Energy Conversion and Management 124 (2016) 130–140

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Influence of phase angle and dead volume on gamma-type Stirling engine power using CFD simulation

S. Alfarawi [*], R. AL-Dadah, S. Mahmoud

Department of Mechanical Engineering, University of Birmingham, Edgbaston, B15 2TT, UK

ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form 4 July 2016
Accepted 5 July 2016
Available online 12 July 2016

Keywords:
CFD
Phase angle
Stirling engine
Dead volume

ABSTRACT

This work presents the development and validation of computational fluid dynamics (CFD) model of 500 W gamma-type Stirling engine prototype to highlight the effects posed by phase angle and dead volume variations on engine performance. The model is based on a realistic Local Thermal Non-Equilibrium (LTNE) approach for porous domains in the engine (cooler and regenerator). The simulation results showed an acceptable degree of accuracy of 9% and 5%, respectively when comparing with experimental results in predicting the indicated and cooling powers at different heating temperatures. It is found that the maximum indicated power is achieved at a phase angle of 105° rather than at the common phase angle of 90°. The dead volume (connecting pipe) is observed to pose negative effects on engine indicated power and therefore, an optimum value of pipe diameter exists.

1. Introduction

Alternative sources of energy are being sought to preserve fossil fuels as well as to reduce the greenhouse effects. In this regard, renewable energy resources (such as biomass, solar, geothermal and wind energy) are deemed to be the promising solution in as much as they are clean, efficient, and sustainable [1]. The Stirling engine is an externally heated engine. It is thermally regenerative, simple in construction, virtually quiet, safe in operation, and intrinsically flexible to adopt any heat source such as solar, biomass, geothermal energy or even an industrial waste [2]. Ideally, Stirling engines work on a highly efficient thermodynamic cycle. The gas inside the engine undergoes four processes; two isothermal heat-exchange processes (expansion and compression) and two isochoric heat-exchange processes (heating and cooling). However, the real cycle is considerably penalized due to the irreversibility and non-ideality of transport mechanisms occurring inside the different components of the engine. The regenerator is a key component of the engine; it is an internal heat exchanger that acts as a thermal sponge that absorbs and releases heat during the cycle, thus, enhancing engine power and efficiency. The heat being absorbed and restored to the gas in the regenerator during one cycle is typically four times the heat that passes through the heater during one cycle [3]. Without a regenerator, such an engine requires a heater with five times the amount of heat needed to generate the same power it did with a regenerator. The conventional regenerator types adopted in Stirling engines are wire mesh or random fibre. Some advantageous features exist in these types such as; high convective heat transfer between the solid and the gas due to the extended surface area of wires and this is similar to a cross flow over repeated cylinder-shaped wires and low axial conduction in flow direction. However, the disadvantage of this type of regenerator is the high flow friction resulting from flow separation, eddies associated with stagnation areas that can degrade the engine performance. The regenerator has to have several features for better performance that might be contradicting and this requires a great effort for designers and developers to find the optimum configuration based on; minimum pressure drop, maximum convective heat transfer and minimum axial conduction in flow direction [4]. There have been numerous numerical models in open literature to analyse and optimize Stirling engines. In their hierarchal order, they are classified as zeroth-, first-, second-, third- and forth-order models. The first four models are ascending in their complexity and accuracy. However, the effects caused by the geometrical variation can't be taken into account by these models. A detailed overview of these models can be found in [5]. The adoption of fourth-order analysis or namely computational fluid dynamics (CFD) analysis can return accurate results. However, this approach is quite challenging and computationally expensive to model the engine as a whole. In terms of full engine CFD modelling, the thermal equilibrium used in porous media models for modelling the regenerator is believed to be a poor assumption in oscillating flow environment since several degrees

---

[*] Corresponding author.
E-mail address: ssa178@bham.ac.uk (S. Alfarawi).

http://dx.doi.org/10.1016/j.enconman.2016.07.016
0196-8904/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

2D	two dimensional
a_{fs}	solid surface area per unit volume, 1/m
CFD	computational fluid dynamics
C_p	gas heat capacity, J/kg·K
C_{ps}	solid heat capacity, J/kg·K
d_w	mesh wire diameter, μm
d_h	hydraulic diameter, m
f	friction factor
K	permeability, m^2
k	gas thermal conductivity, W/m·K
k_s	solid thermal conductivity, W/m·K
$\overline{\overline{k}}_e$	equivalent thermal conductivity, W/m·K
Nu	Nusselt number
p	instantaneous gas pressure, Pa
P_e	Peclet number
R	gas constant, J/kg·K
r	Crank radius, mm
Re	Reynolds number
T	gas phase temperature, °C
T_s	solid phase temperature, °C
$\boldsymbol{u}$	velocity vector, m/s
X_c	power piston displacement, m
X_e	displacer piston displacement, m

Greek letters

β_F	Forchheimer drag coefficient, kg/m^4
λ_c	Crank radius to compression connecting rod ratio
λ_e	Crank radius to expansion connecting rod ratio
θ	Crank angle, rad
ρ	gas density, kg/m^3
ρ_s	solid density, kg/m^3
μ	gas dynamic viscosity, Pa·s
ε	porosity

of temperature difference between gas and solid matrix are reported [6]. The Navier-Stokes equations are either for laminar or turbulent regimes contrasting with the actual flow situation in Stirling environment and hence transition from laminar to turbulent can occur from one spatial location to another over the cycle based on the published results of oscillating flow rig testing. Therefore, more understanding of flow physics is still required [7]. The deformation of engine domains due to pistons movement as a result of gas compression and expansion needs to be handled through a complex algorithm to support moving (dynamic) meshes during the simulation. The time stepping in transient analysis plays a crucial role on convergence and accuracy of the simulation. Movements of the pistons until reaching the dead points, where the mesh is densely compressed, may require smaller time steps for better convergence and hence adaptive time stepping can be a good strategy to return results more accurately. Therefore, using this approach needs more sophisticated codes, and sometime manual tuning is required, in order to return more reasonable and accurate results. There have been fewer studies on using CFD approach than other analysis methods for modelling Stirling engine in general and for modelling gamma-type in particular.

Bert et al. [8] proposed a three-zone finite-time thermodynamic model to simulate and optimize gamma-type Stirling engine with a nominal power of 1 kWe. Effects of speed, gas type, hot end temperature and filling pressure on engine performance were investigated. The pistons kinematics were optimized using particle swarm optimization (PSO) for maximum power. Their results showed that in the optimized crank-connecting rod system, the phase angle varies from 90° at the beginning of the cycle and 100° at the maximum position of each piston.

Chen et al. [9] constructed and tested a twin power piston gamma-type Stirling engine. The engine was incorporated with a moving regenerator housed inside its displacer and filled with a woven-screen material. The effects of different regenerator parameters on engine performance, including regenerator material, wire diameter, filling factor and stacking arrangements, were investigated. According to their results, copper material was found superior to stainless steel on engine performance at the tested conditions and optimum filling factor was proposed.

Hooshang et al. [10] proposed a model for gamma-type Stirling engine optimization based on neural network concepts. The thermodynamic code based on third-order analysis was used to produce a dataset to recognise the relationship between inputs and outputs using the neural network and to search for optimum design parameters. The results showed that engine power and efficiency can be optimized to 878 W and 13.21% compared to the base case of 500 W and 8.5%.

Hachem et al. [11] developed a numerical model, based on classical quasi-steady approach, to optimize gamma-type Stirling engine. Their results showed that the maximum losses were recorded in the regenerator including viscous, conduction and imperfection losses. The effect of key operational parameters, such as engine speed, hot end temperature and charge pressure on engine performance was investigated and they found that the engine speed can cause a conflict of thermal losses mechanisms. Increasing initial filling pressure and hot end temperature were the two influential parameters on the increase of engine brake power.

Araoz et al. [12] developed a thermodynamic model based on second-order analysis to simulate gamma-type Stirling engine. The forced work and mechanical efficiency, based on Senft theory, were considered to predict engine shaft power. According to their results, they found that the engine low power output was attributed to the reduced mechanical efficiency of the system. The dynamics of volume variation and drive mechanism were suggested for further improvements to increase the engine shaft power.

Gheith et al. [13] conducted an experimental investigation on the optimum regenerator matrix material and porosity for gamma-type Stirling engine. Different materials were tested including stainless steel, copper, aluminium and Monel 400. The results showed that stainless steel matrix with 85% porosity is the best configuration to maximize engine performance.

Li et al. [14] proposed a coupled finite speed and isothermal models to analyse a solar-powered gamma-type Stirling engine. A filling material in regenerator gap was not considered in this LTD Stirling engine. Different loss mechanisms affecting the engine performance were considered. They found that the key loss mechanisms are the regenerator gap heat loss and the work loss due to gas leakage through piston/cylinder walls. Some engine improvements; using isolating material for displacer and cylinder walls and reducing the clearance leakage, were proposed.

Mahkamov [15], performed a second-order and 3D CFD analysis on a gamma-type Stirling engine prototype to enhance its power. The CFD results revealed that power reduction was attributed to the high level of hydraulic losses in the regenerator, and the entrapment of the gas in the pipe connecting the two parts of the compression space and to its large dead volume. A further