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Energy and exergy analyses of beta-type Stirling engine at different working conditions

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ABSTRACT

In the current study, a comprehensive thermodynamic analysis (energy and exergy analyses) of a beta-type Stirling engine has been performed at different working conditions. First, a non-ideal adiabatic model has been proposed for performance analysis of the Stirling engine and in order to increasing its accuracy, the frictional and thermal losses of Stirling engine have been considered. Also, for model validation, the operational and geometrical specifications of a beta-type Stirling engine which made in General Motors Corporation called GPU-3 have been used. The results of the present model have been compared with the experimental data of NASA Lewis Research Center and the results of other previous adiabatic models. Then, the effects of engine rotational speed, mean engine operating pressure, and regenerator length on exergy efficiencies and exergy destruction have been investigated for two working gases of helium and hydrogen. The results show that with increasing the engine rotational speed, the frictional and thermal losses increase, and the exergy efficiency reaches to its maximum value at shorter lengths of regenerator. Also, with increase of the mean engine pressure, due to reduction of the effects of frictional and thermal losses, a larger regenerator can be used. Furthermore, the results show that hydrogen has higher exergy efficiency at longer regenerator length due to its low viscosity and high specific heat.

1. Introduction

Stirling engine is an external combustion engine. It operates based on the compression and expansion of a working gas at different temperatures for means of power production. Stirling engines unlike internal combustion engines, have low noise and can use various heat sources such as fossil fuels, solar energy, biomass (such as wood chips), and nuclear energy [1]. Theoretically, Stirling engine thermal efficiency is close to the Carnot cycle, and so it has a higher thermal efficiency compared to other engines [2]. In this engine, in the power production process, a significant amount of heat is dissipated to the environment which can be recovered. Therefore, due to this heat potential, it can be used as prime mover for cogeneration and trigeneration systems. In addition, Stirling engine has been become an interesting research topic, and the plan has recently been commercialized by manufacturing companies, and so is suggested for building applications [3,4]. The main components of the Stirling engine are the expansion space, compression space, regenerator, heater and cooler. Also, the thermodynamic cycle of this engine consists of two isothermal processes (isothermal expansion and compression) and two constant volume processes (heat recovery in regenerator) in ideal state [5]. Different types of the Stirling engines are identified by the names of alpha, beta, and gamma. All of them are similar in terms of thermodynamic cycle, however, there are fundamental differences in their mechanical mechanisms. The alpha-type Stirling engine has two pistons in two separate cylinders. A heater is in one cylinder and a cooler is in another. In the beta-type Stirling engine, there are two pistons inside one cylinder, which are called displacer piston and power piston. The displacer piston moves the working fluid between the cold space and hot space through the heater, cooler, and regenerator and leads to the movement of the power piston. The gamma-type Stirling engine is a combination of alpha and beta types (Fig. 1) [6,7].

In the case of performance analysis of the Stirling engines, addition to design and constructing, many experimental and numerical studies have been presented about different types of Stirling engines:

Cheng and Chen [8] performed experimental and numerical analyses (CFD analysis) on a 1 kW beta-type Stirling engine. In their study, only the pressure drop of gas flow was considered in the numerical model. Jahani et al. [9] designed an alpha type Stirling engine for using in combined cooling heating and power systems. The alpha type Stirling engine was simulated by GT-Suite software. In this software, the pressure drop in the cylinder is presented based on the experimental friction

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Nomenclature

General

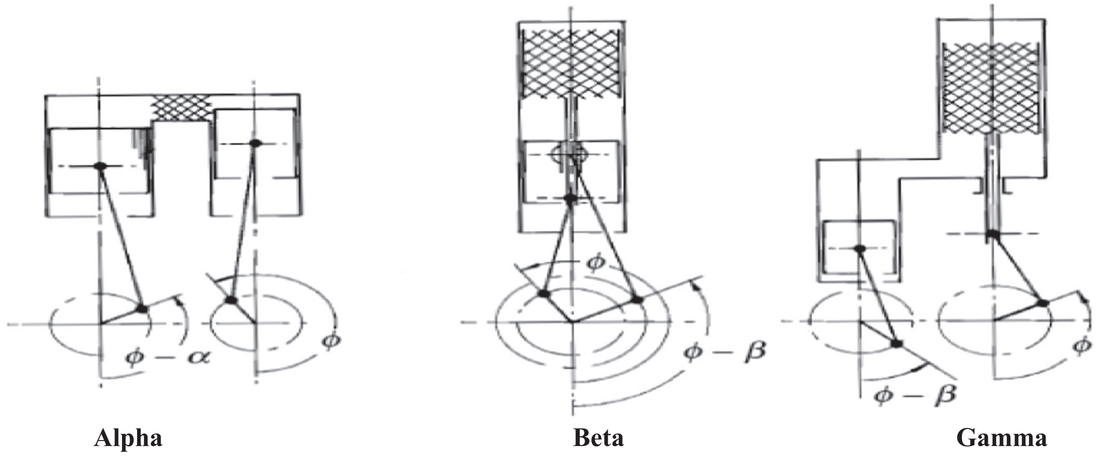
A	cross-section area (m^2)
A_{cond}	conductive area (m^2)
a	coefficient for finite speed thermodynamics
c	average speed of molecules ($m\ s^{-1}$)
c_p	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
c_v	specific heat at constant volume ($J\ kg^{-1}\ K^{-1}$)
D_d	diameter of displacer (m)
d	hydraulic diameter (m)
f	friction factor
fr	frequency of engine (HZ)
G	working gas mass flow ($kg\ m^{-2}\ s^{-1}$)
h	convective heat transfer coefficient of gas ($W\ m^{-2}\ K^{-1}$)
J	gap between displacer and cylinder (m)
k_g	thermal conductivity of working gas ($W\ m^{-1}\ K^{-1}$)
k_r	thermal conductivity of regenerator wall ($W\ m^{-1}\ K^{-1}$)
L_d	displacer length (m)
L_r	regenerator length (m)
M	mass of the working fluid (kg)
NTU	number of the transfer units
n_r	engine rotational speed (rpm)
P	power output (W)
Pr	Prandtl number
p	pressure (Pa)
Q	heat transfer (W)
R	gas constant ($Jkg^{-1}\ K^{-1}$)
Re	Reynolds number
S	displacer stroke (m)
St	Staunton number
T	temperature (K)
V	volume (m^3)
W	work output (J)
w	piston velocity ($m\ s^{-1}$)
X_{dest}	exergy destruction (W)

Greek

θ	crank angle (deg)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ε	effectiveness
η	efficiency
γ	specific heat ratio ($c_p \cdot c_v^{-1}$)

Subscript

ac	actual
adi	adiabatic
c	compression space
ck	cooler-compression space interface
e	expansion space
gh	inside of heater
gk	inside of cooler
h	heater
he	heater-expansion space interface
k	cooler
kr	cooler- regenerator interface
r	regenerator
rh	regenerator-heater interface
sh	shuttle effect
wh	heater wall
wk	cooler wall



Alpha **Beta** **Gamma**

Fig. 1. Different types of Stirling engines [6,7].

results of two-stroke combustion engine, and the geometry of heater and cooler are assumed to be the same. The results of their numerical model were validated with the alpha type Solo V161 Stirling engine experimental data [10]. Damirchi et al. [11] designed and manufactured a gamma-type Stirling engine for micro combined heat and power systems. They performed combustion tests with using the biomass and agricultural wastes.

West [12] presented a new dimensionless parameter called Beal number to predict the power output of the Stirling engine. The Beal number is defined by the power output, mean pressure, swept volume and rotational speed of Stirling engine. Kongtragool and Wongwises [13] performed an experimental analysis for the thermal efficiency of Stirling engines. They found that for predicting the power output of Stirling engine with high temperature ratios, the Beal number could not be used. Therefore, Kongtragool and Wongwises [13] modified the Beal number relation using an appropriate correction factor. In another evaluation, they presented Malmo relation for the calculation of the power output of Stirling engine [13]. The Malmo relation requires only values of the heat input from the heat source and the empirical factors. These empirical factors were the heat source efficiency, and thermodynamic and mechanical efficiency of the Stirling engine [13].

One of the first thermodynamic models for Stirling engines was performed by Schmidt [14]. In this analysis, it was assumed that the temperature of the compression space was constant and equal with the

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