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# Influence of Dead Space Ratio for the Efficient Working of an Alpha Type Stirling Engine – Mathematical Analysis

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***Abstract-*** An Alpha type Stirling engine is different from the other two types in a way that it has two power pistons; one in hot cylinder while other in the cold one. Based on expansion and compression in both cylinders, the engine operates on cyclic manner through external heat source. The efficiency of the engine is recognised by its work done which relies on a number of factors including phase angle, swept volume and dead space. This research demonstrates the efficient working of an Alpha type Stirling engine through optimising the three parameters with a particular focus on the ratio of dead space of two cylinders using Schmidt analysis. Dead space in a Stirling engine is the total void volume in all spaces of engine which does not take part in efficient working of the engine and is unavoidable. The analysis of impact of other parameters to counter the effect of dead space is also the part of examination. The results reveal that negative effects of dead space could be neutralized through suitable selection of other variable parameters. The appropriate combination of swept volumes of both cylinders helps in minimising the effects of dead space and assists in attaining the desired efficiency. The optimal selection of phase angle is also vital, though a little complexed. The results are presented graphically. The examination reveals that negative effects of a parameter could be countered through appropriate selection of other parameters to attain the desired efficiency.

***Keywords-***Alpha type Stirling Engine, Work Done, Dead Space ratio, Phase Angle, Swept Volume Ratio

## I. INTRODUCTION

Continuous efforts are being made for bringing renewable energy as at a level of extracting maximum out-put [1–6]. The importance of renewable energy resources is increasing day by day. In order to compete with carbon emission which is a major source of global warming, it is the need of the day to guarantee developing renewable energy sources that generate little or no carbon [7]. The difference between input and output can be narrowed through optimization and parametrical analysis.

Albeit a number of applications reveal a serious interest of the researchers on existing thermodynamic models but still a wide room is available for efficiency analysis of the Stirling engines particularly the alpha type Stirling engine. The alpha type Stirling engine is different from the rest of the two types (beta and gamma) in a way that it has two pistons which work in the separate working spaces (expansion and compression space) and have two separate cylinders for each of them. While in beta and gamma type Stirling engines, there is a provision of displacer instead of the expansion piston whose purpose is just to displace or shuttle the working gas from one space to another. In order to run tests on an alpha type Stirling engine, it is imperative to have knowledge of the parameters and their respective roles which affect the engine working. The recent tests performed by the authors revealed that there are a number of parameters which play vital roles in the performance of the alpha engine and dead space ratio is one of those parameters. It is the ratio of the dead space to that of the expansion space in an alpha type Stirling engine. The dead space includes voids and cavities in the engine which do not take part in engine performance.

It is very vital to focus that the parametrical values change with the nature of tests and are bounded by the limitations and geometry of the engine is also needed to be kept under consideration which is an important step towards the engine modelling as one parameter can be controlled by choosing the appropriate value of the other parameter. Along with the purpose to identify the optimum conditions at which maximum output (Work-done) could be attained, in the current research, it was requisite to observe if similar results could be achieved at different combination of parameters. This could be realized by drawing the contour plots which help to identify different test conditions concluding the same output. How changes in dead volumes and combination of swept volumes affect the output work-done was needful for modelling the effective and workable alpha type Stirling engine.

A number of researchers have considered this key parameter in their investigation on Stirling engines. Kongtragool and Wongwises (2006) through a theoretical investigation on the thermodynamic analysis of a Stirling engine revealed that the net-work of the engine was affected the dead volumes and that the heat input increased with decreasing regenerator effectiveness and increasing dead volume [8]. Similarly, Cheng and Yang (2012) through a performance analysis of alpha, beta and gamma type Stirling engines found alpha type Stirling engine not suitable for the applications with low temperature difference with a possible reason that its dimensionless shaft vanishes gradually with the likely increase in temperature ratio [9]. In a very recent study, Guven et al., while working on comparative analysis of waste heat recovery (WHR) system of for a heavy duty diesel engine of a truck, revealed that Beta type Stirling engine is more efficient in this regard than that of the other two [10]. In a recent study, Bataineh (2018) through Ross Yoke mechanism, developed a combined thermodynamic and dynamic model for alpha -type Stirling engine and evaluated the influence of dead space ratio, swept volume ratio, effectiveness of the regenerator, and the heat source temperature at the maximum of the engine performance [11]. In another recent investigation on the performance and design of the Stirling engine, the authors illustrated graphically that the optimal dead-volume ratio for the maximum output of work was slightly lower than the optimal dead-volume ratio for maximum thermal efficiency due to a possible reason that the ideal model shows the asymptotical approach for the optimal dead-volume ratio for maximum thermal efficiency, however, for the maximum work output, it appears to be less than unity and decreases with increasing heater's temperature [12].

The current study highlights the analysis of the efficiency of an alpha type Stirling engine with a special reference to the role of dead space ratio for its optimal designing. An alpha type Stirling engine is shown in Figure 1. For both of the pistons (mounted in separate cylinders), there is a clearance between the respective piston and the cylinder walls. The heat is supplied to the hot cylinder through external source and the hot cylinder piston pushes the heated air to the cold cylinder during the expansion of the working gas as the hot cylinder piston moves from top dead centre (TDC) to the bottom dead centre (BDC).

Alpha type Stirling engine has high power-to-volume ratio. However, because of the quite high temperature range in the hot cylinder, this type of engine faces technical problems and faces issues in durability of seals. The phase angle has the major role in the efficiency of the engine. The phase angle has a key role on efficiency of Stirling engine and the best angle is generally found experimentally and 90° is frequently found to be the best one [13]. However, Daoud and Friedrich through their contemporary research on multi-cylinder Stirling engines, claim that the selection of optimum phase angle is dependent on the number of engine's cylinders and frequency of vibrations. This to top dead centre. The gas moves from hot cylinder to the cold cylinder through regenerator where the heat is absorbed. As the gas comes more in contact with the cold cylinder, the gas further cools down and the pressure is decreased. During this working, due to the momentum of the flywheel, the volume in the hot cylinder lowers down and the volume in the other cylinder increases accordingly. As all of the gas gathers in cold cylinder and the cooling of the gas continues resulting the pressure drop along with the contraction of the gas. At this stage, the volume of the hot cylinder is at its minimum level while the volume of the cold cylinder is at its maximum level. Due to the inertia of the flywheel, the cold cylinder piston moves up pushing the gas back towards hot cylinder through regenerator. As the gas enters back to hot cylinder, it pushes the piston down. This cycle continues. The optimum combination of temperatures for both cylinders is equally important like other parameters for efficient working [15].

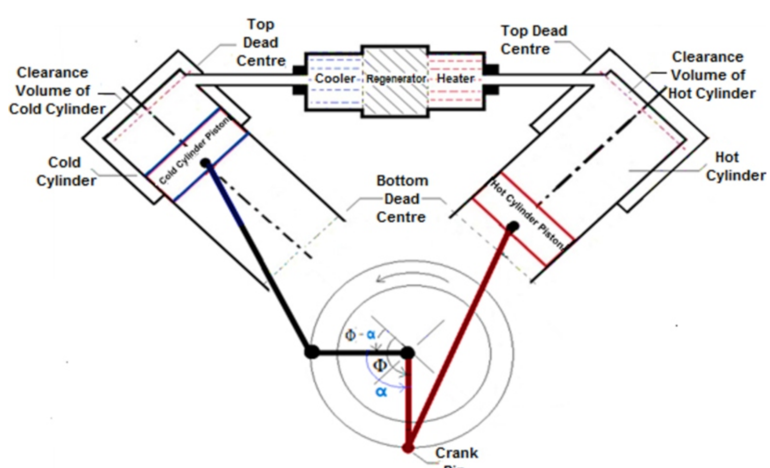


Figure 1 : Schematic diagram of an Alpha type Stirling engine

*Assumptions*: An idealized Stirling cycle follows Schmidt analysis with a number of the assumptions [16]:

- The working gas obeys the perfect/ideal gas laws.
- All the processes of the ideal Stirling cycle are thermodynamically reversible.
- The processes of compression in cold cylinder and expansion in hot cylinder are isothermal.
- No pressure drops occurs in the system at any point.
- The whole mass of the working gas in the cycle at any particular time is in the cold cylinder or the hot cylinder and remains constant i.e. no leakage.
- Regeneration occurs perfectly.
- The cycle is free from any of the frictional losses.

Intermittent piston motion: The Stirling cycle is attained by the system which is governed by intermittent piston operation. A general assumption applies that whole mass of the working fluid in the cycle at any particular time remains constant i.e. it is in either the compression or the expansion space. It can be inferred that at the conclusion of each process, the whole of the working gas is moved to the following phase before its beginning. This demonstrates a kind of discontinuation in the piston operation at the time of process change leading to a clear division for each of the four processes in an idealized Stirling cycle. However, an engine with intermittent piston motion is not practical. The ideal cycle, in practice, is with harmonic motion.

Piston movement: Consider two cylinders containing two pistons with their relative working motion and regenerator between them as shown in Figure 1. Both pistons work in such a manner that one is in the expansion space i.e. hot cylinder while the other is in the compression space i.e. cold cylinder and each is maintained at a respective high and low temperature level. It is a cyclic process and can be illustrated from any stage completing the whole cycle. The movements of the pistons along with their time–displacement can be revealed in four processes.

In the process at stage 1 of isothermal compression, the cold cylinder piston moves upwards compressing the gas towards the regenerator while the hot cylinder piston remains stationary. This process stage takes place at constant temperature and the heat released by compression is rejected. At stage 2, the heat addition is done at constant volume. The cold cylinder piston keeps moving up and at the same time the hot cylinder piston also begins to move away down i.e. away from regenerator revealing that the volume of the working gas in the cylinder stays constant. The gas is heated by the regenerator resulting in increase in pressure. The stage 3 is isothermal expansion process. The hot cylinder piston continues to move down i.e. away from the regenerator and the cold cylinder piston stays at top dead centre i.e. next to the regenerator. This results in an increase in volume of the gas in the cylinder in result of gaining heat. The temperature during this process remains constant. The added heat from the external source is utilised in increasing volume.

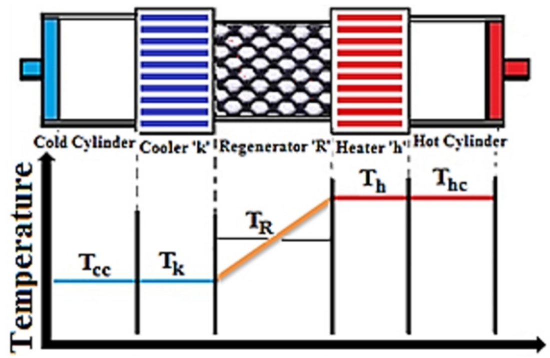


Figure 2: Pseudo model of a Stirling engine

At stage 4, the heat is rejected at constant volume. The cold cylinder piston moves away from top dead centre and the hot cylinder piston moves towards the top dead centre of the hot cylinder and the regenerator subject to the condition that the volume of the working gas remains constant. The heat is absorbed by the regenerator while the gas moves from hot cylinder to the cold cylinder.

## II. Mathematical Analysis

### *A. Calculations for the instantaneous pressure for the running cycle of the engine*

The total mass of the working fluid (gas) can be calculated based on the model demonstrated in Figure 2.At a particular instant, the total mass of the working fluid ($M_T$) for a closed Stirling cycle can be stated as the sum of the gas constituents present in all constituent areas.

$$M_T = M_{CC} + M_K + M_R + M_h + M_{hc} \quad (1)$$

By Universal Gas Law,

$$M_T = \frac{P_{cc}V_{cc}}{R\,T_{cc}} + \frac{P_kV_k}{R\,T_k} + \frac{P_RV_R}{R\,T_R} + \frac{P_hV_h}{R\,T_h} + \frac{P_{hc}V_{hc}}{R\,T_{hc}} \quad (2)$$

where, P, V, R and T represent pressure, volume, universal gas constant and temperature respectively. While, subscripts cc, k, R, h, and hc symbolize conditions in cold cylinder, cooler, regenerator, heater, and hot cylinder correspondingly. At any particular moment, the pressure 'P' in all spaces is considered to be the same.

$$M_T = \frac{P}{R}\left(\frac{V_{cc}}{T_{cc}} + \frac{V_k}{T_k} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{hc}}{T_{hc}}\right) \quad (3)$$

$$\mathrm{P} = \frac{M_T R}{\left(\frac{V_{cc}}{T_{cc}} + \frac{V_k}{T_k} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{hc}}{T_{hc}}\right)} \quad (4)$$

The temperature in the hot cylinder is the same as that in the heater and similarly, the temperature in the cold cylinder is same as that in cooler. Therefore, replacing $T_{cc}$ with $T_k$ and $T_{hc}$ with $T_h$, the Equation (4) becomes,

$$P = \frac{M_T R}{\left(\frac{V_{cc}}{T_k} + \frac{V_k}{T_k} + \frac{V_R}{T_R} + \frac{V_h}{T_h} + \frac{V_{hc}}{T_h}\right)} \quad (5)$$

Through calculations in accordance with the distance of a particular point from the cooler with respect to the overall length of the regenerator, the Equation (5) can be demonstrated as:

$$P = \frac{M_T R}{\left(\frac{V_{cc}}{T_k} + \frac{V_k}{T_k} + \frac{V_R \ln(\frac{T_h}{T_k})}{(T_h - T_k)} + \frac{V_h}{T_h} + \frac{V_{hc}}{T_h}\right)} \quad (6)$$

*B. Calculations for the instantaneous volume for the running cycle of the engine*

For calculation of the volume of the gas during the running cycle of the engine, consider Figure 2, in which volume can be divided into five major components namely, cold cylinder, cooler, regenerator, heater and hot cylinder denoted by $V_{cc}$, $V_k$, $V_R$, $V_h$, and $V_{hc}$ respectively. The total volume ($V_T$) of the engine at any particular instance is:

$$V_T = V_{cc} + V_k + V_R + V_h + V_{hc} \quad (7)$$

By Schmidt analysis, the instantaneous volume of the cold cylinder ($V_{hc}$) i.e. from piston to top dead centre, at any moment is given by:

$$V_{cc} = \frac{1}{2} V_C \; [1+\cos(\phi - \alpha)] \quad (8)$$

Where $V_C$ is the total volume of the cold cylinder, is the crank angle while α represents the phase angle. Similarly, the instantaneous volume of the hot cylinder ($V_{hc}$) i.e. from piston to top dead centre, at any moment is given by:

$$V_{hc} = \frac{1}{2} V_H \; (1+\cos\phi) \quad (9)$$

where, $V_H$ is the total volume of the hot cylinder. The values of VC and VH are calculated through areas of the respective pistons and the radial lengths of the respective crank pins and connecting rods. The specifications of the alpha type Stirling engine are given in Table I. The area of the cold cylinder piston is given by:

$$A_{cc} = \pi (r_{cc})^2 \quad (10)$$

where, $r_{cc}$ is the radius of the cold cylinder piston. Similarly, the area of the hot cylinder piston is given by:

$$A_{hc} = \pi (r_{hc})^2 \quad (11)$$

where, $r_{hc}$ represents the radius of the hot cylinder piston. The values of $V_{cc}$ and $V_{hc}$ calculated through Equations (8) and (9) are put in Equation (7). The rest of the $V_k$, $V_R$, and $V_h$ are standard values as according to size of the engine under consideration.

*C. Calculations for work done for the running cycle of the engine*

In order to calculate work done (*W*) for the running cycle of the engine, a software programme was made and run on *matlab* to for analysing the influence of dead space ratio on engine's performance. The following equation was used for calculating the work done by the engine:

$$W = \sum \left[(V_i - V_{i-1}) * \left(\frac{P_i + P_{i-1}}{2}\right)\right] \quad (12)$$

Where, *P* and *V* signify pressure and volume of the working gas at any particular moment respectively. In Equation (12), 'i' represents the test conducted. In the current case, the tests are conducted at different phase angles and the dead space ratios of the Alpha type Stirling engine and analysis is carried out for achieving the optimised conditions and maximum output i.e. work done by the engine under examination.

## III. RESULTS AND DISCUSSION

In order to analyse the working of an Alpha type Stirling engine and its ideal performance, the values of the parameters are calculated on the basis of optimal conditions. Most of the values of these parameters are able to be altered subsequently in order to achieve the best combination of parameters. In this regard, a programme on *Matlab* software was set to analyse the influence of dead space ratio in the efficiency of an Alpha type Stirling engine. Table I reveals the specifications of an Alpha type Stirling engine under observation. The main specifications of the Alpha type Stirling engine is based on previously published investigation on Stirling Engine of Beta type [17].

*A. Influence of dead space ratio on Work done*

The efficiency of an engine is revealed by its work done. This work done is dependent on the parameters. The results are examined by calculating the overall work done in a cycle for the instantaneous volume and the pressure. Figure 3(a) and 3(b) reveals the trend of change in work done output with the change in dead space ratio. In test 1, results shown in Figure 3(a), the phase angle of the Stirling engine was set at 90°. In a previous research, the phase angle at which maximum work done was obtained for beta type Stirling engine was noted to be the same [13]. However, Alfarawi et al. revealed that maximum indicated power of a gamma type Stirling engine was obtained at phase angle of 105° [18]. While Figure 3 (b) reveals the same test conditions with an exception of the phase angle of 150°.

TABLE I
Specifications of the Alpha type Stirling engine

| Parameters | Specifications |
|---|---|
| Swept volume of the hot cylinder piston | 100 $cm^3$ |
| Volume of the cooler | 34.56 $cm^3$ |
| Volume of the regenerator | 50$cm^3$ |
| Volume of the heater | 17.25 $cm^3$ |
| Swept volume of the cold cylinder piston | Different combinations |
| 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, 1.5, 2, 2.5, 3 |
| Dead space ratio | 0, 0.5, 1, 2 |
| Phase angle | Different combinations |

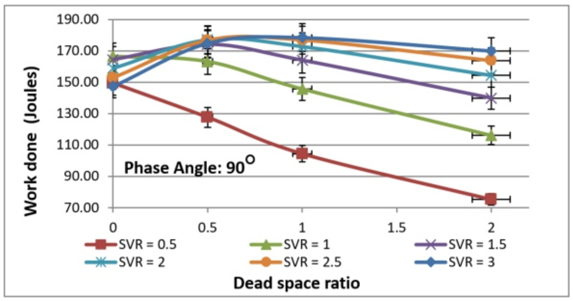


Figure 3 (a): Work done Vs dead space ratio at phase angle of 90° and swept volume ratio (SVR) of range 0.5 – 3.00

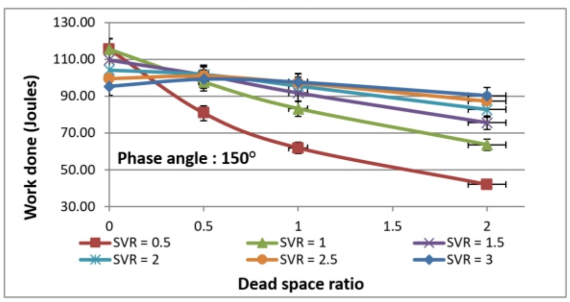


Figure 3 (b): Work done Vs dead space ratio at phase angle of 150° and swept volume ratio (SVR) of range 0.5 – 3.00

Phase angle is the angle by which hot space space piston leads the cold space piston with respect to the volume variations in the engine cycle. Both of these tests validate that with the increase in dead space ratio, the efficiency of the engine decreases which is illustrated through work done (in Joules) in the current case. It is notable that for the tests with phase angle 90°, the curves for work done for swept volume ratio of 0.5 and 1.00 steep down gradually with the increase in dead space ratio from 0 to 3 with an interval of 0.5. However, for swept volume ratios of 1.5, 2, 2.5 and 3, the curves for work done first increase with the increase in dead space ratio from 0 to 0.5 and after that these decrease with increase in dead space ratio from 0.5 to 2. This could be for the reason that for the cases when the swept volume of the cold cylinder piston increases keeping the hot cylinder volume constant resulting in increase in swept volume ratio, and that engine cools down speedily increasing in work done. For the rest of the case when dead space ratio increases further, the work done decreases. In the later cases, the increase in dead space ratio is quite dominant in comparison to the former two cases resulting in decrease in work done. In the case of phase angle of 150, all of the steeps follow the same trend i.e. towards down with the increase in dead space ratio which demonstrates that the energy spent on voids and dead volume would have no effect on efficiency of the engine, rather the later decreases due to extra energy spent on voids and dead space. These issues are needed to be carefully kept in mind by the engine designers. It is further notable in both cases that as the swept volume ratio increases, there is less decrease in work done with increase in dead space ratio. This implies that for the optimised designing of the Stirling engine, the higher swept volume ratio would lessen the effect of increase in dead space ratio. This effect can be clearly seen in case when swept volume ratio is 0.5. The curve of the work done is steeper than those when swept volume ratio is increased. Looking at the trend in Figures 3(a) and 3(b), it can be seen that influence of the dead space

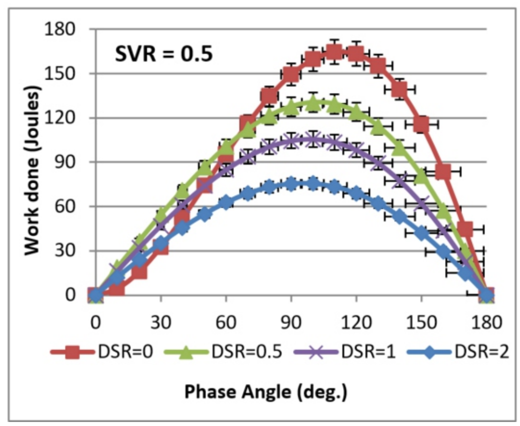


Figure 4 (a): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 0.5

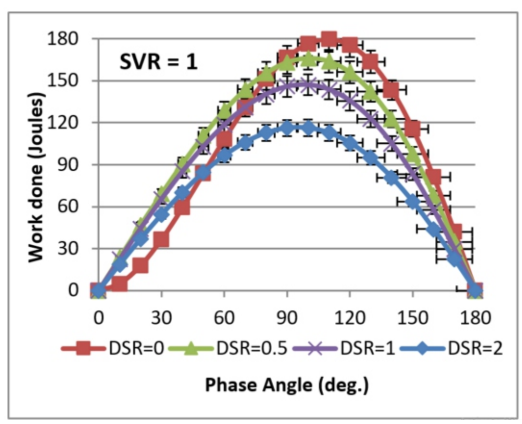


Figure 4 (b): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 1.

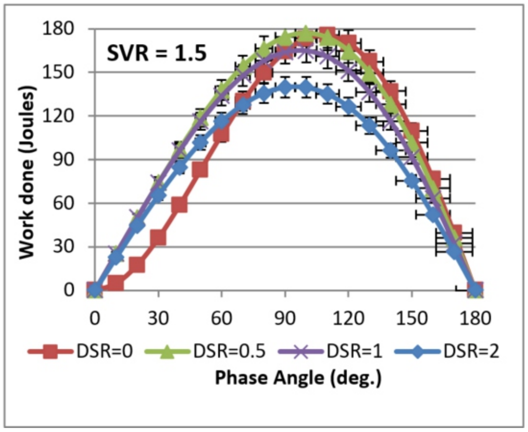


Figure 4 (c): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 1.5

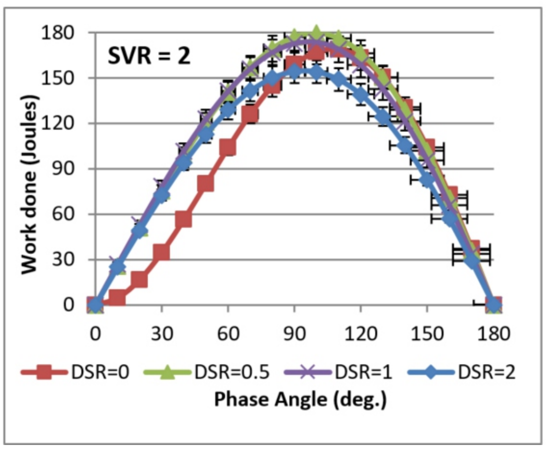


Figure 4 (d): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 2

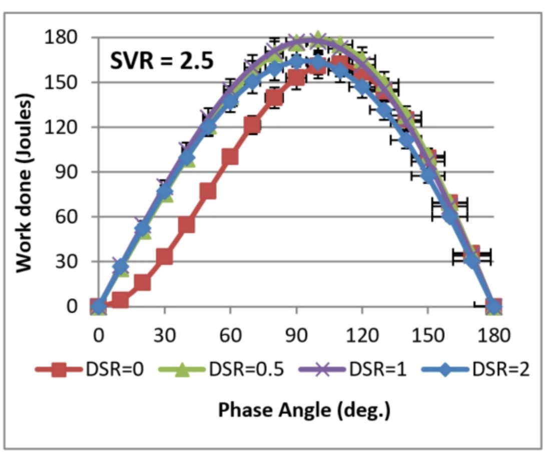


Figure 4 (e): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 2.5

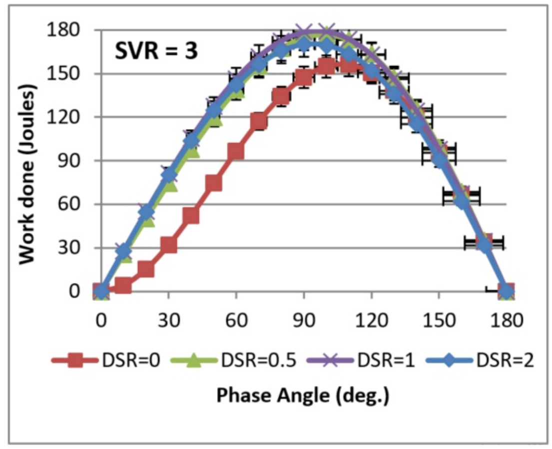


Figure 4 (f): Work done Vs Phase angle for dead space ratio (DSR) range 0–2 at swept volume ratio (SVR) of 3

ratio in efficiency of the engine decreases with the decrease in swept volume ratio. In current cases, at lower values of dead space ratio (i.e. at 0 and 0.5 in particular), the change in swept volume ratio has negligible effect on the efficiency (work done) of the engine. These findings reveal that a smart analysis of dead space ratio is needful for optimised designing of an Alpha type Stirling engine in order to attain maximum efficiency.

*B. Dead space ratio and work done at different values of phase angle*

Figures 4(a)–(j) reveal graphs of work done Vs phase angle of the range of 0° to 180° at different values of dead space ratio (DSR). In order to analyse the impact of dead space ratio, the values of 0, 0.5, 1, 1.5, 2, 2.5, and 3 were selected and the tests were run at particular value. The results reveal that at lower values of phase angle (say 0° to 60°), the impact of dead space ratio on the efficiency of the engine is quite minor (or negligible). According to previous findings, a Stirling engine gives highest power output at optimum phase angle of 90° [12, 19]. In current investigation, at optimum phase angle, the dead space ratio at 0 gives the maximum output in majority of the cases, except a few which will be discussed in next section. As the phase angle exceeds 90°, the difference in work efficiency at different phase angle also lowers down. This would probably due to the reason that at phase angles values lower (or upper) to 90°, the work done is lesser than that of the optimised value, and hence at different values of dead space ratio, the difference in work done also decreases.

It is further notable that at higher values of dead space ratio, the difference in efficiency of the engine appears to be minor in comparison to that of the 0 DSR. This could be attributed to the reason of absence of voids which decreases the efficiency of the engine.

This can be further revealed in Figures 3(a) and 3 (b) that at higher values of DSR, the differences in efficiency (work done by the engine) lessens. This all demonstrates that presence of dead space in engine decreases the efficiency of the engine particularly when engine enters from no dead space to a certain dead space. This is due to the reason that in the presence of dead space, engine has to do extra work on these voids/dead space without any output in return.

For the phase angle of smaller values i.e. 0° to 90°, the efficiency curve is less steeper than in case of the higher values of phase angle i.e. 90° to 180° for almost all values of dead space ratio particularly for the higher values of DSR. Dealing with dead spaces and voids in an engine through the phase angle is a complexed phenomenon but logical in many ways. The timings and relative movement of both pistons in connection with each other is quite imperative in a way that it regulates the movement of gas from hot chamber to cold chamber and vice versa. In between, the dead spaces and voids in both chambers and the regenerator which do not take part in working of the Stirling engine appear to be extra loads in terms of engine working reduces the efficiency. However, there are still limitations in dealing with such consequences through phase angle. The one reason is that phase angle itself needs optimization for its maximum output and is theoretically (as well as practically) observed that at 90° and around, the output of the Stirling engine is maximum. Therefore, altering the phase angle in order to deal with the voids and dead space may deviate engine from its efficient working. However, compromising with a suitable combination of both parameters may lead to desired output and efficiency.

*C. Dead space ratio and work done at different values of swept volume ratio*

Swept volume plays a dynamic role for the efficient working of a Stirling engine. Swept volume ratio (SVR) is the ratio of swept volume of cold cylinder piston to that of hot cylinder piston. The current tests were conducted at different values of swept volume ratio for an alpha type Stirling engine whose specifications are shown in Table I. For obtaining different combinations of swept volume ratios, swept volume of cold cylinder piston was altered for different values while swept volume of hot cylinder piston was fixed at $100cm^3$. Tests were run at swept volume ratios of 0.5, 1, 1.5, 2, 2.5, and 3. The impact of SVR was noted for different values of dead space ratio (DSR) in terms of efficiency curve of work done. It is notable from Figures 4(a) – 4(f) that lower the value of SVR, higher will be the efficiency of the engine at low DSR. As the SVR increases, the difference between the efficiency curves decreases and at higher values of SVR, the efficiency (work done) is noted to be higher than that with low SVR at specified values of DSR for a complete cycle of phase angle i.e. 0° to 180°. It can be further noted that as the swept volume ratio is increased, the efficiency of the engine (particularly those running at higher values of dead space ratio) also increases. This could be due to the reason that the swept volume is increased by increasing the swept volume of cold cylinder piston which is denominator in the swept volume ratio (keeping the swept volume of the hot cylinder piston which is nominator in SVR). Due to the increase in engine's swept volume, the power and efficiency of the engine is increased.

Noting the previous findings that maximum efficiency of a Stirling engine is obtained at phase angle of 90° [13], it can be further observed that phase angle from 0° to 90°, the curve of the work done becomes more steeper as the value of SVR is increased almost for all values of DSR. However for phase angle from 90° to 180°, the shape of the efficiency curve is almost the same in all cases. The reason for this is same that power of the engine is increased due to increase in swept volume of the cold cylinder piston.

It is notable that at increased values of swept volume ratio, the engine's efficiency (in terms of work done) becomes irrelevant of dead space ratio, specifically for the phase angle of range 90° to 180°. In Figures 4(e) and 4(f), there is almost no difference in efficiency at phase angle range of 90° to 180° for all values of dead space ratio. This could be attributes to the reason that increase in dead spaces and voids which contributes in decreasing the engine's efficiency, is compensated by increase in engine's power through increase in swept volume of the cold cylinder piston.

A general investigation in connection with swept volume ratio and dead spaces in engine is that for achieving the maximum output, an optimized and suitable combination of the both parameter is required. In order to enhance the engine's efficiency, the dead spaces in engine could be covered by increase in swept volume ratio of the engine. However, the limitations are always applicable.

## IV. CONCLUSIONS

- Stirling engine holds a prominent place particularly where external source of energy is available and in research and development activities, albeit, not very often in use on practical grounds. This is due to its simple structure, low initial cost and a good reliability factor. The effect of dead space in a Stirling engine plays a significant in concluding its efficiency, however, its presence impacts negatively on engine's performance.
- The efficiency of the Stirling engine decreases with the increase in dead space ratio of the engine or simply the dead space. However, the rate of decrease depends on a few other parameters as well particularly the phase angle. A gradual deviation from a general trend is based on the size of dead

space in the engine.

- The negative effects of dead space in engine's performance could be well optimised with swept volume ratio. With the increase in dead space ratio, there will be less decrease in work done as if the swept volume ratio is also increased likewise. However, the tests reveal that at lower values of dead space ratio (i.e. 0 and 0.5 in particular), the change in swept volume ratio has negligible effect on the efficiency of the engine. An optimised combination of both parameters is always needful as according to requirement.
- The influence of dead space in a Stirling engine could be reduced by optimal selection of phase angle. However, dealing with dead spaces in a Stirling engine through the phase angle optimization is a complexed phenomenon but logical in many ways. Upon gradually increasing the dead space ratio with the phase angle from 0° to 90°, the efficiency of the engine also decreases gradually. But the decrease rate is quite less in comparison to that when engine is running at higher values of phase angle i.e. 90° to 180°. At 90° phase angle, the efficiency of the engine is found maximum.
- The efficiency of an Alpha type Stirling engine could be increased and the effects of dead space in the engine could be minimised if optimum combination of the discussed parameters are selected which results in efficient working of the engine with minimum energy input.

## REFERENCES

[1] Timoumi, Y., Tlili, I. and Nasrallah, S.B., 2008. Performance optimization of Stirling engines. *Renewable Energy*, *33*(9), pp.2134-2144.

[2] Sripakagorn, A. and Srikam, C., 2011. Design and performance of a moderate temperature difference Stirling engine. *Renewable Energy*, *36*(6), pp.1728-1733.

[3] Ahmadi, M.H., Hosseinzade, H., Sayyaadi, H., Mohammadi, A.H. and Kimiaghalam, F., 2013. Application of the multi-objective optimization method for designing a powered Stirling heat engine: design with maximized power, thermal efficiency and minimized pressure loss. *Renewable Energy*, *60*, pp.313-322.

[4] Toghyani, S., Kasaeian, A. and Ahmadi, M.H., 2014. Multi-objective optimization of Stirling engine using non-ideal adiabatic method. *Energy Conversion and Management*, *80*, pp.54-62.

[5] Buliński, Z., Szczygieł, I., Kabaj, A., Krysiński, T., Gładysz, P., Czarnowska, L. and Stanek, W., 2018. Performance analysis of the small-scale α-type Stirling engine using computational fluid dynamics tools. *Journal of Energy Resources Technology*, *140*(3), p.032001.

[6] Sandoval, O.R., Caetano, B.C., Borges, M.U., García, J.J. and Valle, R.M., 2019. Modelling, simulation and thermal analysis of a solar dish/Stirling system: A case study in Natal, Brazil. *Energy Conversion and Management*, *181*, pp.189-201.

[7] Kammen, D.M., 2006. The rise of renewable energy. *Scientific American*, *295*(3), pp.84-93.

[8] Kongtragool, B. and Wongwises, S., 2006. Thermodynamic analysis of a Stirling engine including dead volumes of hot space, cold space and regenerator. *Renewable Energy*, *31*(3), pp.345-359.

[9] Cheng, C.H. and Yang, H.S., 2012. Optimization of geometrical parameters for Stirling engines based on theoretical analysis. *Applied energy*, *92*, pp.395-405.

[10] Güven, M., Bedir, H. and Anlaş, G., 2019. Optimization and application of Stirling engine for waste heat recovery from a heavy-duty truck engine. *Energy Conversion and Management*, *180*, pp.411-424.

[11] Bataineh K. Mathematical formulation of alpha-type Stirling engine with Ross Yoke mechanism. Energy. 2018 Dec 1;164:1178-99.

[12] Wills, J.A. and Bello-Ochende, T., 2018. Second law analysis and constructal design of Stirling engine heat exchanger (regenerator) for medium temperature difference (MTD). *Proceedings of the romanian academy series a-mathematics physics technical sciences information science*, *19*, pp.172-177.

[13] Siddiqui, F.A., Hayat, N., Farhan, M., Farooq, M. and Bilal, H., 2014. Effect of phase angle on the efficiency of beta type Stirling engine. *Journal of Faculty of Engineering & Technology*, *22*(2), pp.99-109.

[14] Daoud, J.M. and Friedrich, D., 2019. Design of the multi-cylinder Stirling engine arrangement with self-start capability and reduced vibrations. *Applied Thermal Engineering*, *151*, pp.134-145.

[15] Baker, R. W. 2004. Membrane technology and applications. *John Wiley & Sons, Ltd*, 96-103.

[16] Karabulut, H., Okur, M., Halis, S. and Altin, M., 2019. Thermodynamic, dynamic and flow friction analysis of a Stirling engine with Scotch yoke piston driving mechanism. *Energy*, *168*, pp.169-181.

[17] Siddiqui, F.A., Chaudhry, A., Farhan, M., Sanaullah, I., Asim, M., Hanif, M.F. and Ambreen, T., 2016. Impact Of Swept Volume Ratio In Designing A Beta Type Stirling Engine. *UET Taxila. Technical Journal*, *21*(2), p.39.

[18] Alfarawi, S., Al-Dadah, R. and Mahmoud, S., 2016. Influence of phase angle and dead volume on gamma-type Stirling engine power using CFD simulation. *Energy Conversion and Management, 124*, pp.130-140.

[19] Farid, Z. M., Rosli, A.B. and Kumaran, K., 2019, January. Effects of phase angle setting, displacement, and eccentricity ratio based on determination of rhombic-drive primary geometrical parameters in beta-configuration Stirling engine. In *IOP Conference Series: Materials Science and Engineering.* Vol. 469.