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Experimental and numerical flow investigation of Stirling engine regenerator

Sol-Carolina Costa [a], Mustafa Tutar [b, c, *], Igor Barreno [a], Jon-Ander Esnaola [b], Haritz Barrutia [b], David García [d], Miguel-Angel González [e], Jesús-Ignacio Prieto [e]

[a] CS Centro Stirling S. Coop, Aretxabaleta, Spain
[b] Mechanical and Manufacturing Department, Engineering Faculty, Mondragon University, Spain
[c] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain
[d] Department of Energy, University of Oviedo, Spain
[e] Department of Physics, University of Oviedo, Spain

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A B S T R A C T

This paper presents both preliminary experimental and numerical studies of pressure drop and heat transfer characteristics of Stirling engine regenerators. A test bench is designed and manufactured for testing different regenerators under oscillating flow conditions, while three-dimensional (3-D) numerical simulations are performed to numerically characterize the pressure drop phenomena through a wound woven wire matrix regenerator under different porosity and flow boundary conditions.

The test bench operating condition range is initially determined based on the performance of the commercial, well-known Stirling engine called WhisperGen™. This oscillating flow test bench is essentially a symmetrical design, which allows two regenerator samples to be tested simultaneously under the same inflow conditions. The oscillating flow is generated by means of a linear motor which moves a piston in an oscillatory motion. Both the frequency and the stroke of the piston are modified to achieve different test conditions.

In the numerical study, use of a FVM (finite volume method) based CFD (computational fluid dynamics) approach for different configurations of small volume matrices leads to a derivation of a two-coefficient based friction factor correlation equation, which could be later implemented in an equivalent porous media with a confidence for future regenerator flow and heat transfer analysis.

1. Introduction

Nowadays Europe faces changes, driven mainly by the economic crisis, globalization, demand on renewable resources, and ageing. Focusing on the demand on renewable resources, the priority is to promote a sustainable growth based on efficient technologies that can operate with different green energy sources; one of the most promising technologies is the Stirling engine [1,2]. The Stirling engines have suitable applications including conversion of solar energy, co-generation, submarine and space applications. Regarding micro-CHP (combined heat and power), the Stirling engine WhisperGen™ is an example of high efficiency with very low levels of chemical and noise pollution.

The regenerator is usually the Stirling engine component that handles more power [3]. Therefore, the function of the regenerator is the key to the efficient performance of Stirling engines. Most of the research works in this field are carried out for the optimization of this component [4–6].

The optimization process for the Stirling engine regenerators mainly focus on increasing the heat transfer capacity and reducing pressure losses. Pressure losses through the regenerator have a direct influence on the Stirling engine indicated power and, consequently, on the electrical power output. Ibrahim and Tew [3] pointed out that a performance survey for small (<100 We) engines indicates that regenerator thermal inefficiency contributes 1.5% to engine thermal inefficiency while pressure drop losses contribute about 11% engine inefficiency. Therefore, the characterization of these phenomena through experimental, theoretical and numerical

* Corresponding author. Mechanical and Manufacturing Department, Engineering Faculty, Mondragon University, Arrasate-Mondragon, Guipuzcoa, Spain. Tel.: +34 943 037 948; fax: +34 943 792 393.
E-mail address: mtutar@mondragon.edu (M. Tutar).

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Nomenclature

A_{wr}	wetted area of regenerator, $A_{wr} = 4V_{dr}/d_h$, m^2
A_{xr}	cross-sectional area of regenerator, $A_{xr} = V_{dr}/L_r$, m^2
a_1	form resistance parameter
a_2	surface friction parameter
C_f	friction factor = Darcy's friction factor $= f_D = \Delta p/{}^1\!/\!_2\, \rho\, u_{mx}^2 d_h/L$
c_p	specific heat of gas at constant pressure, J/(kg K)
c_r	specific heat of regenerator material, J/(kg K)
c_v	specific heat of gas at constant volume, J/(kg K)
d_h	matrix hydraulic diameter, m
d_w	wire diameter, m
E	energy per unit of mass, J/kg
h	convective heat transfer coefficient, W/(m^2 K)
K	permeability, m^2
k	thermal conductivity of the gas, W/(m K)
k_r	thermal conductivity of the regenerator material, W/(m K)
L_r	regenerator length, $L_r = V_{dr}/A_{xr}$, m
$\dot{m}$	mass flow rate, kg/s
Fo	Fourier number $= 4\alpha_r/(\overline{u}\, d_h) = 4\alpha_r/(d_h\sqrt{RT_{ref}})\cdot N_{ma}^{-1}$
Ma	Mach number $= \overline{u}/\sqrt{RT_{ref}} = \dot{m}\sqrt{RT_{ref}}/(pA_{xr})$
Pr	Prandtl number $= \mu\, c_p/k$
Re	Reynolds number $= \rho\, \overline{u} d_h/\mu = \dot{m}\, d_h/\mu\, A_{xr}$
St	Stanton number $= h/(\rho\, \overline{u} c_p) = hA_{xr}/(\dot{m} c_p)$
TCR	thermal capacity ratio $= \rho_r c_r/(\rho c_p) = (\rho_r c_r T_{ref}/p)\cdot(\gamma - 1)/\gamma$
n_s	engine frequency, rev/s
p	pressure, Pa
q	heat flux, W/m^2
R	specific gas constant, J/(kg K)
S_h	heat source term, W/m^3
T_C	compression space temperature, K
T_E	expansion space temperature, K
T_g	gas temperature, K
T_{gL}	gas temperature at hot side, K
T_{g0}	gas temperature at cold side, K
T_{ref}	reference temperature at which physical properties are computed, K
T_{wr}	regenerator matrix temperature, K
T_{wrL}	regenerator matrix temperature at hot side, K
T_{wr0}	regenerator matrix temperature at cold side, K
t	time, s
u	gas velocity, m/s
$\overline{u}$	mean gas velocity $= \dot{m}/(\rho A_{xr})$, m/s
u_{mx}	interstitial gas velocity inside the matrix, m/s
V_{dr}	regenerator dead volume, $V_{dr} = V_r \P_V$, m^3
V_r	regenerator total volume, m^3
x	longitudinal coordinate along the regenerator length, m
α_r	thermal diffusivity of regenerator material, m^2/s
ε	regenerator thermal efficiency
γ	adiabatic coefficient
μ	viscosity of gas, Pa s
$\P_V$	regenerator matrix volumetric porosity
ρ	density of gas, kg/m^3
ρ_r	density of regenerator material, kg/m^3

studies is crucial in co-generation applications to maximize the ratio between generated electrical power and source energy input.

Most of the research works mainly focus on the empirical characterization of the pressure losses for stacked woven wire regenerator matrices. Frequently, the phenomenon is modelled as a case of internal flow through a conduct, and the pressure drop is computed by means of a friction factor correlation based on the Hagen–Poiseuille's law. The correlation by Kays and London [7] is probably the most widely used. It assumes steady, incompressible flow and provides a friction factor, C_f correlation obtained from experiments performed in a perfectly pressed stacked woven wire screen matrices. Urieli and Berchowitz [8] proposed an equation based on Kay's and London's data. Seume and Simon [9] provided a review of the friction factor correlations for steady-state flow, and they also studied the compressibility effects and the characteristics of the oscillating flow in Stirling engine regenerators. Sodré and Parise [10] carried out experiments to determine the pressure drop through an annular conduit filled with a plain square wire-mesh woven-screen matrix. A corrected Ergun equation was used here to correlate the experimental data, considering the wall effects.

Several experimental test benches are used to characterize both pressure losses and convective heat transfer in regenerators under unidirectional, steady flow conditions [11]. However, testing facilities designed for oscillatory flow are more suitable for the operation conditions of Stirling regenerators. Wood et al. [12] used two different test benches, one for oscillating flow and other for steady unidirectional flow. Both test benches are designed for conventional heat exchangers, but they could be adapted for regenerators. The test bench used by Ibrahim et al. [13] consisted of an engine with two horizontal opposite pistons, crankshafts and individual drives which provide oscillating flow. Miyabe et al. [14], Tanaka et al. [6], Gedeon and Wood [15] also used experimental devices under oscillating inflow conditions. The latter three studies [6,15] are classical references concerning friction factor and heat transfer experimental researches for stacked woven wire screens with variety of materials and geometries.

Experimental works are complemented with analytical and numerical approaches, usually related to the flow through wire screen matrices. The FVM (finite volume method) appears to be promising numerical discretization technique for the solution of governing partial differential equations as indicated by Rühlich and Quack [5], Gedeon and Wood [15], Ibrahim et al. [16], Tew [17] and others. These numerical studies suggest that the flow simulation is worthwhile to understand the flow behaviour and hence to characterize fluid flow friction for systems of potential regenerator applications.

Undoubtedly, the most widely used type of regenerator is the metal wire matrix, mainly stainless steel. In this approach, the regenerator volume is filled with wires or fibers of small diameter, typically from 40 to 150 μm (4×10^{-5}–15×10^{-5} m). In the variant most likely used, the wires are previously woven into screen or meshes which are stacked adjoining to each other. There are different types of woven wire which lead to regenerators with different thermodynamic behaviour. Regenerators made of random-fibers or metal felts are cheaper to manufacture than stacked woven wire regenerators [15].

In the present study, a new test bench is designed for experimental characterization of the Stirling engine regenerator to be operated under oscillatory flow conditions. During the design, set-up, and preliminary tests of the test bench, a few limitations and measurement problems are identified. The test simplifications are realized to generalize the flow features and heat transfer characteristics however these also lead to large experimental errors. Therefore, a macro scale-finite volume method (FVM) based