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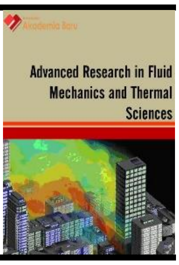

Design and Modelling of a Beta-Type Stirling Engine for Waste Heat Recovery

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Harlinda Helman[1], Syamimi Saadon[1,*]

[1] Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

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ABSTRACT

Apart from development of renewable energy, existing energy resources can be better utilized and used efficiently by recovering thermal waste sources released into atmosphere from many industrial processes. It is crucial that a waste heat recovery system is implemented as a mechanism to recover waste heat that is released to the environment and transform it into another form of energy that can be used more economically. These thermal sources range from low to moderate temperature heat, which can be exploited into usable mechanical power. Therefore, this paper intends to design and model a Stirling engine that can recover waste heat from various thermal sources by using CFD. The design is then validated so that it can be used in the estimation of total heat recovered by this type of engine.

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1. Introduction

Climate change has become a global issue resulting from human activity and natural variability. Emission of greenhouse gases from vehicles and power plants by burning of fossil fuel is one of the factors that have caused global warming. These gases such as carbon dioxide and methane trap heat in the atmosphere leading to the rise in atmospheric temperature. This causes the rise of sea level due to melting of permafrost in the Arctic and Antarctic. Global warming has also impacted global hydrological cycles causing prolonged droughts and floods due to changes in the pattern and amount of rainfalls.

In Malaysia, energy is generated from varying resources including conventional sources of coal, oil and natural gas, and also renewable energy such as hydropower plants, solar installations and biomass. From 1990 to 2016, at least 90% of Peninsular Malaysia's electricity was generated from fossil fuel. In 2016, 52% of the energy was generated from coal and 44% was sourced by gas. Malaysia's heavy reliance on fossil fuel will result in having to import fossil fuel at a marginally higher market price due to the decreasing amount of domestic fossil fuel reserves. Therefore, towards ensuring Malaysia's future sustainability, it has become more significant that the country needs to

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[*] *Corresponding author.*
E-mail address: mimisaadon@upm.edu.my (Syamimi Saadon)

overcome its heavy reliance on fossil fuel as the nation's development is threatened by the depletion of domestic fossil fuel [1].

Depletion of fossil fuels such as coal, oil and natural gas, which is the world's primary energy source has increased awareness on developing new techniques that could better utilize existing resources, improving energy efficiency and development of renewable energies [2]. Reducing greenhouse gas emissions due to the usage of fossil fuels is also a major concern in taking steps to reduce carbon footprint and thus contribute to reduce a cause of climate change. Continuous development and utilization of clean and renewable energy such as renewable bioenergy, solar, wind and waves and also continuous energy supply play an important role towards the initiative for sustainable development in order to maintain the supply at affordable price to meet the future energy demand [3, 4].

1.1 Waste Heat Recovery

Heat generated from combustion of fuel or reactions of chemicals are usually released to the surrounding as waste heat. Waste heat losses from an industrial system results from equipment inefficiencies and the equipment and processes' thermodynamic limitations [5]. Waste heat can be rejected by an industrial process at any temperature; where higher the temperature is associated with higher quality of the waste heat and therefore optimizes the waste heat recovery process. Maximum amount of recoverable heat from a process must be achieved in order to achieve maximum efficiency from a system of waste heat recovery [6]. Recovering these waste heats involves transforming the thermal energy into mechanical or electrical energy which can be stored as extra energy source.

The temperature of the waste heat and economics involved plays an important part on the strategy taken to recover these waste heats. These waste heats can be recovered by various types of heat recovery systems such as the Stirling engines, Thermo-Electric (TE), Organic Rankine Cycles (ORC) and Micro Rankine Cycles (MRC). ORC uses hydrocarbon, refrigerant fluids or other particular fluids such as siloxanes which allows for dry expansion and to avoid problems of operation of turbine with a two-phase flow. In order to improve efficiency and heat recovery, ORC is usually modelled and used as recuperated cycles with a regenerator and has been used in wide applications including in jet engine [7]. Unlike the ORC, MRC is commonly not recuperated cycle. Some MRC models use water and incorporate simple volumetric expanders. Flame is used to input heat and produce hot gas stream facing the evaporator component directly. Depending on the design of the system, the evaporation temperature of steam is lower than the temperature of hot source and in a range that varies widely.

Stirling engines are external combustion engine that performs a thermodynamic cycle using working fluid such helium, air or others. The ideal thermal efficiency of the engine reaches the Carnot efficiency, although actual efficiency values obtained are usually lower than 30 % due to the complexity of the engine architecture and the irreversible processes that occurs while the system is in operation. The preliminary concept of the possibility of using Stirling engine as waste heat recovery has also been discovered [8]. Meanwhile TE systems are based on the technology of semiconductor based on the Seebeck effect. Using TE system, heat is converted directly into electric power and does not involve thermodynamic cycle and has no moving parts. TE system can be used to recover heat of low temperature, although it is not considered as a bottoming thermodynamic cycle because of its principle of operation. Therefore, these waste heat recovery systems can be applied to help reduce the dependency on fossil fuels and as an alternative solution to clean energy production.

1.2 Stirling Engine Configuration

Stirling engines were developed based on the Stirling cycle. Robert Stirling invented the Stirling engine in 1816 before the invention of the Diesel, petrol and electric motor in years 1893, 1860 and 1869 accordingly. Further studies on the Stirling engine was done by the N. V. Philips society since 1936. A Stirling engine is a high efficiency engine, with low emission, low vibration and quiet compared to internal combustion engine. It requires less maintenance because it does not produce explosion, does not have valves and escaping gas and does not deteriorate rapidly like the internal combustion engine. Stirling engines can operate using many varieties of heat sources including solar energy, biogas and geothermal [9].

The Stirling engine incorporates working fluid which is contained in a closed space such as helium, hydrogen and air. The working fluid does not go through phase changes compared to the working fluid in a Rankine cycle. Stirling engine is an external combustion engine and is heated and cooled externally at different ends. Heating process of the cycle will cause the pressure of working fluid to increase in the hot space and causing fluid to expand, whereas cooling process will decrease the pressure in the cold space and leads to compression of the working fluid. The movement of working fluid from the hot space to the cold space is repetitive as they expand and compress. This movement is translated into reciprocating movement by using the piston. The rotational motion is then transformed into mechanical work.

The Stirling's ideal thermodynamic cycle is composed of two isochoric and two isothermal process. These four processes transform the working gas contained in the engine as shown in the pressure-volume (P-V) and temperature-entropy (T-s) diagram (Figure 1). In the first stage of the cycle (from point 1 to 2), working gas volume decreases while pressure increases where heat is being transferred to the cold source. During the second stage of the cycle (from point 2 to 3), working gas volume remains constant as it goes through the regenerator while some of its previous heat is regained. In the third stage of the cycle (from point 3 to 4), working gas volume increases while pressure decreases where energy is absorbed from the hot source and the temperature remains constant. During the last stage of the cycle (from point 4 to 1), working gas volume remains constant as it passes through the regenerator and loose its heat [2].

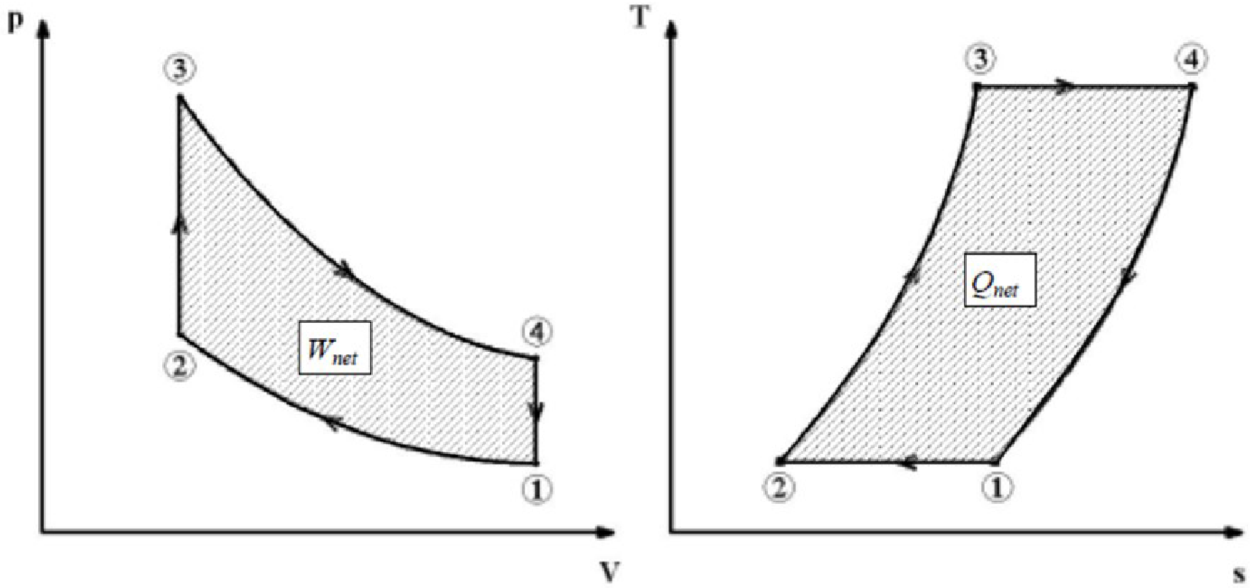


Fig. 1. P-V and T-S diagram for Stirling cycle [10]

Stirling engines can be applied in solar power application, micro-cogeneration (CHP), cryogenic and other applications such as automobile propulsion and space application. Stirling engine are applicable in situations where there is a requirement of multifuel characteristic, availability of very good source for cooling, requirement of silent operation and operations with relatively low speed, constant power output, engine power output changing slowly and warmup time that is longer are permitted [11]. Table 1 shows the relation between technological needs and how Stirling engine characteristics can be applied to fulfill technology requirements.

Table 1
Relation between technological needs and Stirling engine features [12]

Technological needs	Stirling Engine's characteristics
Reduction of conventional fuels usage	Flexibility in fuel sources
Increased in costs of fossil fuels	Low consumption of fuels
Alternative fuels usage	Low levels of vibration and noise
Reduction of gas emissions	Clean combustion
Waste heat recovery	High thermal efficiency

2. Computational Fluid Dynamics (CFD) Modelling

Computational fluid dynamics (CFD) modelling allows for more in-depth investigation into the characteristics of heat transfer in a Stirling engine. CFD simulation in different working spaces of the engine such as the regenerator provides results of velocity, temperature and pressure behaviour of the working fluid. Modelling Stirling engine using CFD can be an advantage as it is capable of resolving effects resulting from geometrical features changes and provides more accurate prediction of the engine performance. Computational fluid dynamics (CFD) approach is one of such numerical models by far that are capable of simulating those complicated processes taking place in Stirling engine and hence returning more accurate prediction on the overall engine performance.

Nevertheless, challenges associated with CFD application on Stirling cycle exist. According to Chen *et al.,* [13], the engine involves moving parts such as displacer and power piston; hence the volume of computational domain is changing with time. From the coding aspect, simulation of reciprocating motions of power piston and displacer requires application of moving mesh techniques that increases the coding difficulty as it introduces complex algorithm. As for the aspect of flow physics, it has incompressible gas flow, involves conjugate heat transfer mechanism and fluid and solid medium. Flows in some cases are turbulent. Therefore, these factors increase the complexity of mass and heat transfer process. In order to resolve these processes, small time-steps and very fine grids needs to be used and coupled governing equations are solved at the same time, which leads to convergence problem and massive CPU hours. These challenges have resulted in application of CFD that is focused on separate components such as the heater or combustion chamber and limited reports on studies of the full cycle of Stirling engine using CFD modelling.

3. Geometric Modelling and Computational Domain

Many experimental works have been done on Stirling engines. However, there is not many experimental data can be found in literature that provides the complete geometry of the prototype and defined the full boundary and operating conditions that is required for the CFD simulation input.

The study by Aksoy and Cinar [14] on the thermodynamic analysis of a beta-type, rhombic-driven mechanism Stirling engine provided sufficient amount of information required for the CFD analysis.

Therefore, the design parameters and data obtained from the study are used for the validation of the CFD modelling [15] and is summarized in Table 2.

Table 2
Dimensions (in mm) of the beta-type Stirling engine used for the simulation

Parameter	Dimensions (mm)
r_1	20
r_2	20.5
G	0.5
$l_1=l_2=l_3=l_4$	18
L_t	158
L	42
L_{pt}	50.93
L_{dt}	163.74
l_d	79.46
R_d	3.5

The model of the beta-type, rhombic-driven mechanism Stirling engine used in [14] is shown in Figure 2.

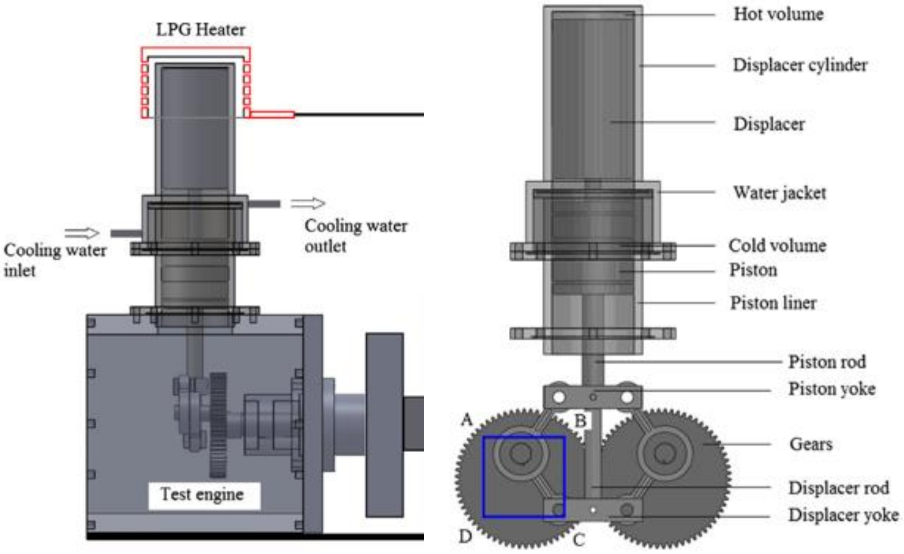
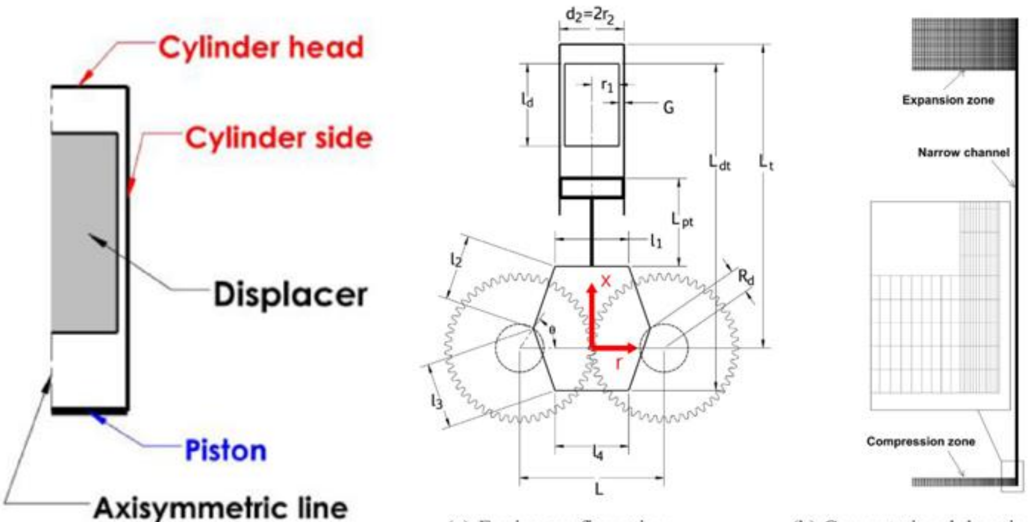


Fig. 2. Model of beta-type, rhombic-driven mechanism Stirling engine [14]

The beta-type Stirling engine is composed of the zones which are the compression zone, narrow zone and expansion zone. The expansion and compression zones are connected by the narrow zone. For the purpose of this study, the narrow zone which is the regenerator is assumed to be empty and without any regenerative material. The domain can adopt an axis-symmetric geometry whereby only half of the geometry is simulated.

The computational domain for this study was modelled based on the study by Ben-Mansour [15] and Abuelyamen [16]. The computational domain for a beta-type SE is as shown in Figure 3.



(a) Engine configuration (b) Computational domain

Fig. 3. Computational domain of beta-type Stirling engine [15, 16]

The governing equations are the conservation of mass, conservation of momentum, conservation of energy and ideal gas equation. These equations are used in the cylindrical coordinates.

4. Validation

Validation is done based on the CFD simulation done [15] for radiation impact analysis on beta-type Stirling engine performance driven by rhombic mechanism.

The working fluid used for the simulation is air and assumed as an ideal gas. The thermal boundary conditions for the cylinder walls are set between hot temperature (T_H) of 800 K (at cylinder top) and cold temperature (T_C) of 300 K (at cylinder bottom). The external cylinder wall's temperature is distributed assumed as the function below

$$T(x) = \begin{cases} T_C(K), if x \leq 8mm \\ T_C + \frac{x-8}{15.8-8}(T_H - T_C)(K), if x > 8mm \end{cases} \quad (1)$$

The cylinder wall material is steel with a thickness of 1 mm. The material's density is 7840 kg/m^3, specific heat is 450 J·kg^{-1}·K^{-1} and thermal conductivity is 43 W·m^{-1}·K^{-1}. The displacer is assumed to be insulated. Therefore, heat will not be transferred through it.

ANSYS Fluent 18.2 software is used for the purpose of this simulation. Finite volume method is used by the program to discretize the conservation of mass, momentum and energy equation based on the. For the solution method, pressure-based solver was adopted with pressure-velocity coupled scheme used. The second order upwind discretization scheme is adopted for continuity, momentum and energy equations. Laminar flow is assumed [15, 17]. The external cylinder wall temperature profile (Eq. (1)) was adopted in the program by using a user defined function (UDF).

5. Results

Figure 4 and 5 below show the results

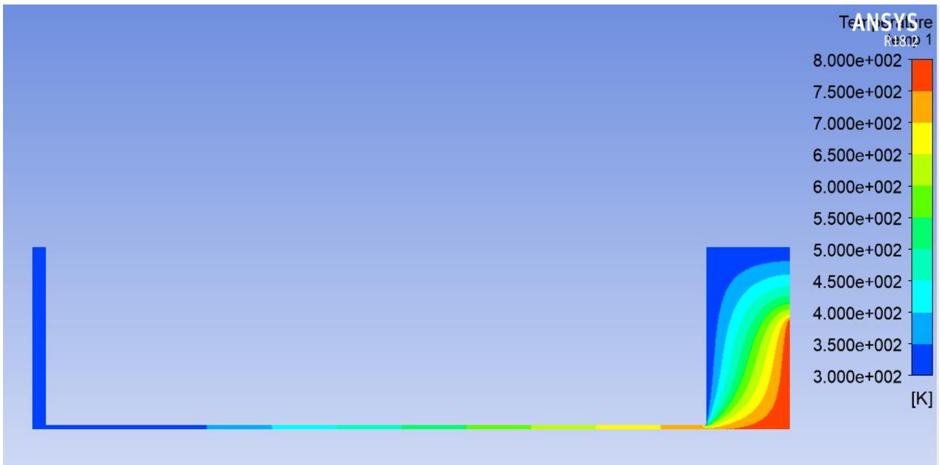


Fig. 4. Temperature contours using air as working fluid

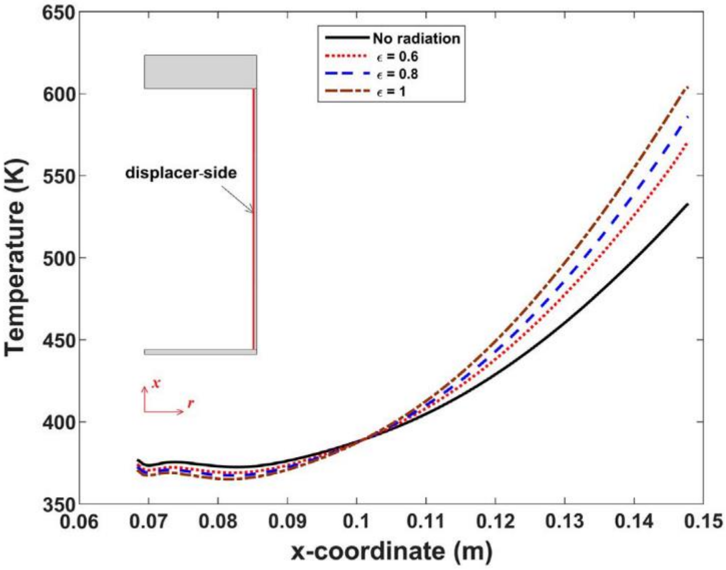


Fig. 5. Temperature profile at the displacer side using air as working fluid by Ben-Mansour [15]

4. Conclusions

Starting from a comprehensive review of Stirling engine and CFD modelling done to understand the behaviour of the fluid flowing in this type of engine, a beta-type Stirling engine has been modelled and validated in this paper. Such result will be very instrumental in the preliminary design of a Stirling engine and can be used in estimation of heat transfer performance of the overall engine.

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References

[1] Suruhanjaya Tenaga. *Malaysia Energy Statistics Handbook 2017*. Malaysia, 2017.

[2] Hachem, Houda, Ramla Gheith, Fethi Aloui, and Sassi Ben Nasrallah. "Technological challenges and optimization efforts of the Stirling machine: A review." *Energy conversion and management* 171 (2018): 1365-1387.

[3] AlQattan, Nael, Michael Acheampong, Foday M. Jaward, Funda Cansu Ertem, Nisha Vijayakumar, and Tolulope Bello. "Reviewing the potential of Waste-to-Energy (WTE) technologies for Sustainable Development Goal (SDG) numbers seven and eleven." *Renewable Energy Focus* 27 (2018): 97-110.

[4] Khattak, Muhammad Adil, T. M. H. T. Yahya, Muhammad Wazif Mohd Sallehhudin, Muhammad Izzuan Mohd Ghazali, Nur Awal Abdullah, Nur Athirah Nordin, Nur Ainida Mohd Mohsein Dzakurnain, and Suhail Kazi. "Global Energy Security and Eastern Europe: A Review." *Journal of Advanced Research Design* 45, no. 1 (2018): 19-42.

[5] Johnson, Ilona, William T. Choate, and Amber Davidson. *Waste heat recovery. Technology and opportunities in US industry*. BCS, Inc., Laurel, MD (United States), 2008.

[6] Jouhara, Hussam, Navid Khordehgah, Sulaiman Almahmoud, Bertrand Delpech, Amisha Chauhan, and Savvas A. Tassou. "Waste heat recovery technologies and applications." *Thermal Science and Engineering Progress* 6 (2018): 268-289.

[7] Saadon, S. "Computational modelling of an Organic Rankine Cycle (ORC) waste heat recovery system for an aircraft engine." In *MATEC Web of Conferences*, vol. 151, p. 02001. EDP Sciences, 2018.

[8] Saadon, S. "Possibility of Using Stirling Engine as Waste Heat Recovery–Preliminary Concept." In *IOP Conference Series: Earth and Environmental Science*, vol. 268, no. 1, p. 012095. IOP Publishing, 2019.

[9] Xiao, Gang, Umair Sultan, Mingjiang Ni, Hao Peng, Xin Zhou, Shulin Wang, and Zhongyang Luo. "Design optimization with computational fluid dynamic analysis of β-type Stirling engine." *Applied Thermal Engineering* 113 (2017): 87-102.

[10] Sedlák, Josef, Adam Glváč, and Andrej Czán. "Design of stirling engine operating at low temperature difference." In *MATEC Web of Conferences*, vol. 157, p. 04003. EDP Sciences, 2018.

[11] Asnaghi, A., S. M. Ladjevardi, P. Saleh Izadkhast, and A. H. Kashani. "Thermodynamics performance analysis of solar stirling engines." *ISRN Renewable Energy* 2012 (2012).

[12] Ferreira, Ana C., Ricardo F. Oliveira, Manuel L. Nunes, Luís B. Martins, and Senhorinha F. Teixeira. "Modelling and cost estimation of stirling engine for CHP applications." In *Proceedings of the 2014 International Conference on Power Systems, Energy, Environment*, pp. 21-29. 2014.

[13] Chen, Wen-Lih, King-Leung Wong, and Yu-Feng Chang. "A computational fluid dynamics study on the heat transfer characteristics of the working cycle of a low-temperature-differential γ-type Stirling engine." *International Journal of Heat and Mass Transfer* 75 (2014): 145-155.

[14] Aksoy, Fatih, and Can Cinar. "Thermodynamic analysis of a beta-type Stirling engine with rhombic drive mechanism." *Energy conversion and management* 75 (2013): 319-324.

[15] Ben-Mansour, R., A. Abuelyamen, and Esmail MA Mokheimer. "CFD analysis of radiation impact on Stirling engine performance." *Energy conversion and management* 152 (2017): 354-365.

[16] Abuelyamen, Ahmed, and Rached Ben-Mansour. "Energy efficiency comparison of Stirling engine types (α, β, and γ) using detailed CFD modeling." *International Journal of Thermal Sciences* 132 (2018): 411-423.

[17] Salazar, Jose Leon, and Wen-Lih Chen. "A computational fluid dynamics study on the heat transfer characteristics of the working cycle of a β-type Stirling engine." *Energy conversion and management* 88 (2014): 177-188.