Mini-project report

Production of Optimised Metal Foams for Stirling Engine Regenerators

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Abstract: This Mini-project report is continued work from the past two-month mini-project. It has the results obtained from the production and testing of the samples created by two different manufacturing processes compared to the coil samples. We tested them in the heat transfer and flow rig as well as in the oscillatory rig, to find out their behaviour under pressure conditions from both sides of the sample in the Ripper Laboratory of Mechanical Engineering. The objective is to determine the differences caused by the three manufacturing processes and see how it affects the measure of properties from different material test samples to find out if any of these samples is suited for Stirling engine regenerator applications.

Introduction: Every thermodynamic engine works with thermodynamic cycles. Thermodynamic engines are classified in two categories: endothermal (internal combustion) and exothermal (external combustion). For example endothermal engines include those on cars, trucks, boats and jets. Exothermal engines include the steam engine and the Stirling engine.
The idea of the Stirling cycle is to alternate hot and cold air within a cylinder using articulated mechanical arms and a flywheel to achieve movement in a soft and endless cycle.

Stirling engines receive energy by heat transfer, so they can take advantage of using fuels of less quality, exhaust gases from other engines, solar energy, geothermal power or nuclear fission; the working fluid is always the same and it doesn't change composition; it operates on a closed regenerative thermodynamic cycle with stages of compression and expansion of the working gas at different temperature levels. This cycle is a reversible one, meaning that if you introduce heat to the system you will obtain mechanical energy; and if you introduce mechanical energy by an electric motor it will produce thermal energy. So it can be used as a heat pump or as a refrigerator without using damaging refrigerants affecting the environment. [1]

Stirling Engine Closed Regenerative Thermodynamic Cycle: The Stirling cycle consists of four stages, each one is reversible: Two isochoric or constant volume transformations in which the working gas passes through a regenerator, absorbing or yielding heat, and two isothermal or constant temperature transformations in which the gas is in contact with a hot or cold source. [2, 3]

Regenerator: It's an element that allows recovering energy. The regenerator pre heats and pre cools the working gas, dramatically improving efficiency.

The design of a good regenerator is a question of compromise between certain factors:

- The most surface area possible to maximise heat transfer.
- The smallest internal volume of working fluid.
- The least resistance to the working gas flow.

One of the solutions for its construction that has been used consists in the fabrication of porous metal foams that allow gas flow through the pores, wire nets, meshes and coils; they possess a large contact surface due to the pores.
The main problem of these regenerators is the opposing resistance to the working gas flow, which is why it is needed to use low viscosity gases like Helium or Hydrogen to minimise losses due to friction. [4, 5]

Sample Production: We made different samples to test out in the heat transfer and flow rig, and compared them to the wire samples made into coils from the first mini-project. The new samples were made with cut wires of a certain length and then hydraulically pressed into the desired sample size. The other manufacturing process served to make metal foams out of aluminium. For this we worked in the Materials Processing Laboratory in the Robert Hadfield Building C-Floor.

a) **Felt Samples:** We used the same wire materials as in the past mini project (Aluminium, Silver, Copper, Stainless Steel 302, Tantalum, Titanium and Tungsten). The wire diameter was 0.25 mm; we used copper as our trial and error material because we had more than enough to work with.
The quantity of material needed to make each sample was calculated based on the density and weight of the sample. The rig is designed to hold a sample with a 22 mm diameter and the porosity we wanted to work with was 70%, so the only variable we had was the length, we tried to make all of them with a length of 11 or 12 mm.

We proceeded to cut the wires and to place them in the sample mould. We did three different tests to find out which length of each wire piece was more convenient for the sample making.

After filling the mould with the cut wires we placed it in the manual hydraulic press. Almost all of the samples got made with 1 ton of pressure at most; the only exception was the Tungsten sample, which needed 15 tons of pressure to make, due to the fact that this material is brittle and hard, making it difficult to work with.

b) **Foam Samples:** To make the foam samples an infiltration rig is used; in this process molten aluminium is forced to merge with sodium chloride ($NaCl$) with the aid of a vacuum pump and an applied argon gas pressure; these are connected to the steel chamber that is placed in the furnace to melt the aluminium. They both have manometers and valves to regulate the pressure.

The steel chamber is coated with Boron-Nitride spray to minimise bonding between the aluminium and the steel cylinder; the $NaCl$ is placed at the bottom. The $NaCl$ grains can vary in size (1.7mm, 2.35mm, 4mm, 5mm, etc.) depending on the type of sample you wish to make. Bulk aluminium (99.7 % pure) is set on top of the salt, approximately in the same proportion.

The chamber is closed tightly using a graphite gasket in its top and bottom and placed inside the furnace, vacuum is applied (25 Torr) and the furnace is turned on with a heating rate of 10˚C/min, the temperature is raised up to 710˚C - 740˚C and held there for 2 hours. The vacuum is disconnected and the argon gas is allowed to fill the chamber for 5 minutes so that the molten aluminium is forced into the salt grains. The cylinder is quenched on a copper block so the aluminium solidifies uniformly from bottom to top. The sample is taken out and rinsed in water to dissolve the salt, finally it can be cut to the desired size.

Sample Tests: After making the felt and foam samples we proceeded to test them in the heat transfer and flow rig and in the oscillatory rig. We wanted to obtain the temperature readings before and after each sample at 13 different flow rates, to calculate the energy that each sample trapped in a certain amount of time and the pressure drop in the oscillatory rig.

a) **Heat transfer and flow rig:** The samples were set in white PVC fitting with 2 PVC pipes holding the sample in place. Air flow was provided from the lab, regulated by a knob and connected to the rig; heat was provided by a rope heater and was regulated by an electric control unit. Pressure readings were taken with a manometer connected to the PVC pipe before and after the samples well as the two thermocouples for temperature readings connected to a data logger.

What really is of interest in the experiment is the change in temperature of the first seconds after we connect the PVC pipe to the rig; this lets us know how the sample is behaving when heat is suddenly applied. We obtain the energy lost by the air while crossing the sample by calculating $E = mCp\Delta T$.

Test # 3 Oscillatory Rig: This rig works at a higher velocity compared to the single flow rig and its flow goes in both directions; it creates pressure drop through porous media. It consists of two V-type twin cylinder compressors, a 1 kW 3-phase AC motor operated by a controller with a range between 1 and 50 Hz; joined by belts and pulleys. The two compressors are set at a 180 degree out of phase to generate the push and pull mechanism without compressing the air. The test section is a copper pipe of 22 mm in diameter and 80 mm in length, in the middle of which goes the sample. The pipe is connected to both compressors. On top of the pipe the pressure transducer is placed, connected to an oscilloscope and a computer with LabView Signal Express 2009 software to process the data. [9]
After the data was ready, we calculated the angular velocity, the flow displacement and the maximum velocity converted to litres/minute to compare it with the single flow rig.

Conclusions and Further Work

Test # 1: By reducing the variables in the manufacturing of the samples they come out with a more uniform shape compared to the coil samples of the past mini project. We also increased the reading points from 7 to 13 in this project, to have a wider range of behaviour of the samples.

Within the felt samples the one with the most pressure drop was the Stainless Steel, probably due to the fact that it had the lowest porosity (68 %) and it was the first sample to be made after the 3 tests with the Copper wire. The best sample was the Tungsten, probably because since it is the less ductile material it moves less when the air passes through it.
Within the foams the worst sample was S4 due to its low porosity (61.2%); the best sample was S3 since it was the foam with the highest porosity (67.1%).

Test # 2: Based on the results obtained we can't say that in order to build a good regenerator it must be made of a material with high heat capacity, further testing is needed, stainless steel absorbed more energy even though that it has roughly half of aluminium's heat capacity.
From another batch of results we can say that low thermal conductivity is important; we can see that stainless steel has the lowest thermal conductivity, capturing the most energy, tantalum also scored high.

In the third group of results we proved the results found in Timoumi's paper which says that a regenerator needs to have a high heat capacity and a low conductivity to minimize internal heat loss. [6]

In the comparison between the three manufacturing processes the aluminium foam sample was the one that absorbed the most energy and had the lowest pressure drop, which is what we are looking for; low resistance to flow and high energy capture is what makes the most efficient regenerator.

Test # 3: With the oscillatory rig we obtained the same behaviour from the samples as with the single flow rig; even with the great increase in pressure and analysing it from both sides. The samples resisted this increase and did not fall apart.

In further work a heater will be installed in the oscillatory rig to find out the energy absorption under high pressure; we have to find out if other properties of materials need to be addressed to make a more efficient regenerator. A faster data logger and thermocouples should be used, to get the real temperature gradient of the samples.

Perhaps it would be a good idea to create stainless steel foam and see how it behaves, however due to its high melting point (1420°C) it will be a bigger challenge to process, it might need a powder metallurgical technique; the advantage is that foams are more rigid than wire meshes it will take longer for them to crumble into pieces.

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