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Overall performance of the duplex Stirling refrigerator

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ABSTRACT

The duplex Stirling refrigerator is an integrated refrigerator consists of Stirling cycle engine and Stirling cycle refrigerator used for cooling. The equality of the work generation of the heat engine to the work consumption of the refrigerator is the primary constraint of the duplex Stirling. The duplex Stirling refrigerator is investigated thermodynamically by considering the effects of constructional and operational parameters which are namely the temperature ratios for heat engine and refrigerator, and the compression ratios for both sides. The primary concern is given to the parametric effects on the overall coefficient of performance of the duplex Stirling refrigerator. The given diagrams provide a design bounds and benchmark results that allows seeing the big picture about the cooling load and heat input relation. Moreover they ease to determine the corresponding work rate to the target cooling load. As regard to the obtained results, a definite region for coefficient of performance of the refrigerator and a definite region for the thermal efficiency of the heat engine of the duplex Stirling are identified.

1. Introduction

Governments are investing huge amount of money in projects to efficient use of energy to improve the performance of renewable energy systems and air conditioning systems. Green and clean energy solutions include the development studies of Stirling cycle engines, Stirling cycle refrigerators and heaters. Well known advantages of Stirling cycle systems are more attractive than traditional systems. The improvement of the Stirling cycle systems is necessarily considered as a part of not-in-kind technologies for residential and commercial buildings.

Stirling engines always catches the attention as a rising alternative due to its superior features that let to run the system by diverse heat sources and working fluids even under tough working conditions. Unlike the limited allowance of the conventional systems for the varying working conditions, the Stirling engines emerge with the flexibility on these by the closed cycle used in the system. Since it is invented in 1816, even though several types of Stirling engines has been developed and reported in last decades, duplex Stirling engine is the best match as the alternate solution which involves both power generation and refrigeration.

In duplex Stirling concept [1], a Stirling engine drives a Stirling cycle heat pump. Two free-piston Stirling cycle machines are involved in the duplex Stirling in a back-to-back configuration. The freely moving double-acting piston and displacers at an appropriate phase angle provide this. There are no major mechanical links guiding the piston or displacers which are controlled by springs (gas or mechanical) and gas forces. The heat engine part using a fuel like natural gas and helium as working fluid produces power to operate the refrigerator part. It have been shown by researchers [2] that the Duplex Stirling arrangement have high efficiency, high reliability, low noise with long life and low emission and low operating cost in comparison with vapor compression units at similar capacities. In the past decades the researches are concentrated on the commercial use of Stirling engine and in the meantime, many problems from thermodynamics and mechanical aspects have been met and solved. Various companies and researchers [3] worked on Stirling engines and developing the engine according to the requirements and constraints. As a result of these investigations the design of the engine has reached a level which allows the design for wide loading capacity and performance range.

The analyses of the Stirling engine cycle are performed by two simple methods; namely the isothermal analysis of G. Schmidt [4] and slightly more realistic model provided by Finkelstein [4]. In the Finkelstein's model the isothermal expansion and compression of the working fluid in the Stirling cycle are replaced by the assumption of adiabatic processes. The literature is replete with empirical investigations than theoretical investigations about Stirling engine. Various researchers investigated Stirling engine for

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Nomenclature

C	specific heat, J/kg K
COP	coefficient of performance
k	ratio of the specific heats
m	mass, kg
n	polytropic exponent
Q^*	heat transfer, J
Q	dimensionless heat transfer
R	gas constant, kJ/kg K
r	compression ratio, V_{max}/V_{min}
T	temperature, K
W^*	work, J
W	dimensionless work
V	volume, m^3

Greek letters

η	thermal efficiency of the heat engine
τ	temperature ratio

Subscripts

C	compression
H	heat engine side
$overall$	duplex Stirling engine
R	refrigerator side
th	thermal
v	constant volume

different applications [5,6] such as natural gas liquefiers, free piston Stirling cooling unit (mini-coolers), and duplex Stirling cryocoolers. In these communications, the comments and outcomes pertain to different cooling loads and ambient temperatures are reported [2,7,8].

Furthermore, a solar-driven Stirling heat engine system composed of a Stirling heat engine, a solar collector, and a heat sink is studied by Liao and Lin [9] based on the irreversible thermodynamics and Lagrange multiplier method, numerically. The efforts on the Stirling engines' irreversibility analysis continued by Chen [10] for predicting the performance of a Stirling refrigerator using an ideal or Van der Waals gas as the working substance at an irreversible cycle model, in addition Ahmadi et al. [11] studied an irreversible Stirling heat pump cycles that includes both internal and external irreversibility's together with regard to finite heat capacities of external. Besides, Ahmadi et al. [12] investigated external and internal irreversibility's in a parametric demonstration of irreversible Stirling cryogenic refrigerator cycles as well.

In another study Tyagi et al. [13] presented a parametric study of irreversible Stirling and Ericsson cryogenic refrigerator cycles including external and internal irreversibility's along with finite heat capacities of external reservoirs. In some other studies finite speed approach is reported, a new model called PFST (polytropic-finite speed thermodynamics) was developed based on the combination of polytropic analysis of expansion/compression processes and the concept of finite speed thermodynamics (FST) by Hosseinzade et al. [14]. They implemented on a prototype Stirling engine. Besides, Ahmadi et al. [15] employed the finite speed thermodynamic analysis instead of finite time thermodynamic analysis for studying Stirling heat engine based on the first law of thermodynamics for a closed system with finite speed and the direct method. Numerical thermal models are also a method to identify the performance of the Stirling engines. Babaelahi and Sayyaadi [16] developed a numerical polytropic model to determine the average polytropic indexes of the Stirling engine. In another study, they [17] generated a convective-polytropic model by considering various loss mechanisms and they compared the accuracy of the model with the previous models. A genetic algorithm was developed by Ahmadi et al. [18] to investigate the Stirling heat pump cycle parametrically. They tried to maximize the heating load and the coefficient of performance of the cycle.

The effect of maximized power on the Stirling engine was investigated by Ahmadi et al. [19,20] in two individual studies. In the first study [19], the output power and the engine thermal efficiency were optimized and the pressure losses were minimized by using an algorithm that depends on finite speed thermodynamics. In the second one [20], they developed a thermal model to maximize the output power and the thermal efficiency of the solar system considering the rate of heat transfer, regenerative heat loss, conductive thermal bridging loss, finite regeneration process time and imperfect performance of the solar dish.

Some researchers reported CFD investigations of the Stirling engines in literature, one of them is released by Alfarawi et al. [21]. They presented the development and validation of two-dimensional computational fluid dynamics (CFD) model of a gamma-type Stirling engine prototype to highlight the effects posed by phase angle and dead volume variations on engine performance. Even though several articles could be found in open literature about the experimental efforts on duplex Stirling, there is a few parametric study has been released on this topic. The lack of the thermodynamic explanations of this discrepancy triggered series of studies [22–24] for thermodynamic analysis of the duplex Stirling.

The endeavors to reveal the true thermodynamic response of the system begins with Erbay and Yavuz [22], in this valuable study, authors offered polytropic processes instead of isothermal heat transfer processes at the theoretical Stirling cycle to ensure temperature difference between the hot and cold fluid flows in regenerators, and hence to get more realistic analysis. As a further step, Erbay et al. [23] made a thermodynamic analysis of duplex Stirling to clarify the appropriate range of the parameters. Furthermore, Öztürk and Erbay [24] performed the thermodynamic analysis of the duplex Stirling by considering cooling load density which is defined as the cooling load per unit volume. Although duplex Stirling has been in use for almost three decades, with regard to the outstanding advantages of the system as listed at the beginning, it stepped forward once again in the NASA's new project for Venus by Ritzert et al. [25] to protect the sensitive and crucial components of the surface exploration equipment. Since Venus has a very harsh environment conditions, the ultimate purpose of the researchers is finding the best cooler which can stand to extreme temperatures while allowing benefiting from various heat sources to operate successfully. But at this point the need for a satisfying parametric study from thermodynamics aspect arises, in order to ease the research.

The hysteresis effects, engine and compressors coupling and low coefficient of performance are some difficulties. Due to these technical barriers related with the accurate cycle modeling capability should be tackled first. There is a gap in the literature on the detailed thermodynamic analysis of a duplex Stirling refrigerator. There is a benchmarking requirement. In this study, it is aimed to uncover hidden parts of the design of duplex Stirling refrigerator from the thermodynamics point of view by considering the effects of constructional and operational parameters. The compression