Analysis of thermal losses for CSP applications

Analysis of thermal losses for CSP applications: Abstract

Renewables technologies are expected to play a key role in the future energy scenario because of the environmental impact linked with the use of fossil fuels. Among the renewables technologies, the Concentrated Solar Power (CSP) is very promising because of the abundant solar resource available that exceed several times the current world energy demand and because of the possibility to storage the thermal energy providing dispatchable power.

This thesis focuses on the thermal-hydraulic analysis of the solar receiver in the context of the CSP technology. Particularly, this work aims at evaluating numerically with high accuracy the heat losses mechanisms that lower the receiver efficiency increasing in this way the Levelized Cost Of Electricity (LCOE) of the CSP technology. Several receiver typologies have been proposed during the years depending on the specific kind of CSP system.

The numerical multiscale approach adopted to predict the thermal-hydraulic behavior of those receivers consists in studying the receiver both at the component and at the system level. At the component scale, a detailed Computational Fluid Dynamics (CFD) analysis of the receiver is conducted in order to derive constitute relations to be exploited at the system-level scale. The latter represents the scale of interest for the analysis of the receiver under steady-state and transient conditions; however, a detailed analysis at this scale is unrealistic because of the huge computational cost. For this reason, the system-level model is developed as a simpler and computationally cheaper lumped-parameter model, whose accuracy is ensured by the fact that it is based on the thermal-hydraulic characterization performed at the component scale by means of a detailed analysis.

First, the multiscale modular approach was applied to an open volumetric receiver of the honeycomb-type, which consist of a matrix of equal cups that are in turn made of thousands of prismatic channels. At the micro-scale (single-channel), an optical ray-tracing analysis was combined with a steady-state 3D CFD model. A parametric analysis was conducted at the micro-scale, which indicates that increasing the porosity allows enhancing the receiver performance. At the meso-scale, the cup has been modeled as a dynamic 1D porous medium model in the Modelica language, which has been characterized from a hydraulic (friction factor) and thermal (HTC) point of view exploiting the results of the micro-scale single channel model. The macro-scale receiver model has been finally modularly generated as a matrix of cups model, which are thermally coupled by means of the air gap that divide neighboring cups. This model allows simulating the full receiver considering the air return flow and the non-uniform heat flux distribution with an acceptable computational cost. This model was used to investigate the effect of the air return ratio on the receiver performance, which increases as the air return ratio increases. In addition, a transient scenario, consisting of a fast passing cloud, was analyzed proving the capability of the model of providing reasonable results also in the case of unsteady conditions.

The sodium-cooled billboard receiver has been studied at the component and at the system-level. At the component-level, a 3D CFD analysis of the external air flow was conducted to accurately assess

the convective and radiative heat losses. The CFD model allows considering the actual receiver shape, including the external structure equipped with later wings and a top overhang that leads to a semi-cavity behavior. This analysis allows concluding that the external structure acts as a cowling and determines a reduction of the convective heat losses of about 25%. A parametric study has been also conducted considering different wind speeds and directions. This study indicates that both the wind speed and the direction affect significantly the convective heat losses; however, the total heat loss is always dominated by the heat transferred by radiation to the external ambient. At the system-level scale, a dynamic lumped-parameter model was developed in the Modelica language. The system-level has applied to transient scenarios and it has been combined with the CFD model by means of an iterative procedure in order to accurately simulate both the internal and the external flow.

Finally, two receiver configurations based on the encapsulated tube (simply encapsulated and evacuated) were numerically compared considering different ambient conditions (wind, DNI and sun position) in terms of thermal performance. The entire receiver length is simulated thanks to the low computational cost of the system-level model, which allows quantifying the benefit of using the evacuated tube for the pilot plant considered as a reference in this study. Particularly, the latter performs only slightly better than the simply encapsulated one as a consequence of the relatively low temperatures (< 573 K) reached by the working fluid, which lead to very low heat losses that represent only a small share of the absorbed heat.