Experimental Measurement of Oscillating Flow in a Stirling Engine Regenerator

Songgang Qiu1*, Koji Yanaga2

1Faculty of mechanical and aerospace engineering, West Virginia University, Morgantown, USA
2Department of mechanical and aerospace engineering, West Virginia University, Morgantown, USA

*corresponding author: songgang.qiu@mail.wvu.edu

Abstract Regenerator is the key component in a high efficiency of Stirling engine. Currently, most regenerators are made of either the random fibers or woven screens. However, these regenerators have high flow losses, leading to low engine performance. To solve this problem, a new robust foil regenerator was developed. This regenerator has only parallel flow channels. Therefore, it is expected that the flow losses through the regenerator are significantly low compared to the conventional regenerators. In this research, a regenerator test rig was designed and manufactured to measure the flow losses in the oscillating flow of Stirling regenerators. The test rig was designed to generate the sinusoidal flow motion as in typical Stirling engines. Foil regenerators were tested under oscillating flow conditions. Dynamic pressure transducers were implemented to determine the pressure drops. Testing was conducted over a few hundred cycles and the measured pressures were ensemble-averaged to generate cyclic variation of pressures at the inlet and outlet of the regenerator. The friction coefficient was calculated based on the Darcy-Weisbach equation. The calculated friction coefficient was compared to the parallel plate, random fiber regenerator, and woven screen regenerator correlations. The result shows that the friction coefficient of the foil regenerator is slightly higher than the parallel plate friction coefficient and much lower than the conventional regenerators friction coefficient.

Keywords: regenerator, Stirling engine, oscillating flow, friction coefficient

1 Introduction

The Stirling engine is one of the solutions to decrease the environmental impact of power generation because of its high efficiency and flexible energy source such as solar, bio-mass, and industrial waste heat. The essential component in a high efficiency Stirling engine is the regenerator since it works as an energy storage in the Stirling engine to recover part of the waste energy. In general, a regenerator is made of random fibers or woven screens due to their high heat transfer performance. Ibrahim et al. [1] studied a random fiber regenerator with experimental testing. They found a master correlation for the random fiber regenerator friction coefficient. As a result, based on their figure of merit analysis, it is revealed that the regenerator with 96% porosity shows the most efficient performance. Costa et al. [2] reported on woven screen regenerator. They found a new correlation of friction factor which is valid in the Reynolds number range less than 350 and specific wire diameter range 0.080 to 0.110 mm. However, the random fiber and woven screen regenerator have relatively high flow losses since both of them are composed of wires. Mancisidor et al. [3] designed and fabricated a new type regenerator. The regenerator has a lattice structure to decrease the pressure drop. As a result, they found out that the new regenerator pressure drop is significantly lower than conventional regenerators. However, based on their CFD result, heat transfer performance is not high enough compare to the conventional regenerators. Therefore, overall regenerator performance is relatively the same as conventional regenerators.

In the previous study, a new robust foil regenerator was designed to reduce the flow loss of the regenerator [4]. The regenerator flow channels are consisted of parallel flow channels which is ideally efficient. The thermal expansion of the regenerator is critical because it changes the flow distribution in the regenerator and leads to a higher pressure drop. Therefore, the robustness of the new regenerator is important not to change the flow distribution [5]. In this research, to reveal the new regenerator characteristics, a test rig was designed and manufactured. By using the linear motor as a driving system, the oscillating flow can be generated in the same manner as a typical Stirling engine working fluid. The flow loss through the regenerator was measured by two dynamic pressure transducers which were installed at the inlet and outlet of the regenerator. The measured pressure drop was ensemble-averaged and converted to the friction coefficient. The derived friction coefficient was compared to other published regenerator correlations.
2 Robust foil regenerator

Fig. 1 shows the robust foil regenerator. The regenerator was designed based on the analysis of Sage 1-D simulation software. The regenerator is made of Inconel 718 and manufactured by direct metal laser sintering (DMLS) (a method of 3-D printing). The regenerator inner diameter and outer diameter are 35 mm and 52 mm, respectively. The wall thickness between each channel and the fluid path thickness are both 0.3 mm. The length of the regenerator is 50 mm.

3 Test rig

Regenerator test rig has been designed based on stress analysis with a minimal safety factor of 1.5 and has been properly manufactured to measure the flow loss and the effectiveness of the regenerator. The maximum charge pressure of the test rig is 45 bars. Fig. 2-(a) shows the schematic of the regenerator test rig. In Fig. 2, the test rig is composed of: 1 – hot side pressure vessel, 2 – band heater, 3 – diffuser, 4 – pressure transducer, 5 – test section, 6 – cooler, 7 – linear alternator piston, 8 – cold side pressure vessel, 9 – Linear alternator, 10 – displacement transducer holder, and 11 – displacement transducer. During the measurement of the pressure drop, the heater and cooler were turned off. However, they were still sitting in the test rig as part of the fluid path. Fig. 2-(b) represents the flow path in the test rig. As the piston moves up, the fluid goes upwards. In reverse, when the piston moves down, the fluid goes downwards. While the flow is oscillating, the pressure drop through the regenerator is measured by two pressure transducers which are installed right above and below the regenerator.
4 Data acquisition

All data was recorded via National Instruments (NI) data acquisition devices. Through the LabVIEW VI, the data from the two dynamic pressure transducers and the piston position were recorded at the same time. NI modules of cDAQ-9178, NI9225, and NI9234 modules were used. The NI9225 module was used to measure the current from the displacement transducer, and to record the piston motion of the linear alternator. NI9225 was employed to acquire the voltage output from the power source CHROMA 61604. The NI9234 module was for recording the pressure data through the pressure transducers.

5 Result

The flow loss test was conducted with a charge pressure of 2 bars and 20 Hz of linear alternator frequency. Also, the maximum Reynolds number was changed from 100 to 800. Fig.3 shows the pressure drop through the regenerator when maximum Reynolds number is 400.

![Fig. 3 Pressure drop when maximum Reynolds number is 400](image)

The Reynolds number in the regenerator is calculated with equation (2).

\[
Re_{\text{max}} = \frac{u_{\text{max}}D_h}{\nu}
\]  

(1)

The maximum friction coefficient can be calculated using the maximum velocity in the regenerator and the maximum pressure drop across the regenerator with the following equation (3).

\[
C_{f,\text{max}} = \frac{\Delta P_{\text{max}}D_h}{\frac{1}{2} \rho u_{\text{max}}^2 L}
\]  

(2)

Here, the delta pressure max ($\Delta P_{\text{max}}$) is the maximum pressure difference measured by the two dynamic pressure transducers. Fig.4 depicts a comparison of measured friction coefficient to the parallel plate, woven screen, and random fiber [1]. The test result is considerably smaller than the random fiber and woven screen friction factor correlations. In addition, since the robust foil regenerator configuration is similar to the parallel plate, the friction coefficient is similar to the parallel plate friction coefficient.
6 Conclusion

The regenerator test rig was designed and built to measure the pressure drop of the robust foil regenerator under the oscillating flow condition. Based on the data from the pressure transducers and linear displacement transducer, the friction coefficient was derived. The result shows that the friction coefficient of the regenerator is much smaller than conventional regenerators and similar to the parallel plate correlation.

7 Acknowledgement

The authors would like to acknowledge and appreciate the generous financial support from DOE ARPA-E, as this project was funded under United States DOE ARPA-E contract, DE-AR0000864

7. References


