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Numerical investigation of a ceramic high-temperature pressurized-air solar receiver

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Abstract

The focus of this paper is on the characteristics (in terms of pressure loss and heat transfer) of an isothermal turbulent flow inside the absorber of a solar receiver. After a short description of the receiver and the power plant, we will focus on a certain kind of internal geometry: straight fins. A preliminary study based on correlations will be presented. This study allows us to define the optimal configuration of the absorber. Following that, a more detailed analysis – based on 3-D simulations – of an elementary component of the absorber is made in order to understand the physical phenomena taking place in the channels. Two simulation methods, Reynolds Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES) are used in order to determine precisely the characteristics of the flow inside the absorber. A comparison between all the models is carried out. It appears that the correlations do not exactly match the simulation results for all types of flow. However, even if the correlations cannot accurately describe the physics of the flow for this type of flow, the results of the simulations show that the studied solar absorber geometry allows reaching the targeted outlet temperature with an acceptable pressure drop.

Keywords: Solar receiver; Absorber; High temperature; Numerical simulations; Fluid mechanics; Turbulence

1. Introduction

Renewable energy involves natural phenomena such as sunlight (solar energy, biomass, hydropower and wind power), tides (ocean energy) and geothermal energy. The Concentrating Solar Power (CSP) technology is a way of producing electric power by converting sunlight into heat at high temperature using various mirror configurations. For example, the power tower system uses numerous sun-tracking mirrors to focus sunlight on a receiver at the top of a tower. The heat is then channeled through a conventional generator. The plants consist of two parts: one that collects solar energy and converts it into heat, and another that converts heat energy into electricity. One distinctive feature of this technology is the possibility of storing heat, which enables you to supply electricity regardless of the weather conditions.

At present, the CSP technology allows us to achieve the greatest efficiency for producing electricity using solar energy, even if this efficiency does not exceed 20% (Schwarzbozl et al., 2002) over the course of 1 year. The key to increase this efficiency is to increase the temperature of the working fluid: the higher the temperature at the outlet of the solar receiver, the greater the efficiency of the power plant. For example, an installation with a receiver outlet temperature that reaches 1500 K could have a global efficiency of 40%. Our goal is to reach an outlet temperature of about 1300 K.

The conception of the receiver, that is the device that absorbs concentrated solar energy and transmits it to the

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working fluid, is essential for increasing the efficiency of the power plant. There are two principal kinds of receivers: open receivers and pressurized receivers. With open receivers, air is pumped into the receiver from the outside through a porous structure at ambient pressure (PROMES. PEGASE). As it is technically difficult to compress a gas which quickly reaches a high temperature, we focus our interest on the technology involving pressurized receivers.

The volumetric receivers could be distinguished from other receivers in the pressurized branch. In both cases, the fluid flows into the receiver while under pressure (between 10 and 20 bar). Even if – for the volumetric receiver – the fluid is separated from the outside by a transparent shield window, it operates on the same principle as an open receiver: the fluid flows through a porous structure, which is irradiated by the sun. The main drawbacks of this shield window – that allows us to work with a pressurized fluid – is the fact that it is very fragile and very expensive. Even if this is currently the leading technology for plants using a gas cycle (Jakob, 1949), thermal shocks should be avoided and the smallest stain can lead to the overheating and thus destruction of this window. Therefore, the development of a high-pressure receiver without any shield window is very attractive.

The PEGASE scheme (PEGASE stands for “Production of Electricity from Gas and Solar Energy”), a 1.4 MW_{el} experimental 3rd generation pilot power plant – built on the site of the former power plant THEMIS (Targassonne, France) – will employ this kind of receiver. This plant, using a hybrid solar gas turbine at high temperature is expected to reach a great solar-to-electricity efficiency (from 25% to 30%, PROMES. PEGASE) and low electricity production costs thanks to a “cheap” power block (see Fig. 1). Ambient air is sucked in by this power block, consequently compressed and heated up. For this process, the main part of the heat comes from concentrated solar radiation but, if necessary further heating could be provided by a combustion chamber (passing of clouds). The hot compressed air then expands in the gas turbine; mechanical energy is recovered for the generator to produce electricity and before the air is released a certain amount of waste heat can be recuperated. Another advantage of this technology is its reduced water consumption.

In order to work with the expansion turbine, the receiver must accept a total mass flow rate of about 7 kg/s at a 10 bar working pressure. The total irradiated area of the receiver is about 20 m^2. A fraction of the fluid circulates in parallel in each stage (see Fig. 2) of the absorber; if the number of stages increases, the mass flow rate in the stage and the average speed decrease, leading to a reduction of the pressure drop in the receiver. For the receiver, a compromise between low pressure drop and good heat transfer needs to be reached. In order to minimize the pressure drop, the number of stages should be greater than one. For the whole receiver, the pressure drop should not exceed 250 mbar (limitation due to the compressor of the THEMIS power plant).

The studied absorber, located at the bottom of the cavity of the receiver, looks like a box (total irradiated area of about 20 m^2) irradiated by the concentrated sunlight on one of its faces (see Fig. 2) and traversed by the working fluid. This square parallelepiped, with a length of 4.5 m and an inside thickness of 10 mm, is divided into stages, panels where the air flows in parallel sharing a common outlet (see Fig. 2, which shows a two stage absorber). Due to manufacturing constraints, each of these stages is itself divided into modules (see the grey parallel panels in Fig. 2). As the required outlet temperature is quite high, a ceramic that withstands high temperatures (Silicon carbide, SiC) was chosen as the material for absorber and its internal geometry has to be designed so as to allow for high heat transfer. Therefore, we either have to increase the heat transfer coefficient (enhancement of the fluid turbulence intensity) or enlarge the heat exchange area.

One of the more basic geometries that works for both of these targets simultaneously is the channel with straight fins. In Fig. 2, a module with two channels delimited by straight fins (the wall of the lateral channel) is portrayed. The presence of straight fins indeed increases the exchange area and, by decreasing the stream section, straight fins would also increase the average speed of the fluid as well as the heat transfer coefficient. The presence of straight fins

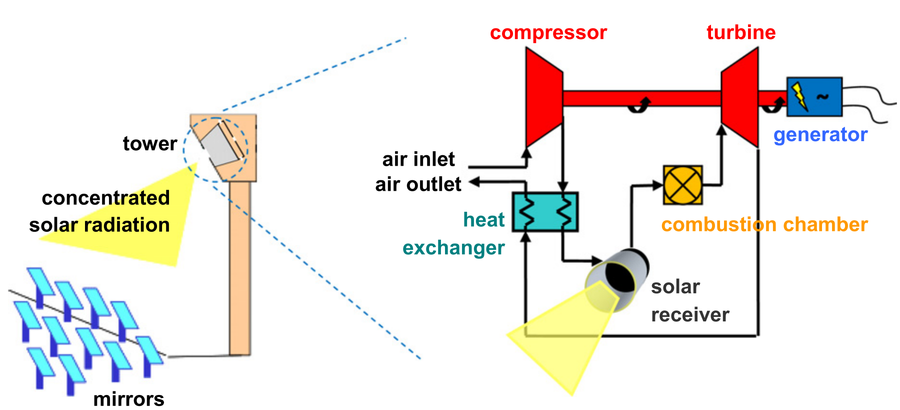

Fig. 1. Schematic view of the PEGASE scheme with details of the power block.