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Parametric study on beta-type Stirling engine

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ABSTRACT

In this work, a parametric study on a β-type Stirling engine with no regenerator was conducted numerically using ANSYS fluent 14.5 software. The three parameters that were studied are; initial charge pressure, thermal boundary condition; and three different types of working fluids (Air, He and H_2). Variable thermal properties of these gases were adopted to get more realistic results. The results include a comparison of the amount of heat transfer, power output, and thermal efficiency. It was found that the best engine performance is achieved when H_2 gas is used as working fluid. Moreover, results revealed that each of the power output and the efficiency has different optimum charge pressure. Additionally, it was found that there is a small variation in the pressure across the engine chambers, which results in miss matching between the net heat transfer rates and power output calculated from PV-diagram. This error is higher when the air is used as working fluid, especially at high charge pressure.

1. Introduction

Stirling engine is one of the most promising innovations that is expected to help in solving energy conversion problems. It attracts researchers in industry and academic fields due to its interesting characteristics. It is classified as an external combustion engine. It can utilize various types of heat resources. For instance geothermal heat, industrial waste heat and even heat from fossil fuel combustion. However, when solar energy is utilized, the system will be environmentally friendly with no more carbon dioxide produced. In addition, it has a quiet operation with a low level of noise. The most important feature of the Stirling engine is its ability to operate in the absence of oxygen. That makes it an area of research for outer space applications. Another main application of Stirling engine is by using solar parabolic mirrors focused on the hot chamber of Stirling engine to generate electricity. So it is useful for countries with abundant solar energy.

There are five methods used to design and predict the performance of Stirling engine; zero-order analysis, first-order analysis, second-order analysis, third-order analysis (or nodal design method) and fourth order analysis (or CFD simulation) [1,2]. The term "order" used here is a kind of classification according to the complexity of the model that increases as the order increases.

Mahkamov [3] is one of the leaders in numerical modeling of Stirling engine. He simulated a prior manufacturing prototype of gamma-type Stirling engine. The engine was already designed using first-order model and the power expected was far less than the actually obtained power. His investigation showed that there are two major factors limiting the power output; firstly, the hydraulic losses in the regenerator and, secondly, the large dead volume. Consequently, he modified the prototype by eliminating some of the dead volumes through converting Stirling engine configuration from γ-type to α-type. Ibrahim [4] developed a 2-D-axisymmertic CFD model to simulate the experimental test rig developed by Jiang and Simon [5]. The original experimental (3-D) geometry had radially oriented slots in the heater. So it could not be simulated as 2-D-axisymmetric. However, using same hydraulic diameter, Ibrahim [4] found a good agreement between experimental and CFD results in the region far away from the heater. He showed that most of the pressure drop occurs in the regenerator at 90° and 270° crank angles where the piston and flow had the highest velocity. His results showed an error in the heat transfer coefficient fluctuating between 23% and 75%. Costa et al. [6] studied numerically the pressure drop in a 3-D wound woven wire matrix for Stirling engine. They studied two various regenerators; stacked wire and wound woven wire matrix. Their study focused on the effect of porosity. They derived a correlation to estimate the pressure drop friction factor for stacked woven wire. They included the wire mesh diameter in the correlation as well as *Re* number because it showed an effect on the friction factor. Another investigation of a compact porous-sheets heat exchanger was conducted by Li et al. [7]. They run a 3-D simulation for α-type Stirling

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Nomenclature

a, b, c, d	constants
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
g	gravitational acceleration (m s^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
l_1, l_2, l_3, l_4	lengths of the linkages of the rhombic drive mechanism (m)
l_d	height of displacer (m)
n	normal direction to a plane
p	pressure (Pa or bar)
q	heat flux (W m^{-2})
r_1, r_2	radius of displacer and cylinder (m)
t	time (s)
u, v	velocity components in x- and r-direction (m s^{-1})
$\tilde{u}, \tilde{v}$	relative velocity in x- and r-direction (m s^{-1})
u_c, v_c	moving frame velocity components in x- and r-direction (m s^{-1})
u_p, u_d	piston and displacer velocities (m s^{-1})
x, r	cylindrical coordinates in x- and r-direction
G	regenerative channel gap (m)
L	distance between two gears (m)
L_{dt}	length from the linkage $l_4$to top surface of the displacer (m)
L_{pt}	height from the linkage $l_1$to top surface of the piston (m)
L_t	height of the engine (m)
Q_{in}, Q_{out}	heat absorb and rejected from the Stirling engine (W)
Q_i	total heat transfer during step i (W)
R	gas constant (J kg^{-1} K^{-1})
R_d	offset distance from the crank to the center of gear (m)
T, T_C, T_H	temperature, cold-end temperature, and hot-end temperature (K)
V	volume (m^3)
W_{out}	power output (W)

Greek symbols

δ	solid wall thickness (cylinder wall) (m)
η	thermal efficiency (%)
μ	viscosity (kg m^{-1} s^{-1})
θ	crank angle (degree or radian)
ρ	density (kg m^{-3})
ω	rotational speed (rad s^{-1})

Subscript

f	fluid

engine in which the piston motion is controlled by Ross mechanism. The engine was charged with Helium at atmospheric pressure. They concluded that in a comparison between the conventional wire mesh regenerator and the porous sheet regenerator, the later has the lowest entropy generation rate. Thus, the use of the porous sheet regenerator results in high thermal efficiency and high power output. Chen et al. [8] developed a CFD code to study the characteristics of heat transfer for 3-D γ-type Stirling engine driven with crankshaft mechanism. Their studies were conducted for very simple geometry without a regenerator for the sake of simplifications. They found differences between their results and those obtained by the second order method especially in the heat transfer rates. Moreover, they discovered a highly non-uniform temperature distribution within the engine during the cycle which reflects an inaccuracy of some of the one-dimensional models. Alfarawi et al. [9] adopted an ideal adiabatic model in order to estimate the performance of a β-type Stirling engine. Besides, they carried out a CFD investigation to optimize the geometry of the heater and the cooler. The ideal thermal efficiency was found to be 40% with a power output of 1.5–2 kWe. Another numerical and experimental study of Stirling engine regenerator was conducted by Tutar et al. [10]. They studied the pressure drop losses in wound woven wire matrix regenerator. They tested a porosity range between 52% and 72% and Reynolds number (*Re*) ranging from 5 to 50 in the laminar flow regime. Then they came up with a correlation related the friction coefficient factor with *Re*.

Furthermore, Costa et al. [11] developed a thermal non-equilibrium porous media model for Stirling engine. They found that the stacked configuration has better overall performance compared with the wound woven wire matrices. Chen et al. [12] investigated the impacts of moving regenerator on the performance of β-type Stirling engine driven by rhombic mechanism. They studied the effect of different values of porosity and discovered that despite the fact that the pressure loss is proportional with the porosity, the increase of porosity improves the overall engine performance in terms of net power output and thermal efficiency. Mahkamov and Ingham [13,14] investigated the performance of complex geometry of an alpha-type Stirling engine. Their results showed that a second-order analysis produces almost double the value of CFD analysis in terms of power. NASA also paid attention to developing and improving Stirling engine. One of the fastest simulations of the whole Stirling engine was performed by Dyson et al. [15]. They simulated a free-piston configuration of Stirling engine using axisymmetric. A comparison of their results with an actual performance data showed that the axisymmetric simulation is more accurate than Sage code results. Sage code is one-dimensional analysis tool supports simulation and optimization of spring-mass-damper resonant system and Stirling engine cycle [16]. It is worth mentioning here that they set the boundary condition for the cold-end temperature in their simulation lower than temperature value in actual data by about 14 °C. Because there might be some losses in the experiment, it needs to be overcome by increasing the source temperature a little bit. The outcomes of heat supply, heat rejected and generated power of the simulation have good agreement with the experimental data. Lin et al. [17] conducted a simulation analysis of 3-D free-piston Stirling engine, which used a helium as the working fluid. Unfortunately, their results in terms of heat added to the cycle did not match the experimental data. The CFD model reflected a high amount of heat input compared to the experimental data. Costa et al. [18] studied heat transfer in a 3-D wound woven wire matrix of a Stirling engine regenerator. Firstly, they developed a 3-D model for stack woven and validated the obtained correlation of heat transfer coefficient against empirical relationship of Tanaka et al. [19] and Gedeon and Wood's work [20]. After that, they extended the model for wound woven wire matrices. They considered the flow to be laminar in the low *Re* number range and turbulent at higher *Re* number range. Their results reflected a value of *Nu* number lower by 20% for wound woven matrices compared with that of stack woven matrices for $20 < Re < 400$. Moreover, they did not notice a significant impact of volumetric porosity on *Nu* due to the small range of volumetric porosity (0.6–0.68). Therefore, they suggested studying it in further investigation. Salazar and Chen [21] investigated the characteristics of rhombic-drive beta-configuration Stirling engine working with air as the working fluid. The problem was treated as axisymmetric laminar and thermal properties along with the viscosity were assumed to be constant. In addition, it was proposed