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Analysis of a high performance model Stirling engine with compact porous-sheets heat exchangers

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ABSTRACT

A high performance model Stirling engine, in which the heater, regenerator and cooler as a whole is formed by hundreds of porous metal sheets, is identified for theoretical analysis to facilitate the future scale-up design. The reciprocating flow and heat transfer both in the heat exchanger and in the full engine is simulated by a dynamic mesh Computational Fluid Dynamics (CFD) method, and is validated by analytical solutions and experimental data. An optimization method is also developed to incorporate the entropy generation caused by flow friction and irreversible heat transfer. The results show that relatively high indicated power of 33.4 W is obtained, corresponding to a specific power of 1.88 W/cm^3 and a thermal efficiency of 43.9%, which are attributable to the extremely small flow friction loss and excellent heat transfer characteristics in the regular shaped microchannels, as well as to the compact heat exchanger design that significantly reduces the dead volume. Given the same operating conditions, the optimized porous-sheets regenerator has a significantly lower total loss of available work while maintaining even higher thermal effectiveness in comparison with the optimized conventional wire mesh regenerator.

1. Introduction

Stirling engine has a wide application prospect in the power generation field due to its many advantages including adaptability to versatile heat sources, high thermal efficiency and environmental friendliness [1]. However, the relatively low specific power compared to that of the internal combustion engines is still one of the major obstacles hindering its development. So far, extensive research has been done on the regenerator, the central and crucial component of the Stirling engine in order to improve the engine performance [2].

The traditional wire mesh type regenerator is most popularly adopted in Stirling engines due to its huge heat transfer area, high convective heat transfer coefficient brought by the cross flow around numerous cylindrical shaped wires, and low axial thermal conductance. However, there are some inherent disadvantages associated with the wire mesh type regenerator [3], such as: (1) the numerous cylinders in cross flow produce flow separation, wakes, eddies and stagnation zones, resulting in high flow friction and considerable thermal dispersion, a loss mechanism that increases apparent axial conduction, damaging power output and engine efficiency; (2) the wire screens have some randomness in stacking, causing locally non-uniform porosity and flow distribution, which might increase axial conduction and damage its thermodynamic performance; (3) the mesh wires are subject to the impact of high-speed high-frequency oscillating flow during operation, so there exists the possibility of working loose or fiber breakage, thus damaging vital engine components; (4) the wire mesh type regenerator also requires long assembly time which tends to increase their cost.

Theoretically a regenerator with heat transfer surfaces parallel to the oscillating flow has a better performance than wire mesh type regenerators [4]. With the emerging micro-fabrication techniques, properly designed regular-shaped microchannel type regenerator can be fabricated to obtain extremely low flow friction while maintaining high heat transfer. The main features of the regular microchannel type regenerator include: (1) the heat transfer surface is smooth; (2) the flow acceleration rates are controlled; (3) the flow separation is minimized; (4) the axial thermal conduction is reduced by interrupting the axial continuity of solid structure, for example, using porous sheets with intermediate gaps or clearance. Other advantages include improved structural durability, no gas leakage or short-circuit loss owing to

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tight tolerance, low cost for mass production, thus realizing significantly higher comprehensive performance [5].

Researchers in the US has conducted a series research on the regular microchannel type regenerator under the NASA support [6]. The oscillating-flow rig test showed the highest figures of merit ever recorded for any regenerator tested in that rig over its ~20 years of use, demonstrating a shift strongly in the direction of the theoretical performance of ideal parallel-plate regenerators. Numerical projections of engine performance using the "SAGE" code indicated a performance improvement by 6%–9%. Takizawa et al. [7] developed a porous sheet type regenerator with electrically etched holes. Performance test in a 3-kW Stirling engine shows that the engine performance was improved by about 5%–10% compared to conventional stacked wire mesh regenerator. A series of engine tests were also done by Matsuguchi et al. [8] to optimize the geometrical parameters of the porous-sheets regenerator.

Nam et al. [9] developed a parallel wire type regenerator. The axial conduction loss is alleviated by wire segmentation, but the number of segmentation is limited for the parallel wires.

Commonly used traditional methods for analyzing and designing Stirling engines include the first, the second and the third order analysis [10]. Recently, Cheng and Yang [11] developed a lumped-mass analytical model to determine the temperature variations in expansion and compression spaces as well as the shaft power output corresponding to different operating speeds. Cheng and Yang [12] also developed a numerical model to predict the transient variations of temperatures, pressures and working fluid masses in the individual working spaces, so as to obtain the thermodynamic behavior of a Stirling engine. Rogdakis et al. [13] analyzed the thermodynamic performance of the Solo Stirling Engine V161 unit using a computer code based on an adiabatic model. Campos et al. [14] developed a dimensionless mathematical model, which combines fundamental and empirical correlations, and principles of classical thermodynamics, mass and heat transfer accounting for variable heat transfer coefficients, to simulate the thermodynamic behavior of a Stirling engine. These analyses generally fall into the second order analysis according to Martini's [10] classification, in which the engine is divided into several (usually five) chambers. Zero- or one-dimensional equations of mass continuity, momentum and energy conservation are solved. Correlations of various flow friction and heat transfer losses are treated as mutually independent and are used to modify the total power output. However, in order to gain a deeper insight into the complex fluid flow and heat transfer processes that occur in the internal gas circuit, and to more accurately predict the engine's performance, a three-dimensional (3D) dynamic mesh computational fluid dynamics (CFD) method is recommended to aid the engine design [15] since it can accommodate complex geometries, complicated boundary conditions and variable physical properties, depends less on empirical correlations that are usually obtained under certain limited experimental conditions. With the rapid development of computing power and CFD tools, the utilization of CFD method in the research and development of Stirling engines [16], thermoacoustic engines [17], pulse tube refrigerators [18] and Stirling regenerator [19] is in an increasing trend in recent years. This method is especially useful in this work since no exact experimental correlations are readily available for the reciprocating flow and heat transfer problem in a hexagonal channel with relatively thick wall.

In this work, a high performance model Stirling engine installed with a compact porous-sheets regenerator that has won the first prize in the 14th Stirling Techno-rally in Japan is identified for theoretical analysis, in order to understand the inherent physical mechanism, and to provide guidance for the future scale-up design. A commercial CFD code FLUENT is utilized to simulate the reciprocating flow and heat transfer in the porous-sheets heat exchanger by a dynamic mesh method, and validated with analytical solutions and experimental results. Then the flow and heat transfer in the entire Stirling engine are numerically simulated using the 3D dynamic mesh CFD method. The output power and the thermal efficiency are also obtained. Finally an optimization method is evolved by further taking the total entropy generation into account, and comparison of comprehensive performance is made between the optimized porous-sheets regenerator and the optimized wire mesh regenerator.

2. Description of the model Stirling engine installed with a porous-sheets regenerator

A schematic of the model Stirling engine is shown in Fig. 1(a), the detailed drawings of which can be found at Mr. Fukui's website [20]. The engine is composed of a cold cylinder, a heat exchanger and a hot cylinder arranged in α type configuration. The heat exchanger includes a heating section, a regenerating section and a cooling section, all integrated into the same unit. Two stainless steel end caps form two chambers, connecting the heat exchanger with the cold cylinder and the hot cylinder. The heating section of the heat exchanger together with the hot end cap is heated by a gas burner, and the cooling section together with the cold end cap is cooled by a heat pipe connected to a heat sink. A Ross drive mechanism ensures a phase shift of 90° between the two pistons. The bore and stroke of both cylinders are 32.5 mm and 21.4 mm. The heat exchanger is constituted by 365 pieces of 0.2-mm-thick, circular shaped, porous, stainless steel sheets, each porous sheet having 685 hexagonal shaped holes arranged as shown in Fig. 1(b), each hole having a side length (a) of 0.4 mm. The porous sheets are laminated and inserted into a cylindrical container with an inner diameter (Φ) of 28.8 mm, the holes of all sheets being aligned with each other so as to form 685 flow channels for the working gas, each channel having a hexagonal cross section and a length (L) of 73 mm. The engine is charged with helium at atmospheric pressure. The measured rotational speed (n) is = 2600 rpm under load when the engine is driving a model car.

3. The reciprocating laminar flow and heat transfer in a single channel

In order to validate the dynamic mesh method used in the CFD simulation, a single channel model is created as shown in Fig. 2. The channel outer wall is taken along the center planes of the solid skeleton that divide the adjacent channels. The calculation domain includes a single fluid channel with exactly the same shape and size as the actual fluid channel, a solid wall with half the thickness of the real sold material and two cylinders with diameters 3 times that of the hydraulic diameter of the fluid channel.

Some general assumptions are made as follows according to the practical condition,

(1) The working fluid is an ideal gas;
(2) No leakage of working fluid exists;
(3) Adiabatic boundary condition is specified on the outer wall of the engine except at the heating and cooling portions of the heat exchanger;
(4) Sinusoidal movement of the two pistons are specified;
(5) Cyclic steady state with constant frequency is assumed.

3.1. The reciprocating laminar flow

The basic equations for transient fluid flow and heat transfer can be found in the user manual of the FLUENT 14.0 software [21],