Experimental Study of a Rotary Heat Exchanger with a Metal Mesh Matrix

A V Kostukov\(^1\), L A Kosach\(^1\), A A Dementiev\(^1\)

\(^1\)Power plants for transport and small power generation dept., Moscow Polytech University, Moscow, Russia

Abstract. This paper describes the experimental study of a metal mesh matrix of a rotary heat exchanger model including calculation of its regeneration ratio. Temperature oscillograms showing the temperature in the matrix channel are shown. Also, the pressure loss value is found for channels of the matrix. The pressure loss value for the case of having a matrix formed by flat metal plates was also calculated in order to compare the calculated values with the ones obtained experimentally for the mesh matrix.

1. Introduction
Recent studies show that microturbines have a great potential due to their ability of stable and efficient work using hydrogen \([1-5]\). It is obvious that there may be some problems but there are ways of solving them \([5-9]\). Microturbines using hydrogen can be competitive compared with the engines using fuel cells in fuel economy and cost. Such position requires further efficiency improvement to stay competitive.

Increasing the maximum temperature value of the engine’s thermodynamic cycle up to 1250°C and using a heat exchanger with regeneration ratio equal 95% make it possible for an engine with power of 70-100 kWt to get the efficiency values about 44-45%. Getting such values of regeneration ratio along with reasonable heat exchanger size is possible when using a rotary regenerator due to its high value of compactness coefficient \([10, 11]\).

Matrices of such heat exchangers can be made of steel plates forming gaps of certain wideness (slots). Also, they can be formed by the plates made of metal mesh what can cause some changes in the structure of the gas flow. It can result, for example, in a different value of pressure loss in the matrix channels. That’s why a study is needed to obtain the data describing the gas flow in metal mesh matrices.

2. Methods
An experimental study was carried out for a model of a rotary heat exchanger in order to obtain the values of its regeneration rate and the pressure loss in its matrix.

The scheme of the experimental stand is shown in Fig. 1.
In the model, the heat-exchanging matrix consists of twelve elements in a metal frame with five elements working simultaneously in each fluid channel. Each element is a set of flat metal mesh plates. The mesh plates are placed in the way to form a set of slot channels through which gas flows. Geometrical properties of the heat-exchanging matrix elements are as follows:

- element’s length: 94 mm;
- slot’s width: 0.5 mm;
- mesh plate’s thickness: 0.12 mm.

The regenerator model was provided with air by a piston compressor. A DC motor connected with the regenerator via a worm reducer provided rotation of the matrix. Electric heaters were installed inside the channel after the "air" side of the heat exchanger to simulate the heat rise performed by a combustion chamber in a real gas turbine engine. After passing the electric heaters air was referred to as "gas".

Air mass flow rate at the matrix inlet was calculated by measuring the pressure drop at a diaphragm.

The value of air and "gas" temperature at the regenerator’s inlet and outlet were obtained by two quick response thermocouples (copper–constantan, diameter: 0.07 mm) installed inside the matrix for continuous temperature monitoring (Fig. 2).

The thermocouples used in the experimental study were calibrated using reference platinum rhodium thermocouple.

A data acquisition unit was installed in the way to rotate together with the regenerator. The unit transferred the thermocouple signals via wireless connection to a personal computer where they were processed to obtain the temperature values.

The experimental studies were performed for the following case:

- air and "gas" mass-flow rate: 3.5 g/s;
- air temperature at the regenerator’s air channel inlet: 20°C;
- "gas" temperature at the regenerator’s "gas" channel inlet: 130°C;
- regenerator rotation frequency: 18.5 rpm.

**Figure 1.** The scheme of the experimental stand.
After processing experimental data was presented in the form of two oscillograms: the first one – air temperature at the regenerator inlet and "gas" temperature at the regenerator outlet, the second one – air temperature at the regenerator outlet and "gas" temperature at the regenerator inlet. Such combination was obtained because of the thermocouples' location.

The obtained data was processed as follows: average temperatures of air and "gas" at the regenerator inlet and outlet were calculated as follows:

$$\bar{T} = \frac{1}{t} \sum_{i=0}^{n} T_i * \Delta t_i$$

where $\bar{T}$ was the average temperature, K, $T_i$ was the temperature upon the i-th measurement, K, $\Delta t_i$ was the i-the time increment, s, $t$ was the time of measurements, s, $n$ was the number of time increments during overall time of measurements.

Then the obtained temperature values were used for calculating the heat exchanger’s regeneration rate as follows:

$$\sigma = \frac{T_{g,\text{in}} - T_{g,\text{out}}}{T_{g,\text{in}} - T_{a,\text{in}}}$$

where $T_{a,\text{in}}$ was the air temperature at regenerator inlet, K, $T_{g,\text{in}}$ was the "gas" temperature at regenerator inlet, K, $T_{g,\text{out}}$ was the "gas" temperature at regenerator outlet, K.

The pressure loss in the matrix channels with mesh elements was measured via differential manometers.

A calculation was performed to find the pressure loss in a heat-exchanging matrix having the same geometrical properties but made of flat metal (steel) plates. The other comparison condition was the same value of Reynolds number in both matrices. It was obtained by processing the experimental data, namely, the stand’s inlet air temperature and pressure and mass-flow rate value. Using those values it was possible to find air density, viscosity and velocity for calculating Reynolds number using its definition:
\[ Re = \frac{\rho \cdot c \cdot 2 \cdot s}{\mu} \]

where \( Re \) was Reynolds number, \(\rho\) was air density, kg/m\(^3\), \( c \) was airflow velocity, m/s, \( s \) was the slot’s width, m, \( \mu \) was dynamic viscosity, Pa*s.

The pressure loss in a slot channel formed by metal plates was calculated via Darcy–Weisbach equation [12]:

\[ \Delta P = \lambda \frac{l}{2 \cdot s} \cdot \frac{\rho \cdot c^2}{2} \]

\[ \lambda = \frac{96}{Re} \]

where \( \Delta P \) was the pressure loss in the channel, Pa, \( \lambda \) was Darcy coefficient, \( l \) was the channel’s length, m.

3. Results

The temperature oscillograms obtained during the experimental study are shown in Fig. 3. The blue line represents the temperature measured by the thermocouple placed at the top position of the matrix, the orange line represents the same at the bottom position.

![Figure 3. Graph of air and "gas" temperature as functions of time.](image)

At Fig. 3 there are two pairs of lines showing the range of temperature values used to calculate the time averaged values for further calculation of regeneration ratio.
After processing the experimental data the time-averaged temperature values and the regeneration ratio value were obtained as well as the pressure loss values (obtained via the experiment for the mesh matrix and via calculation for the flat plates matrix). Those values are shown in the table below.

| "Gas" Temperature at the inlet, K | "Gas" Temperature at the outlet, K | Air Temperature at the inlet, K | Regeneration ratio | Pressure loss (mesh), Pa | Pressure loss (plates), Pa |
|----------------------------------|-----------------------------------|---------------------------------|-------------------|------------------------|--------------------------|
| 130.5                            | 30.3                              | 24.3                            | 0.943             | 226                    | 217                      |

4. Discussion

The calculated value of regeneration ratio is about 94.3%, which is relatively high. It should be noticed that there is a potential for increasing the regeneration ratio by making the slots between metal mesh plates smaller. That will make it possible to have bigger heat-transferring surface area in the same volume of the matrix. On the other hand, it will lead to increasing of the pressure loss due to increasing the friction surface area so this direction of modifying the heat exchanger requires some experimental or computational studies.

The pressure loss value obtained via the experimental studies of the matrix with metal mesh elements is 225 Pa. The value calculated for the case of having a matrix with metal flat plates elements is 217 Pa. It can be said these values are quite close what makes it possible to use simple equations defined and verified for flat slots for the analysis of mesh matrices.

5. Conclusion

1. Thermal and hydraulic properties of a heat-transfer matrix consisting of metal mesh elements have been experimentally studied, the time-averaged temperature values and the pressure loss value were obtained.

2. For the heat exchanger model the value of regeneration ratio was calculated, it equals 94.3% what shows a great potential of making compact rotary heat exchangers with high values of regeneration ratio.

3. The pressure loss value was calculated for the case of using a heat-transfer matrix made of flat metal plates. It was shown that the pressure loss values are almost the same for matrices made of metal mesh elements and for the ones made of metal plates when the Reynolds number stays the same for both cases.

6. References

[1] Ioanna Aslanidou, Moksadur Rahman, Valentina Zaccaria and Konstantinos G Kyprianidis 2021 Micro gas turbines in the future smart energy system: fleet monitoring, diagnostics, and system level requirements” in Frontiers in Mechanical Engineering vol 7

[2] Emmanouil Kakaras 2021 The economics of hydrogen in Turbomachinery International vol. 62 5

[3] Jens Dickhoff, Atushi Horikawa, Harald Funke 2021 Hydrogen combustion in Turbomachinery International vol. 62 4

[4] Ancona M A, Bianchi M, Branchini L, De Pascale A, Ferrari F, Melino F, Peretto A 2021 Optimal Design of Renewable Hydrogen Production for Gas Turbine Test Facilities at ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition

[5] Antonio González García-Condé, Cristina Lucero Martínez, Guillermo Gómez Prada, Verónica Mesa Vélez-Bracho, Jesús Maellas Benito 2014 Modifications of an existing microturbine to use hydrogen as fuel at 20th World hydrogen energy conference

[6] Marin G E, Mendeleev D I, Osipov B M 2021 A study on the operation of a gas turbine unit using hydrogen as fuel Journal of Physics: Conference Series 1891
[7] Thomas Bexten, Tobias Sieker, Manfred Wirsum 2021 Techno-Economic Analysis of a Hydrogen Production and Storage System for the On-Site Fuel Supply of Hydrogen-Fired Gas Turbines at Conference: ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition

[8] Agbadede R, Nkoi B, Kainga B 2020 Performance Analysis of Industrial Gas Turbines Fueled with Hydrogen in Nigerian Research Journal of Engineering and Environmental Sciences 5(1)

[9] Alessandro Cappelletti, Francesco Martelli, Enrico Bianchi, Eduardo Trifoni 2014 Numerical redesign of 100kw MGT combustor for 100% H2 fueling" in Energy Procedia 45

[10] Kostukov A V, Kosach L A, Gornovskii A S 2019 Microturbine with Heat Exchanger with Regeneration Ratio Equal 95%" in Lecture Notes in Mechanical Engineering

[11] Ivanov V L, Leontiev A I, Manushin E L, Osipov M I 2003 Heat exchangers and cooling systems of gas turbine and combined plants (Moscow)

[12] Idelchik I E 1992 Handbook of hydraulic resistances (Moscow)