp}^2}\sin^2\phi})] - V_{_overlap} - V_{cl\text{-}pist} + V_{D_pist} + V_K + V_h + V_R + (A_{disp})\,[(r_{disp})\,(1-\cos\phi) + L_{disp}(1-\sqrt{1-\left(\frac{r_{disp}}{L_{disp}}\sin\phi\right)^2})] + V_{Ddisp} + V_{cldisp}$$

The overlap volume shared by the displacer and the piston space is given as:

$$V_{overlap} = \frac{V_{swpt_disp} + V_{swpt_pist}}{2} - \frac{\sqrt{(V_{swpt_disp})^2 + (V_{swpt_pist})^2 - 2\,(V_{swpt_disp})\,(V_{swpt_pist})\cos(\alpha)}}{2} \quad (7)$$

C. Calculation of Work done

For calculating work done (W), a programme was set on *matlab software* to observe the impact of any parametrical change. The following expression was used for work done:

$$W = \Sigma\,[(V_{i+1} - V_i) * (\frac{P_{i+1} + P_i}{2})] \quad (8)$$

Where, P and V represent the instantaneous values of pressure and volume respectively.

III. Results and Discussion

Table-I illustrates the specifications of a small beta type Stirling engine. These values are calculated on the basis of optimal application of different parameters in connection with their mutual adjustment. Most of the parameters are limited to be changed or altered consequently.

A *Matlab* programme was designed to analyse the optimum working conditions.Helium was taken as the standard working gas inside the engine.

A. Swept volume ratio and the Work done

The net work done reflects the efficiency of the engine. The results are analysed through calculating the net work done in a cycle for the instantaneous volume and the pressure. Pressure-Volume (PV) diagrams in Fig. 4 represent the calculated work done at different values of swept volume ratio, i.e., the ratio of swept volume of the piston space to that of the displacer space. The phase angle (ϕ) in each case is taken as 90° to be the optimum value for the other parameters as mentioned in Table 1.

It is notable that the value of calculated work done is being increased as the value of the swept volume ratio is increased. This means that as the swept volume of the piston (cold space) is increased or that of the displacer space (hot space) is decreased, the efficiency of the engine increases. This might have the reason that the hot gas coming from the displacer space through regenerator would have larger space to be cooled down and at larger extent (if not up to 300K). That is the reason that in the modern designed engines, an improvement in adsorption kinetics is obtained by using the finned structure (increased surface area) of heat exchangers [xvii] which can be seen widely in automobile engines. This improves the cooling capacity of the engine to a larger extent. The Pressure–Volume (P-V) diagram in Fig. 5 indicates the work done at different phase angles ranging from 30 to 150. It reveals that the PV diagram for the phase angle of 90 has the widest area and hence the maximum work will be achieved when the engine would run with the phase angle around 90 (5). With the set program in *matlab*software and generated spread sheets, the value of work done by the beta engine was calculated for phase angle values ranging from 1 to 180°. The results are illustrated graphically in Fig. 4(a)-(f).

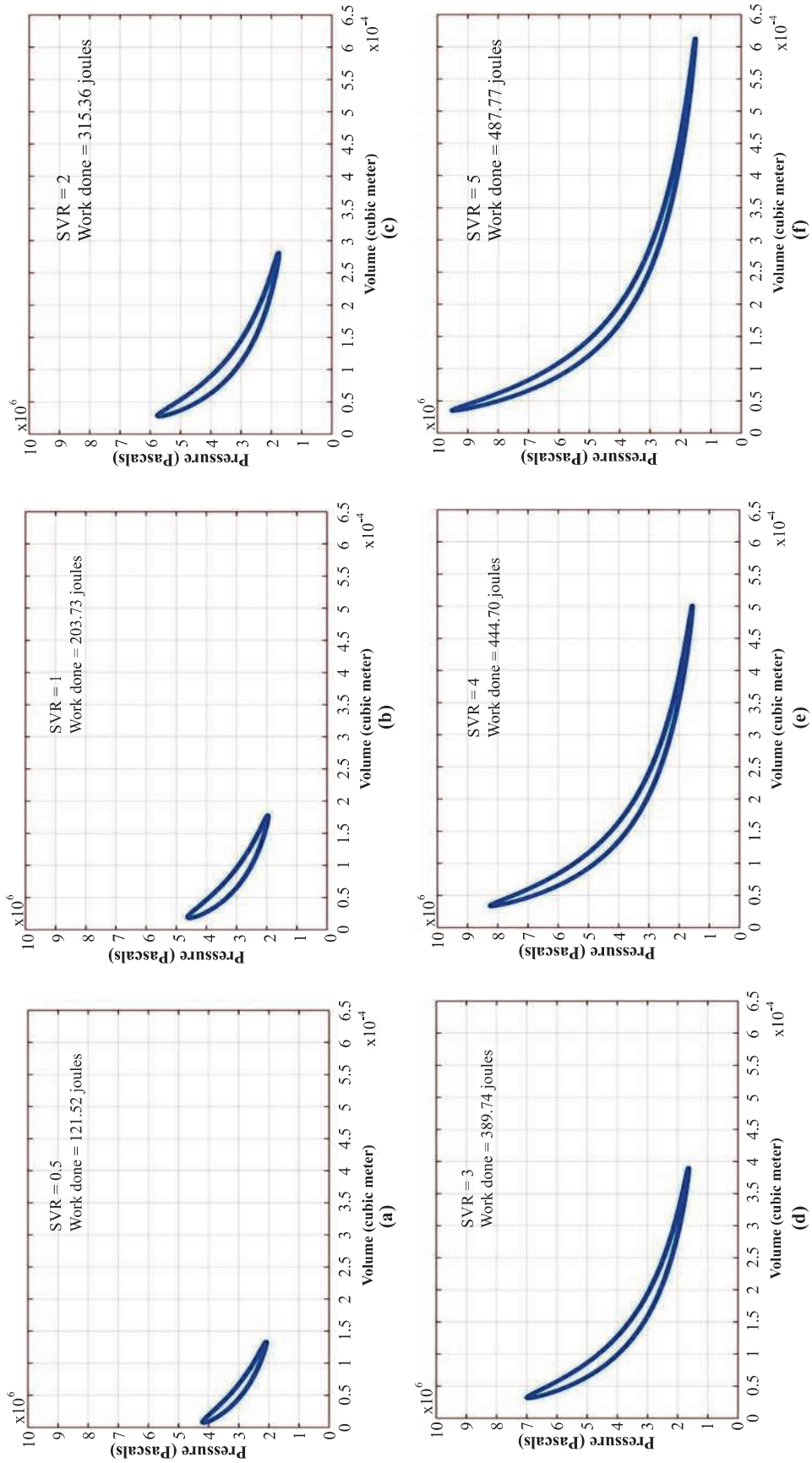

Fig. 4. Pressure–Volume diagrams for the given Beta type Stirling engine at phase angle 90° and swept volume ratio (SVR) of 0.5,1,2,3,4 and 5 respectively

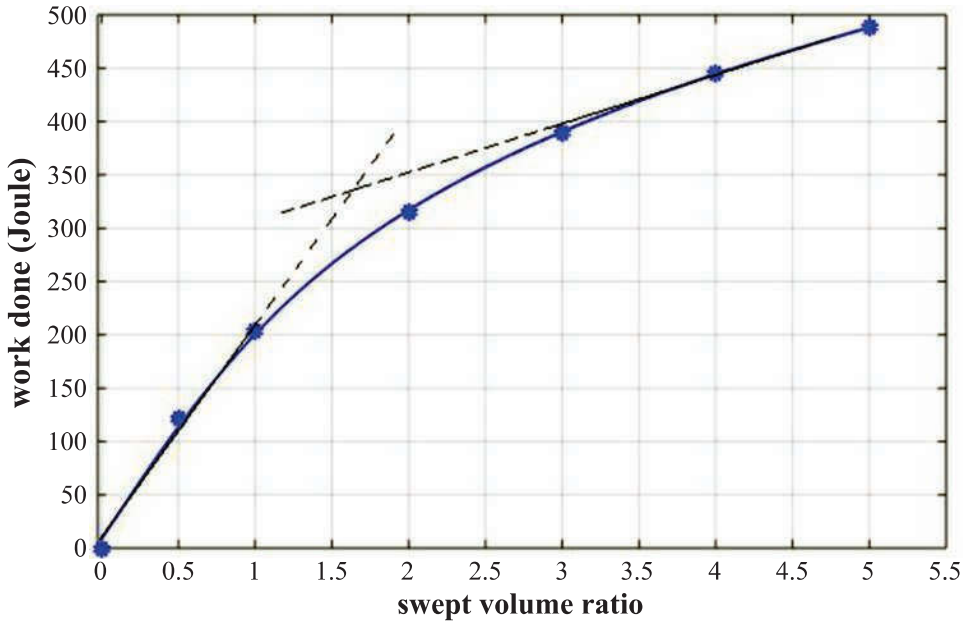

Fig. 5. Work done Vs Swept volume ratio for the beta type Stirling engine for Phase angle 90°

The graphs in Fig. 4 indicate that the efficiency of the engine in the form of work done increases with the increase in swept volume ratio. It is least in Fig. 4 (a) where the swept volume ratio is 0.5 and is found maximum in Fig. 4 (f). Fig. 5 reflects the trend of work done with the swept volume ratio.

It is notable that the there is an increasing trend in efficiency in the form of work done with swept volume ratio but the angle of the steep decreases as the SVR crosses beyond unity. This indicates that increasing the SVR by unity may not give as promising results in connection with the efficiency as it remained till SVR value as 1 for the set conditions. Nevertheless, there is impact of many other parameters like phase angle, overlap volume, temperature difference etc., but it is evident that a 'limit' has to be followed for SVR in order toachieve optimum efficiency.

B. Swept volume ratio and the overlap volume

In beta type Stirling engines, the overlap volume is the part of swept volume that is shared by both piston space and the displacer space. Overlap volume can be changed by altering the length of the connecting rod in the slider crank mechanism of either displacer or piston. In order to analyse the impact of overlap volume in connection with the swept volume ratio (SVR), four suitable combinations of overlap volume (7 cm^3, 14 cm^3, 28 cm^3, 35 cm^3) were selected in combination with varying values of SVR. The same impact with also noted for setting the overlap volume as *zero*. The graph in Fig. 6 depicts the increasing trend of efficiency with increase in SVR at different combinations of overlap volume of the beta type Stirling engine along with indication of change in steep after a specified value of SVR.

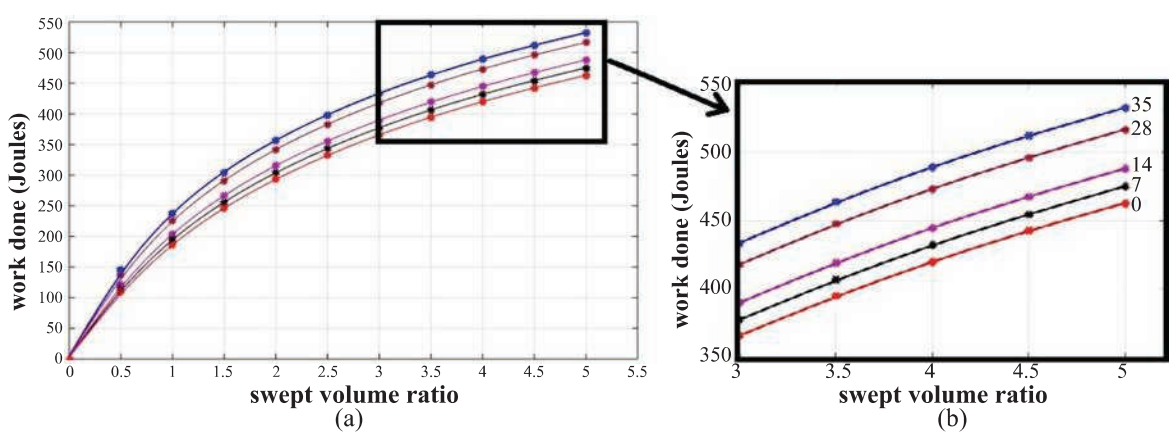

Fig. 6. Work done vs Swept volume ratio for beta Stirling engine at different overlap volumes

In Fig. 6 (a), it is obvious that the efficiency of the engine increases with the increase in swept volume ratio along with the overlap volume. It is indicated more clearly in Fig. 6 (b). The efficiency is at minimum when the engine is set with no overlap volume and attains its maximum value when the overlap volume was set to 35 cm^3 i.e. the highest of the set values. It is further notable that the steep angle for each graph remains almost constant till the value of SVR is 1, after that it decreases gradually. This indicates that increasing the overlap volume for a set value of SVR more than 1 may not promise to follow the same trend of increasing efficiency as it was till unit value of SVR. This confirms the result obtained previously in 3.1 that optimum value of SVR after which the inclination changes gradually is 1 for the presently set conditions.

C. Swept volume ratio and the phase angle

Phase angle is the angle by which displacer leads the piston for volume variations in beta Stirling engine cycle. Due to its significant role in the efficient working of a beta type Stirling engine, the synergistic effect of phase angle in connection with swept volume ratio are examined. Fig. 7 represents the relationship of SVR with work done at different phase angles.

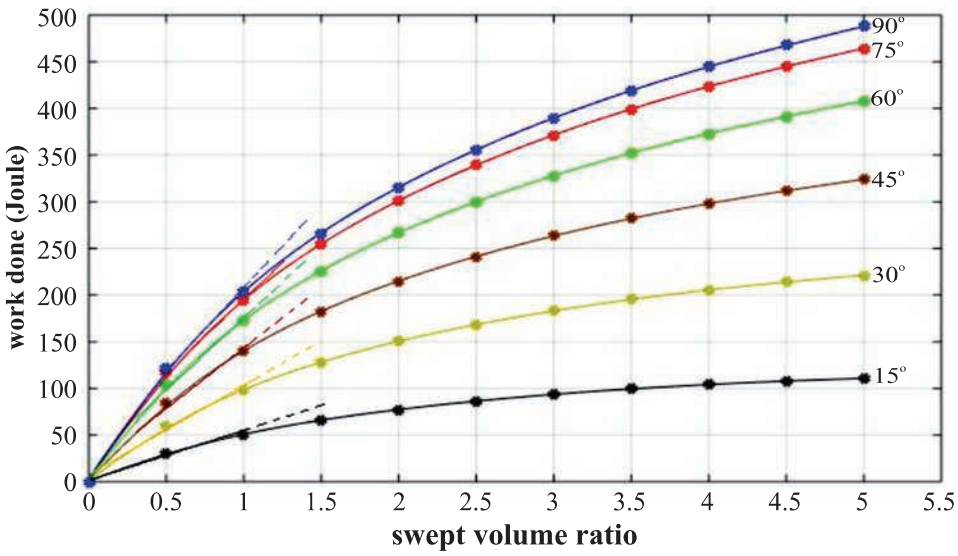

Fig. 7. Work done vs Swept volume ratio for beta Stirling engine at different swept volume ratios

It is evident that the efficiency of the engine increases with the phase angle till 90° after which it decreases gradually in the same manner. However, the steep angle reduces as the swept volume ratio increases; even at lower phase angle, the work done becomes almost independent of higher values of the swept volume ratio i.e. between 4.5 and 5. In Fig. 6, the angle of steep seemed to be unchanged until SVR increases by the value of 1.This again confirms the hypothesis of existence of an optimum value of swept volume ratio in the working of beta type Stirling engine. The optimum phase angle for the beta type Stirling engine detected elsewhere [9] is around 90° below and above which the efficiency decreases constituting a bell-shaped graph between work done and the phase angle. This also generates a notion that swept volume ratio and the phase angle could ensure the required work done at different combinations compensating each other. Contour plot in Fig. 7 demonstrates this concept for the optimal combination of swept volume ratio and the phase angle for attaining the required efficiency in the form of work done.

From the contour plot in Fig. 8, it is revealed that the required efficiency (in the form of work done) of the beta type Stirling engine is achievable based on the suitable combination of swept volume ratio and the phase angle; keeping the other parameters in account for their respective role. In the plot, the different coloured patterns represent the set values of work done (in Joules) as according to the numbers mentioned inside the graph. It is notablethat the work done becomes almost negligible at the phase angle 0° and 180°. It also confirms that increasing the swept volume ratio, keeping the phase angle constant, increases the work done by the engine. However, at fixed swept volume ratio, the work done increases with the phase angle till its optimal value (i.e. around 90°) and then it decreases in the same way as phase angle increases gradually.

This useful information indicates the synergistic effect of both discussed parameters upon the efficiency of the beta type Stirling engine for designing. It also reveals that one parameter may compensate the other keeping in sight of the other parameters and the other defined limits.

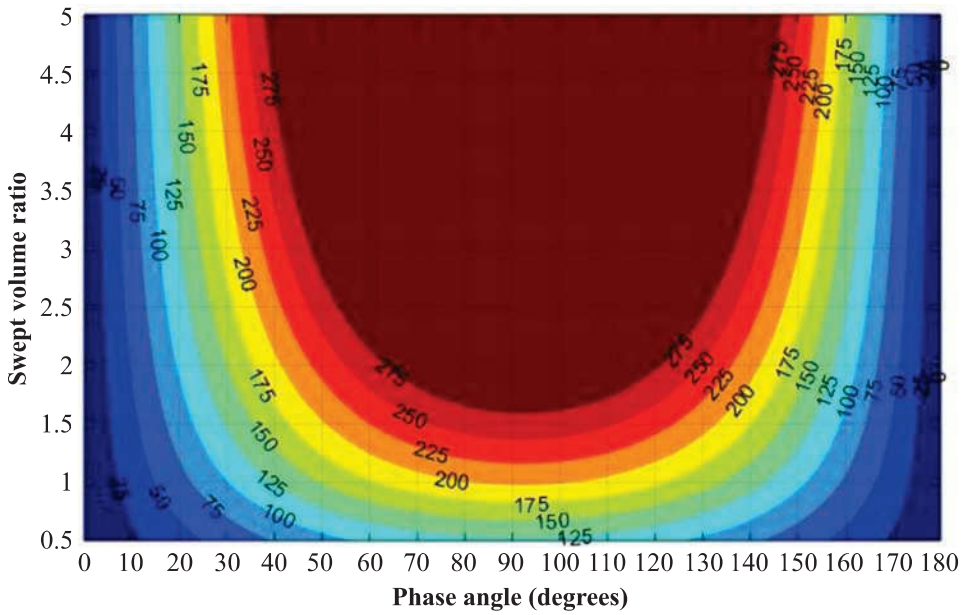

Fig. 8. Work done Vs swept volume ratio of the beta Stirling engine at different phase angles

IV. Conclusions

- Apart from not being that much popular as internal combustion engine, Stirling engine still appears to grab a promising future due to its simplicity of structure and a high energy to cost ratio. Swept volume relationship between both places of displacer and spacer plays a vital role and a defining parameter for the efficiency of beta type Stirling engine.
- The efficiency of the engine increases with the increase in ratio of swept volume of piston space to that of the displacer space. It was also revealed that this increment remains linear at some particular (optimum) value of swept volume ratio (SVR) and then rate of increment of efficiency with SVR decreases gradually with the further increase in SVR. In present case this optimum value of SVR was found to be unity subject to other parameters in consideration.
- There is a joint impact of swept volume ratio and the overlap volume of piston and displacer space of beta type Stirling engine on its efficiency. Efficiency is found to be increased with the increase in values of both parameters; a limit is always needed to be followed for optimum output though. The targeted efficiency of the beta Stirling engine could be achieved by suitable combination of both parameters as one compensates the other keeping other parameters constant.
- An optimum combination of phase angle with the swept volume ratio promises the effective working of the beta type Stirling engine with maximum output. As indicated by the counter plot in Fig. 8, the required amount of work done is achievable through suitable combination of both parameters as one parameter compensates the other.
- Targeted efficiency in the beta type Stirling engine is achievable if optimum values of the discussed parameters are selected with a special consideration to the swept volume ratio. This promises the maximum output with less energy consumption.

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