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Finite Physical Dimensions Thermodynamic Analysis for Gamma Stirling engine†

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Abstract: In the foreseeable future, the depletion of finite fossil fuel reserves is a growing concern due to the increasing consumption of these resources by humans. Moreover, the emission of greenhouse gases from fossil fuel consumption contributes to global warming, resulting in significant harm to the Earth's ecosystem. The Stirling engine (SE) offers an outstanding solution for harnessing various heat sources, including solar, nuclear, and fossil fuels, among others. It provides numerous advantages, such as high efficiency, a long lifespan, low noise levels, and minimal or no emissions. This paper conducts a finite physical dimensions thermodynamic analysis (FPDT) on a gamma-type double piston cylinder engine and compares the results with other isothermal models and experimental data. The current model's results align closely with other thermodynamic models.

Keywords: Stirling engine; Thermodynamics; Power; Efficiency

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1. Introduction

In the forthcoming years, the depletion of fossil fuel reserves poses a critical concern, primarily due to the ever-increasing human consumption of these non-renewable resources. Notably, the heightened usage of fossil fuels contributes significantly to the emission of greenhouse gases, exacerbating global warming and causing substantial damage to the delicate balance of the Earth's ecosystem [1,2]. Consequently, there is an urgent need for alternative energy sources to address this pressing issue. Among the potential solutions, solar energy stands out as a safe, environmentally friendly, and cost-free option, presenting a viable competition to conventional fossil fuels. With the escalating demand for sustainable energy, solar power emerges as a promising choice to alleviate the strain on fossil fuel resources and mitigate their adverse impact on the planet.

In this context, the Stirling engine (SE) comes into focus as a promising mechanism for harnessing solar power effectively. The Stirling engine boasts a range of advantageous features, including high efficiency, a long operational lifespan, low noise levels, and minimal or virtually no emissions [3,4]. By leveraging these benefits, the Stirling engine provides a sustainable and reliable means of converting every form of energy into usable power, offering a pathway to reduce our reliance on fossil fuels and curbing their detrimental effects on the environment. With the pressing need to address climate change and preserve the planet's ecological balance, the adoption of solar energy, particularly through the utilization of Stirling engines, becomes a crucial step towards a more sustainable and greener future.

Within this research paper, an investigation delves into the performance of a gamma type Stirling engine through the implementation of a finite physical dimensions thermodynamic (FPDT) model. The outcomes produced by the FPDT model are subjected to a comparative analysis against another established thermodynamic model. The findings exhibit that the power output and efficiency yielded by the FPDT model reach 154.89 W and 34.1%, respectively. These values surpass the outcomes obtained from experimental estimates, as well as those documented in the existing literature. This particular model proves instrumental in uncovering insights regarding diverse losses present within the Stirling engine. Notably, a meticulous examination highlights that hysteresis losses within the Stirling engine supersede other forms of losses. This phenomenon can be attributed to the unique operational characteristics of the closed-cycle system in consideration.

2. Engine Data and Mathematical Equation

The engine under study is a gamma-type double-piston Stirling engine. In this engine, the exhaust gas of the diesel engine is used as the heat source [5]. To heat the heater tubes of the Stirling engine, especially the cap is made for the Stirling engine. Further details of Engine data are given below.

Table 1. Engine data of gamma type double piston Stirling engine [5].

Engine Data	Values	Engine Data	Values
Cooler temperature	294	Pressure (bar)	3.58
Heater temperature	424	Rotational speed (rpm)	882
Cooler volume	223E-6	Phase angle (degree)	88°
Heater volume	87.28E-6	Regenerator volume (m^3)	308.93
Expansion swept volume (m^3)	221E-6	Compression swept volume (m^3)	194E-6
Expansion clearance volume (m^3)	24E-6	Compression clearance volume (m^3)	35E-6

In this finite physical dimensional thermodynamic analysis, the important equations are described here and for the further information about the description of equation, readers are referred to this [6]. In finite physical dimensions thermodynamic (FPDT) approach, finite physical dimensions are taken into account, including factors like heat transfer area and the speed of the working piston. These considerations align better with an engineering perspective. The losses within the engine can be represented as functions of gas speed or rotational speed. These losses encompass elements such as mechanical friction, hysteresis loss, pressure reduction from the finite speed movement of the piston, and the dissipation of energy through viscosity within the heat exchanger channels.

Stirling engine is an important machine. The volume of expansion and compression space of gamma type Stirling machine can be expressed as[6]

$$V_e = \frac{V_{e0}}{2}\left[1-\cos\left(\omega t\right)\right] \tag{1}$$

$$V_c = \frac{V_{e0}}{2}\left[1+\kappa+\cos\left(wt\right)-\kappa\cos\left(\omega t-\phi\right)\right] \tag{2}$$

$$\kappa = \frac{V_{c0}}{V_{e0}} \tag{3}$$

The total volume of the engine is calculated as

$$V_t = V_e + V_c + V_t = \frac{V_{e0}}{2}\left[2+\kappa-\kappa\cos\left(\omega t-\phi\right)+2\chi\right] \tag{4}$$

$$\chi = \frac{V_r}{V_{e0}} \tag{5}$$

$$P = \frac{mr_g T_e}{V_{e0}} \left[\frac{2\chi}{1+\tau} + \frac{1+\tau+\kappa}{2\tau} + \frac{(1-\tau)\cos(\omega t)}{2\tau} + \frac{\cos(\omega t - \phi)}{2\tau} \right]^{-1} \tag{6}$$

Where $\tau = T_c / T_e$ and the indicated mechanical of Stirling engine is calculated as

$$\dot{W} = \frac{1}{2\pi / \omega} \oint P dV_t \tag{7}$$

After the integration, the indicated mechanical power of the engine is denoted as

$$\dot{W} = \omega m r_g \frac{\tau(1-\tau)\kappa \sin(\phi)}{a^2+b^2} \left[\frac{\beta}{\sqrt{\beta^2 - (a^2+b^2)}} - 1 \right] \tag{8}$$

Where $a = 1 - \tau - \kappa\cos(\phi), b = \kappa\sin(\phi), \beta = \frac{4\tau\chi}{1+\tau} + 1 + \kappa$, heater tranfer flow in the heater, rejected from the cooler and stored in the regenerator can be calculated.

$$\dot{Q}_h = \omega m r_g T_e \frac{\tau\kappa \sin(\phi)}{a^2+b^2} \left[\frac{\beta}{\sqrt{\beta^2 - (a^2+b^2)}} - 1 \right] \tag{9}$$

$$\dot{Q}_k = -\omega m r_g T_e \frac{\tau^2\kappa \sin(\phi)}{a^2+b^2} \left[\frac{\beta}{\sqrt{\beta^2 - (a^2+b^2)}} - 1 \right] \tag{10}$$

$$\dot{Q}_r = \dot{m}_{av} c_p (1-\varepsilon_r)(T_e - T_c) \tag{11}$$

Where m_{av} is a average mass flow rate, ε_r is efficiency of regenerator. For the detailed information about losses in the Stirling engine, readers are referred to this [6].

3. Results and Discussion

3.1. Model Validation

For the model validation, detailed analysis of FPDT model, the p-V diagram is shown below which describe the performance of Stirling engine. Furthermore, table 1 shows the summary of thermodynamic model, in which work, power, efficiency of FPDT model is compared with Simple model, adiabatic model and experimental data. The indicated work of FPDT model is 10.7 J while the experimental value of determined by Abdul Rab et al. [5] is 7.50 J which is 41 % more than experimental estimated value. The average pressure of the engine is 3.58 bar butt the estimated values of by using this method is comes out to be 4.75 bar pressure and the peaks values of p-V diagram curve also more than estimated values.

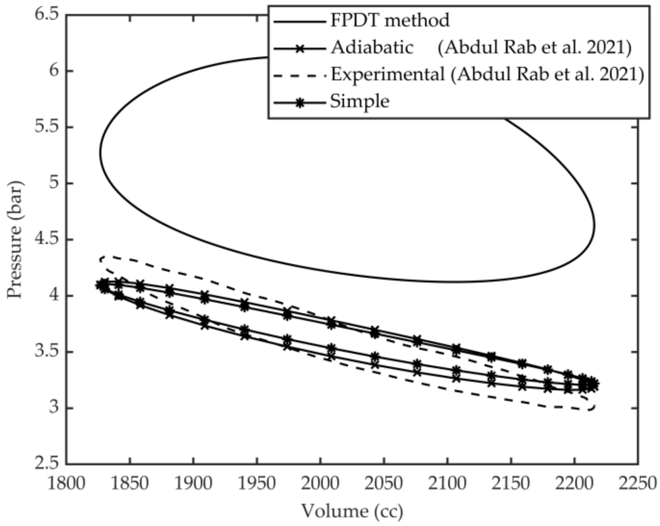

Figure 1. Comparison of FPDT model with other isothermal model and experimental data.

Table 2. Summary of thermodynamic models.

Parameters	Simple[5]	Adiabatic[5]	Experimental[5]	FPDT model
Work (J)	6.30	9.70	7.50	10.7
Power (W)	93.2	143.75	111.43	154.89
Efficiency (%)	21.2	30.90	24.70	34.1

There are various losses also estimated in this research work i.e., the average power losses, shuttle losses, hysteresis losses, average fluid friction losses. Table 3 shows the projected values of these losses. The working gas goes a close cycle, therefore, hysteresis losses in the Stirling engine is more than other losses which is estimated as 27.53 W.

Table 3. Different type of losses estimated for gamma Stirling engine.

Different losses (W)	Values
Power Losses	7.8
Shuttle Losses	9.7
Hysteresis Losses	27.53
Fluid friction Losses	24.73

Upon closer examination, it becomes evident that hysteresis losses within the Stirling engine hold precedence over other forms of energy dissipation. This intriguing phenomenon can be attributed to the distinctive operational dynamics characterizing the enclosed cyclic system under scrutiny.

4. Conclusion

In this research paper, performance of gamma type Stirling engine is analyzed using finite physical dimensions thermodynamic (FPDT) model. The results of FPDT model are compared with the other thermodynamic model. The results shows that power and efficiency obtained by FPDT model is 154.89 W and 34.1 % which is more than experimental estimated values when comparing this model results with the literature. By using this model, various losses in the Stirling engine are also analyzed. It is found that hysteresis losses in the Stirling engine is more than other losses due to working condition of close cycle.

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