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Transient performance of an impinging receiver: An indoor experimental study

Wujun Wang*, Anders Malmquist, Lukas Aichmayer, Björn Laumert

Department of Energy Technology, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden

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ABSTRACT

The impinging receiver is a new member of the cavity solar receiver family. In this paper, the transient performance of a prototype impinging receiver has been studied with the help of a Fresnel lens based solar simulator and an externally fired micro gas turbine. The impinging receiver can offer an air outlet temperature of 810 °C at an absorber temperature of 960 °C. The radiative-to-thermal efficiency is measured to be 74.1%. The absorber temperature uniformity is good but high temperature differences have been detected during the 'cold startup' process. The temperature changing rate of the receiver is within 3 °C/s for the startup process and 4 °C/s for the shut-down process. In order to avoid quenching effects caused by the impinging jets, the micro gas turbine should be turned off to stop the airflow when the radiative power is off.

1. Introduction

Solar hybrid Brayton systems have great potential in offering stable power outputs independent of solar energy variations with higher solar shares than any other concepts (up to 100%) [1,2], and higher thermal-to-electric net annual average conversion efficiencies by being combined with Rankine cycles [3] or Stirling cycles [4]. In a typical solar hybrid dish-Brayton system, the receiver is integrated into the compressed air circuit of the gas turbine, between the recuperator and the combustor [5]. The compressed air is firstly preheated by the recuperator, and then heated to an elevated temperature by the absorbed solar radiation and the fuel combustion for powering a turbine. Due to the pre-heating of the compressed air, the fuel flow in the combustion chamber can be controlled rapidly, allowing the combustor to compensate for rapid variations in the solar heat input and thus to maintain stable operation of the gas-turbine [6]. At the moment, the gas-turbine technology is more mature than the solar collection and conversion technologies, so developing more efficient solar collectors and receivers is crucial for enhancing the competitiveness [7]. Solar receivers, where the concentrated solar irradiation is absorbed and transferred to the working fluid, is one of the limiting components for such a solar hybrid dish-Brayton system. It has to sustain a high light flux as well as operate under high temperature (1000–1600 K) and high pressure (3–30 bar) over long periods [8].

Recently, in the authors' previous work, a new type cavity receiver (impinging receiver) has been developed by introducing jet impingement technology for taking the heat efficiently from the absorber and managing the heat flux peak on the absorber surface [9,10]. In a typical impinging receiver, round orifices/nozzles are distributed evenly in the circumferential direction (can be single row or multi row [11]) above the peak flux region on the cylindrical absorber accurately with the help of an inverse design method [9]. Earlier, cavity receivers were mainly designed based on forced convection heat transfer which is difficult to adapt to manage the peak flux region efficiently, and significant temperature peak have been detected in the receiver designs published by Strumpf et al. [12], Hischier et al. [13], Hathaway et al. [14], Le Roux et al. [15] and Daabo et al. [16]. Thanks to the high heat transfer efficiency offered by the jet impingement array, numerical studies have shown the ability and the potential of the impinging receiver in improving the temperature uniformity on the absorber surface and minimizing the temperature difference between the absorber and the outlet air, which are two of the most important parameters for the performance of a cavity receiver [10]. Moreover, the radiative-to-thermal efficiency of an impinging receiver can reach 82.7% at an outlet air temperature of 800 °C and a DNI level of 800 W/m^2 [11] which is competitive when compared with the efficiencies of other cavity receivers in recent publications by Le Roux et al. [15], Qiu et al. [17], Pozivil et al. [18] and Zou et al. [19]. Unlike the traditional high temperature volumetric receivers which feature brittle ceramic porous materials and quartz glass window [20], the impinging receiver can be designed with only using high temperature alloy. Hence, the risk of the ceramic debris from the absorber damaging to the high speed gas turbine can be avoided. However, as a new impinging receiver concept, the information obtained by the numerical study is far insufficient.

* Corresponding author.
E-mail address: wujun@kth.se (W. Wang).

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Nomenclature

C_p	heat capacity (J/(kg·°C))
I	current (A)
$\dot{m}$	mass flow (kg/s)
Q'	power (W)
t	time (s)
T	temperature (°C)
U	voltage (V)

Greek

η	efficiency

Subscripts

abs	absorber
air	compressed air
b	xenon bulb
e	electrical
e-r	electrical to radiative
in	inlet
lamp	xenon lamps in the solar simulator
loss	energy loss
min	minimum
max	maximum
out	outlet
rad	radiative
r-t	radiative to thermal
sol	solar

Abbreviations

CSP	concentrated solar power
DC	direct current
DN	nominal diameter
DNI	direct normal irradiance
EFMGT	externally fired micro gas turbine
HFSS	high flux solar simulator
KTH	Royal Institute of Technology
MGT	micro gas turbine
SOG	silicone on glass

Hence, more experimental investigations are required in the future for evaluating the performance of the impinging receiver in the real application.

Due to the natural intermittent characteristic of the solar irradiation (mainly caused by local weather, such as clouds, fog, sand storm, etc.), a receiver usually has to work under a rapid change in heat flux boundary conditions [21]. Then, the absorber surface will experience a quick change in temperature which might cause a severe thermal shock, especially for an air receiver which has relative low heat capacity [22]. A latest study shows that the life time of a pressurized-air receiver under a cycling load could be only less than 1/3 of its life time under a steady load [23]. Moreover, for a hybrid dish-Brayton system, the rapid change in heat flux could also cause significant fluctuations in thermal power input and turbine inlet temperature, which would cause challenges in controlling the turbine and the combustor for a hybrid system [24]. These response characteristics are important in improving the future receiver design, developing the control system for the turbine [25] and enhancing the total efficiency of the hybrid system [26]. Due to the heat capacity and the heat transfer efficiency of the receivers, the response characteristics could vary for different receiver designs [27]. Hence, the transient performance test is critical to a receiver, especially to a high flux and high temperature air receiver.

In this paper, the transient performance of a prototype impinging receiver (originally designed for the EuroDish [28]) has been studied with the help of a Fresnel lens based high flux solar simulator (HFSS) at KTH [29]. An externally-fired micro gas turbine (EFMGT), a product from Compower® [30], is used for offering compressed air flow with a controllable mass flow and receiver inlet temperature. Due to the radiative power limitation of the HFSS, the required absorber temperature and receiver outlet temperature are achieved by reducing the mass flow. The temperature uniformity on the absorber is studied by comparing the temperatures measured at different positions on the absorber. In order to minimize the impact from the thermal shock, the temperature changing rate on the absorber is also investigated. Furthermore, the energy losses (heat losses and optical losses) of the receiver at its working temperature is obtained. Since the absorber

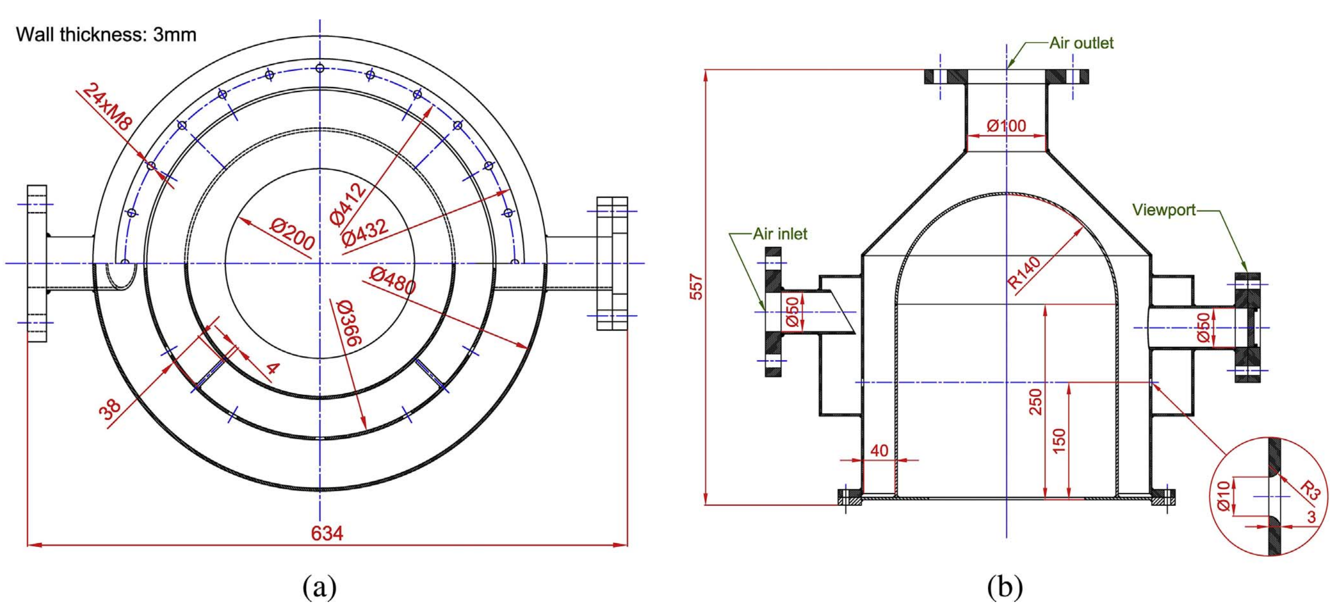

Fig. 1. Schematic of the prototype impinging receiver (D280L350t3d10n12): (a) front view; (b) top view.