3D-Printed solar cavity receiver for heating pressurized air – A preliminary evaluation

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Abstract:

High-temperature solar receivers experience non-uniform solar flux, which induces thermal stress in the receiver tubes. This stress is more pronounced in gas solar receivers due to the lower thermal conductivity of gases. To address these limitations, this paper introduces a novel 3D-printed solar receiver featuring a conical cavity and a honeycomb lattice structure. The design integrates a double helix heat exchanger with a tear-drop cross section to reduce thermal stress, enhance optical performance. Manufactured using Direct Metal Printing (DMP) with Nickel superalloy Inconel 718, the receiver is designed for high-temperature and high-pressure applications. Simulation results, conducted using Ansys-Fluent and an in-house code, demonstrate the temperature distribution, pressure drop, and outlet temperature variations as a function of heat flux and air mass flow rate. The findings indicate that the receiver can operate under a maximum heat flux density of 230 kW/m², corresponding to the maximum working temperature of Inconel 718 (1000°C), with minimal pressure drop, making it a promising solution for mitigating thermal stress in solar receivers.

Keywords: solar receiver, 3D printing, Concentrating solar power, cavity receiver.

1. Introduction

High temperature solar receivers are subject to a non-uniform solar flux. The heat flux along the tubes is non-linear, with circumferential variations [1]. The higher heat flux causes greater temperature gradient [2], which induces thermal stress [1,2].

Indeed, a limiting factor to heat flux is thermal stress in the heated receiver tubes on account of the temperature difference between irradiated front and concealed back tube side, observed as a bending moment along the axial or longitudinal coordinate direction [3]. The temperature difference between the front and back side of the tube is higher for the case of gases than for the case of molten salt because of the low thermal conductivity of gases. Thus, it is important to introduce an innovative solution that reduces or eliminates the thermal stress in high temperature solar receivers.

This paper aims to address these practical limitations by proposing a novel, first-of-its-kind, metal 3D printed solar receiver. The receiver includes a conical cavity surrounded by honeycomb lattice structure. Pressurized air is heated in the receiver using a double helix heat exchanger with a tear-drop shaped cross-section. The honeycomb structure provides many advantages:

- increases the optical performance of the receiver,
- allows the radiation to reach the back of the helical tube,
- and allows the helical tube to extend freely and thus eliminated the thermal stress on the helical tube.

2. Design and Manufacturing

The receiver, as show in figure 1, was designed as a tubular cavity type, for heating pressurized gases. The cavity has a conical geometry, housing a double helix heat exchanger within a honeycomb lattice structure. To ensure 3D printing compatibility, the heat exchanger tubes have a tear drop cross section. The honeycomb lattice is divided into three sections, with decreasing pore sizes towards the walls. This design aims to improve thermal, optical and mechanical performance of the solar receiver. Additive manufacturing of the receiver was done using Direct Metal Printing (DMP) / L-PBF technology with the DMP Flex 350 Dual Laser Machine. For the material, Nickel superalloy Inconel 718 (LaserForm Ni718) was used due to its high melting point and ability to withstand high pressure. Post-printing, Homogenization with double aging (HAA) heat treatment was also carried out to ensure high temperature heat resistance. Figure 2 shows the solar cavity receiver.

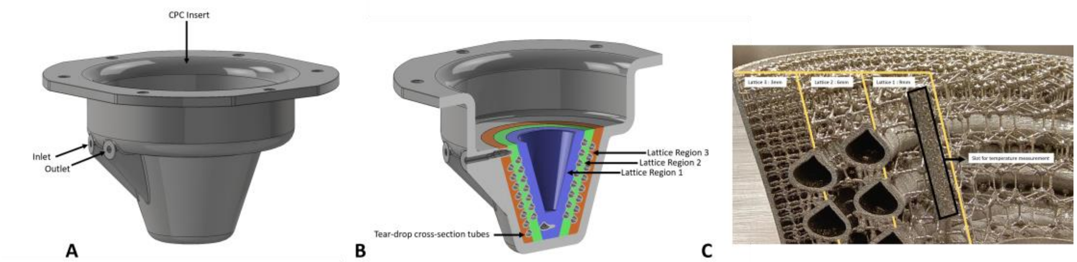

Figure 1: 3D design of the solar cavity receiver.

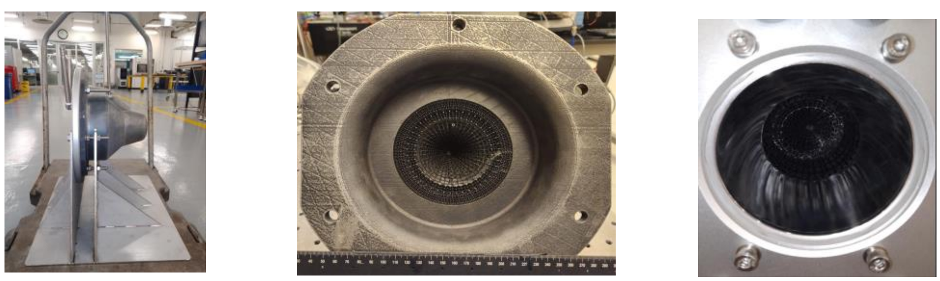

Figure 2: Pictures of the solar cavity receiver. CPC-receiver assembly mounted on the support (left), front of the solar cavity receiver without (middle) and with (right) the CPC.

3. Results and Discussion

Figure 3 (left) shows the temperature distribution of the air for an air mass flow rate of 0.002 kg/m^2 and heat flux of 300 kW/m^2. The results are obtained using Ansys-Fluent. Figure (right) shows the pressure drop in the helical tube. As can be seen the pressure drop is low (about 170 mbar)

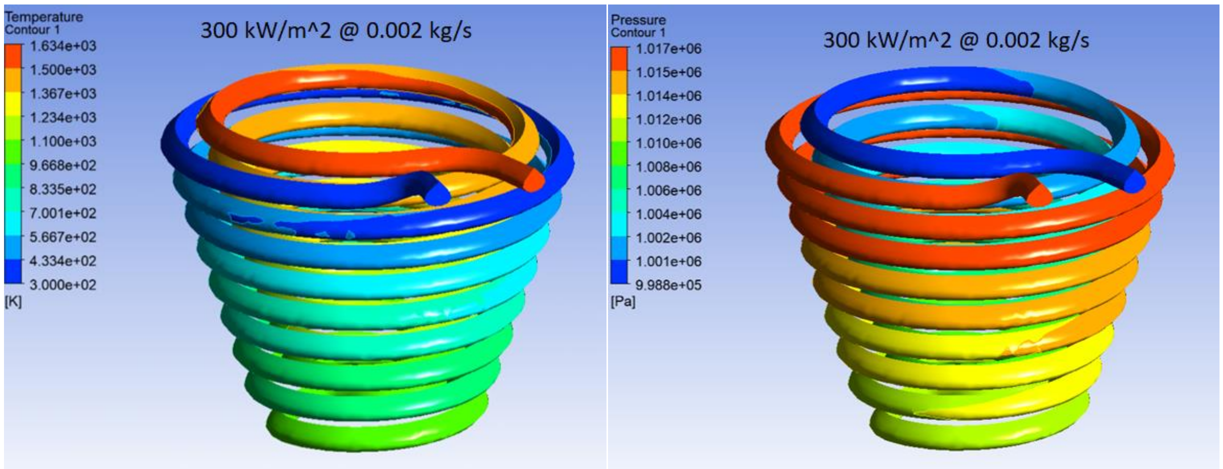

Figure 3: Temperature (left) and pressure drop (right) along the helical tube of the solar receiver.

Figure 4 (left) shows the variation of air outlet and wall temperatures as a function of heat flux on the cavity of the receiver for an air mass flow rate of 0.002 kg/m^2. The results are obtained using an in-house code. The maximum heat flux density on the cavity that corresponds to the maximum workning temperature of Inconel (1000C) is about 230kW/m^2. Figure 4 (right) illisurates the variation of outlet temperature as a function of mass flow rate.

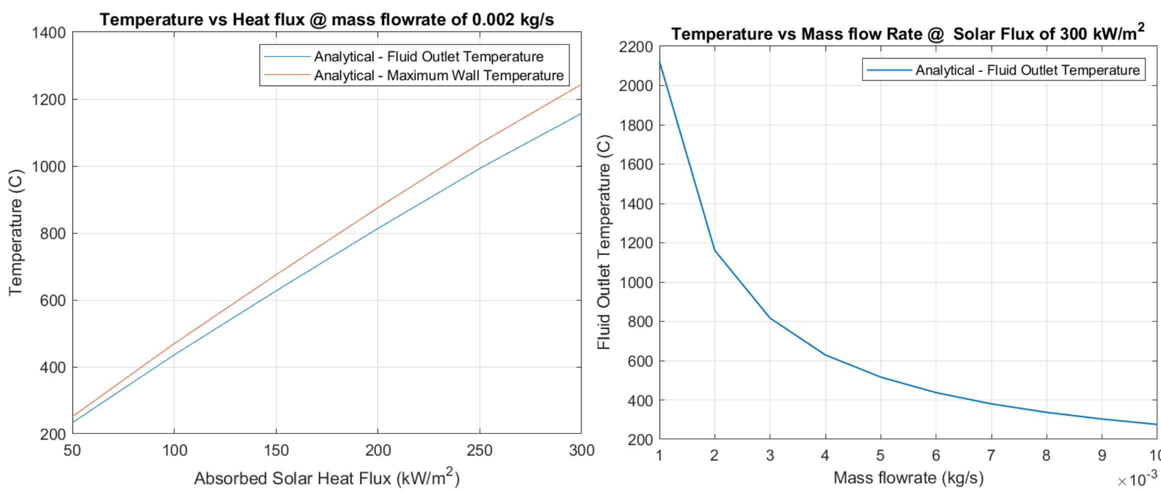

Figure 4. Variation of the air outlet temperature as a function of absorbed heat flux (left), Temperature vs. mass flow rate (right).

4. Conclusions

This study presents a novel approach to addressing the thermal stress limitations of high-temperature solar receivers by using a 3D-printed receiver with a conical cavity and honeycomb lattice structure. The innovative design, which incorporates a double helix heat exchanger with a tear-drop cross section, not only reduces thermal stress but also enhances the optical and thermal performance of the receiver.

Simulation results indicate that the receiver operates efficiently at a maximum heat flux density of 230 kW/m², corresponding to the maximum working temperature of Inconel 718 (1000°C), while maintaining a low pressure drop of approximately 170 mbar. The design allows for significant improvements in temperature distribution, particularly in gas-based receivers where thermal stress is more pronounced due to lower thermal conductivity.

Future work will focus on further experimenting, optimizing the design, and exploring its potential in large-scale applications.

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