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Thermal performance measurement of additive manufactured high-temperature compact heat exchangers

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Thermal performance measurement of additive manufactured high-temperature compact heat exchangers

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Abstract. Due to increased distribution of high-temperature processes in energy and process plants, more efficient and compact high-temperature heat exchangers are being developed. The additive manufacturing allows the construction of compact sizes and application-specific requirements. To evaluate the thermal performance of these heat exchangers, experimental investigations are evident. This study presents a test rig for testing compact high-temperature heat exchangers as well as a first set of thermal performance data of an additively manufactured plate-fin heat exchanger. The test rig can provide a maximum fluid temperature of 900°C and a maximum mass flow rate of 0.8 kg/min. A steam unit can add steam to the fluid stream to evaluate the influence of gas radiation on the thermal performance. The capabilities of this test rig are being tested with the plate-fin heat exchanger, varying the mass flow rate between 0.2 - 0.52 kg/min at a hot and cold inlet temperature of 750°C and 250°C. The overall effectiveness of the heat exchanger is approx. 0.9.

1. Introduction

For high-temperature applications in energy- and process engineering, the heat recovery and the energetic integration of heat flows plays an important role for the energy efficiency. Due to the progress made in the development of high-temperature fuel cells and electrolysis systems, such as Solid Oxid Fuel Cells and Molten Carbonate Fuel Cells, the number of high-temperature applications is increasing drastically [1]. Also, the thermodynamic efficiency of many energy converters, such as Stirling-Engines and micro gas turbines [2] depends on the maximum process temperature. Therefore, a lot of research is done to increase this upper temperature limit. In all of these applications high-temperature heat exchangers are involved and the main challenge is to design them as powerful as necessary, but as small as possible. This mostly results in complex manufacturing procedures, such as sintering, while the geometry remains simple [3].

The 3D-Metalprinting technology offers many new degrees of freedom, to create more compact and more complex geometries in an easier way, by using high temperature steel- or nickel-based alloys. This results in completely new heat exchanger designs and offers new possibilities to avoid the disadvantages of common manufacturing procedures, such as gas leakage or large construction volumes [4].

This leads to the objective of this study, evaluating the thermal performance of 3D-metalprinted heat exchangers by several experiments. For this purpose, a test rig was set up to measure the thermal performance of different types of high-temperature heat exchangers, that will be described in a detailed way in this study. The results of first tests with an additively manufactured heat exchanger, demonstrate the capabilities of this test rig.

2. Methodology

In the following subsections the test set up and the test procedure will be explained. This includes the construction components installed in the test rig and the operating parameters such as temperatures, fluid and mass flows.

2.1. Test rig

The test rig is divided into three main stream loops (two air streams A and B and one steam stream). The following schematic (Figure 1) gives an overview.

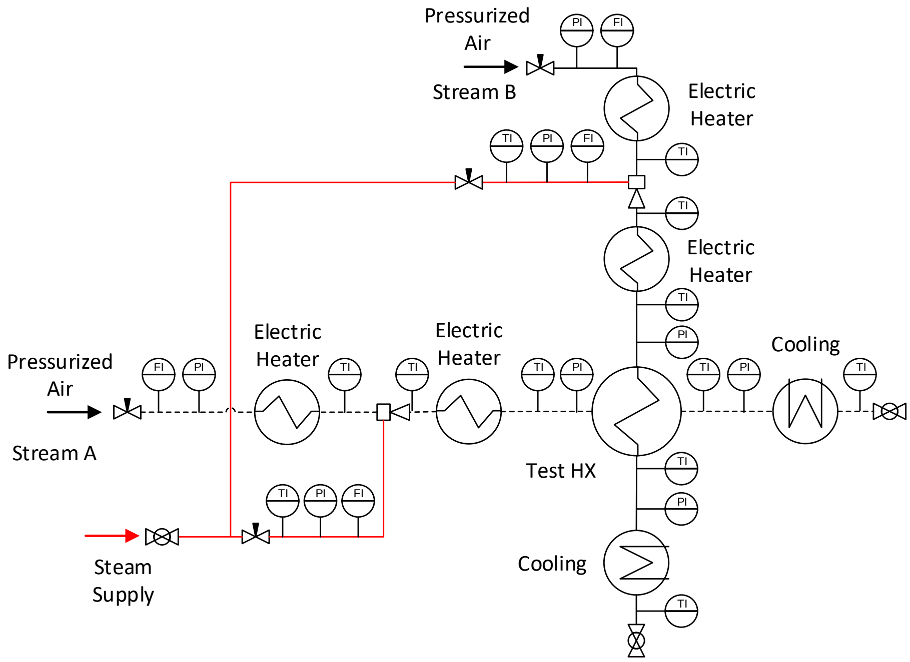

Figure 1. Flowchart of the test rig

The working fluid is air with an optional injection of steam. The pressurized air of both streams is throttled and pre-heated with electric pre-heaters (electric power: 3.7 kW) to 200°C, preventing condensation of the injected steam (~150°C). Then the air/steam mixture of stream A und stream B are heated up to 900°C and 750°C by electric main-heaters, each with an electric power of 8 kW, before entering the heat-exchanger to be tested. The air flowrate is measured by one Coriolis flow meter on the Stream B and a mass flow controller on Stream A and can be varied between 0.1-0.8 kg/min. The electric steam generator (total power: 20 kW) provides a maximum operating steam pressure of 5 bar (Saturation temperature: 151°C) and a maximum steam flow rate of 0.5 kg/min, which is measured by two Vortex flow meters. A water softener is used to reduce calcifying in the steam generator.

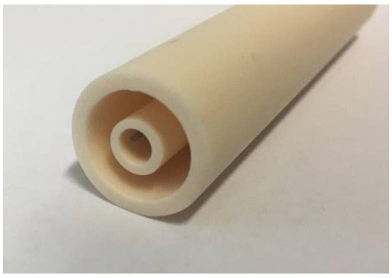

Figure 2. Radiation protection of the thermocouple

The temperatures at the inlet and outlet of the heat exchanger are measured with thermocouples type K. The thermocouples are protected by two ceramic tubes to reduce measurement errors by heat radiation [5], depicted Figure 2. The differential pressure of the hot and cold gas side of the heat exchanger is measured by two U-tube manometers. Figure 3 shows the whole test setup, with stream A on the left, Stream B at the top and in the centre the steam supply unit with control valves and steam flow sensors. On the left side in the front, the two electric power supply units are shown, each powering an electric main heater. Figure 4 demonstrates the insulated heat exchanger, with the cold gas inlet on the left side and the hot gas inlet on the right side (both already connected). The insulation of the fluid in- and outlets of the heat exchanger consists of two layers**.** The first one is a high temperature insulation wool with a thermal conductivity of λ=0.15 W/(m K) (white wool), the second layer is common rock/mineral wool (λ=0.04 W/(m K)) (green wool), see also Figure 3, top left. The heat exchanger is insulated with two layers (each thickness: 25 mm) of a microporous insulation material with a thermal conductivity of λ=0.038 W/(m K).

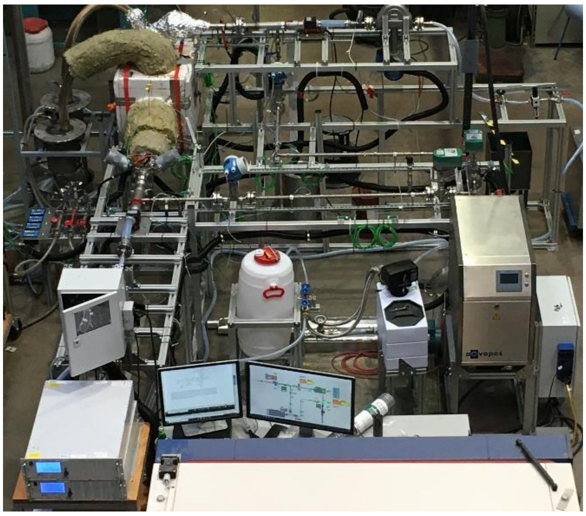

Figure 3. Complete test rig, heat exchanger in the top left

Figure 4. Close up of the insulated additively manufactured plate-fin heat exchanger

The hot- and cold-gas-outlet of the heat exchanger is cooled down by a water injection system, located in the background on the left side in Figure 3.

2.2. Heat Exchanger Details

The heat exchanger tested in this study is an additively manufactured plate-fin heat exchanger in counter-flow configuration, made of a high temperature stainless steel alloy. The heat exchanger has an overall construction volume of less than 7 litres and a maximum length of 370 mm. For the fins, the wavy fin type is used, to ensure high heat transfer coefficients and mechanic stability at high temperatures. This heat exchanger is meant to replace an existing heat exchanger in a fuel cell system for ships applications.

2.3. First evaluation of thermal performance and effectiveness

There are several possibilities to evaluate the thermal performance of the heat exchanger, depending on the specific situation. For a first evaluation we use the effectiveness ε [6], the ratio between the transferred heat flow and the maximum possible heat flow, which can be calculated by Equation (1), with $\dot{m}$ as the mass flow rate and c_p the specific isobaric heat capacity

$$\epsilon = \frac{\dot{Q}_{\mathrm{cold}}}{\dot{Q}_{\mathrm{max}}} = \frac{\dot{m}_{\mathrm{cold}}\, c_{\mathrm{p,cold}}\, (T_{\mathrm{out,cold}} - T_{\mathrm{in,cold}})}{(\dot{m}\, c_{\mathrm{p}})_{\mathrm{min}}\, (T_{\mathrm{in,hot}} - T_{\mathrm{in,cold}})}\ . \quad (1)$$

To get more details on the thermal performance of the heat exchanger, additional test procedures has to be established, like a multivariable Wilson-Plot method for determining the heat transfer coefficients on the hot- and cold gas side. Also, the influence of heat radiation and longitudinal heat conduction on the thermal performance is an important part for the overall evaluation of this heat exchanger and will be a part of a future study.

3. Preliminary test results

The presented set of measured data is for the plate-fin heat exchanger. For these first tests, only air was used as working fluid.

The first tests were carried out with four different mass flow rates on the cold side, while the hot mass flow rate was kept constant. The inlet temperatures were held constant at 750°C for stream A and 250°C for stream B. Figure 5 indicates the corresponding in- and outlet temperatures and Figure 6 shows the effectiveness ε.

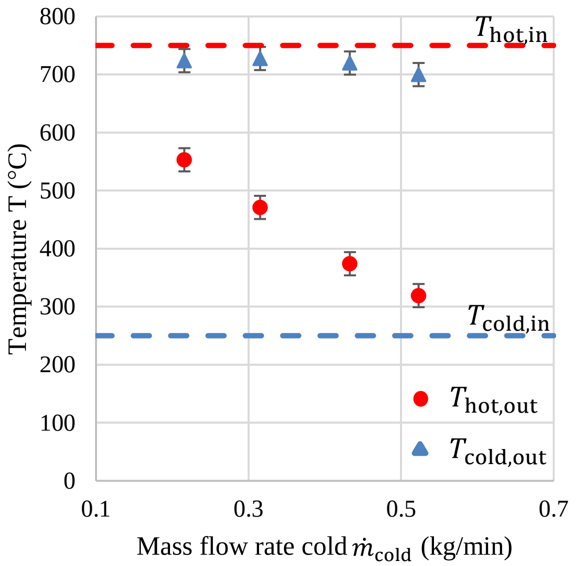

Figure 5. Outlet temperatures for different cold mass flows

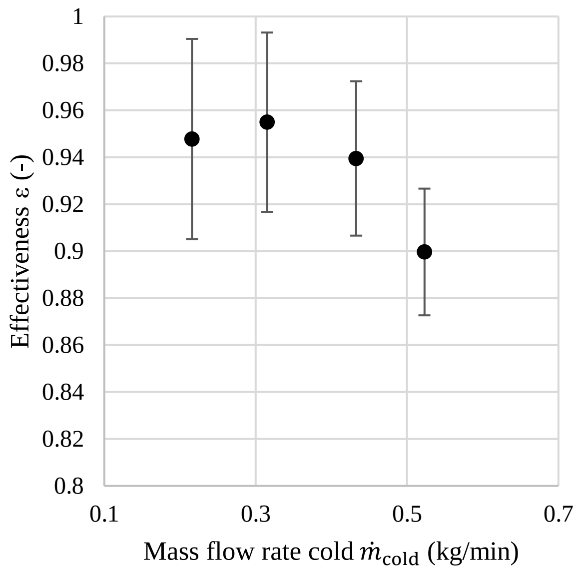

Figure 6. Effectiveness ε of the plate-fin heat exchanger for different cold mass flows

With increasing cold mass flow rate, the ratio of the heat capacity rates approaching a value of 1, and therefore the hot outlet temperature is decreasing continuously (see Figure 5). The cold outlet temperature at 0.2 kg/min is slightly lower than expected due to uncertainties in the temperature measurement. Due to the reduced velocity, the heat transfer from the air to the thermocouple pin is smaller than for the previous cases and therefore, the influence of heat radiation on the thermocouple, despite the "double radiation shield", is increased, leading to higher errors in the measured temperature. The pressure loss ranges between 11-15 mbar on the hot side due to changes in mean temperature and on the cold side the pressure loss differs between 4-9 mbar. The effectiveness of the heat exchanger ranges between 0.9 and 0.955 and is decreased with higher cold mass flow rate. As a consequence of the higher error in temperature measurement at 0.2 kg/min, the effectiveness is smaller than for the next higher mass flow rate. Overall, the additively manufactured heat exchanger offers a high effectiveness over a large mass flow range, also for high temperature applications.

4. Conclusion

First measurements with a new test rig for compact high temperature heat exchangers were carried out. The first test was done with a 3D-printed counterflow plate-fin heat exchanger with wavy fins on the hot and cold side. A maximum inlet temperature of 750°C for the hot air stream was chosen for the first test runs, the cold air stream was heated up from 250°C at the heat exchanger inlet to 700-727°C at the outlet, depending on its mass flow rate, resulting in an effectiveness ε of 0.9 or higher.

Overall the test rig offers the necessary variability in flow rates and temperature levels. Also, the measurement procedure of the temperature at high temperature levels meets the desired requirements, although a minimum mass flow rate is necessary, to ensure a valid temperature measurement.

With more test data in the future and ongoing experiments, the multivariable Wilson-Plot method will be applied for determining the heat transfer coefficients of both streams, and further investigations of the influence of longitudinal heat conduction and heat radiation on the heat exchanger thermal performance will be conducted.

Acknowledgement
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