THERMODYNAMIC APPROACH TO THE OPTIMIZATION OF CENTRAL SOLAR ENERGY SYSTEMS

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1. Introduction

The sun is equivalent to a 5800 K thermal reservoir. If we should be capable to concentrate the sun light on the earth, close to the thermodynamic limit and to use its power almost without losses, we should obtain the most powerful thermal engine with a fantastic efficiency of more than 90%. Unfortunately this seems to be impossible and we must be content with much less. Only a minute process of optimization of all the system components that take the solar energy and transform it in a transportable energy form (i.e. electricity) will increase the actual (rather) low efficiency and will transform it in a competitive efficiency comparative with the non-renewable energy process efficiencies. The central solar energy systems seem to be unique qualified of efficiently producing of high temperatures capable to achieve high thermodynamic efficiencies and therefore the future looks to be more promising for the central receiver (or solar tower) concept. This work is dedicated to an attempt to optimize a central solar energy system from the thermodynamical and optical points of view.

The overall efficiency of a such system is the product of its subsystem efficiencies' components. A central receiver system is composed of a few subsystems: optical collector subsystem, thermal receiver (mounted in a tower or, its challenger, the ground receiver that uses a tower reflector [1, 2]) and final conversion subsystem. Design of this system essentially involves determining the sizes, types and configurations of each of the subsystem's components that would maximize a certain performance criterion (and/or minimize a certain cost criterion) while satisfying the technical specifications and performance requirements. For this central solar receiver system, the computationally feasible approach is to decompose the system and to design each subsystem separately. In that sense the overall system efficiency $\eta_{overall}$ is the product of three subsystem efficiencies:
\[ \eta_{overall} = \eta_{opt}(C) \cdot \eta_{rec}(C,T_{rec}) \cdot \eta_{ph}(T_{rec}, \rho_T) \] (1)

where \( \eta_{opt} \) is the efficiency of the reflecting and concentrating optical components (primary and secondary; \( \eta_{rec} \) is the efficiency of the conversion of sunlight to heat in a receiver and \( \eta_{ph} \) is the efficiency of the conversion of heat to electricity (or mechanical work) in the power block. As is seen in the previous relation, the subsystem efficiencies are interdependent on three main design parameters: the concentration ratio \( C \), the receiver average temperature \( T_{rec} \), and gas turbine pressure ratio \( \rho_T \) (when the power block is based on a gas-turbine as will be discussed further). In a first approximation, as the concentration \( C \) is increased, \( \eta_{opt} \) decreases and \( \eta_{rec} \) increases; as the receiver average temperature \( T_{rec} \) is increased, \( \eta_{rec} \) decreases and \( \eta_{ph} \) increases. The efficiency of the optical subsystem, \( \eta_{opt} \) commonly decreases with concentration, since achieving a high concentration usually requires special devices (secondary concentrators) which will introduce their proper losses due to the imperfections of these devices, inherent absorption, back reflections and so one. Ignoring these losses and considering an ideal machine which converts the heat in the mechanical work, (i.e. \( \eta_{opt} = 1 \), \( \eta_{ph} = \eta_{Carnot} \)) Fletcher [3] represented the combined effect of temperature and concentration on the overall system efficiency. He found that this efficiency increases with concentration ratio, with an optimal temperature for each concentration.

Further we will define and will analyze the possibilities (and the limits) for the optimization of the three principal subsystems: the primary concentrator (heliostat field), the receiver together its concentrator (secondary/receiver concentrator) and power block system (from the thermodynamic point of view only).

2. The Optimization of the Collector Field Layout

From all subsystems component a central solar plant, the most expensive item is the collector subsystem. It composed of an individually sun tracking mirrors (heliostats) that continuously tracks the sun during daylight hours so that the specular component of incident direct beam solar radiation is reflected to a common single aim-point or to multiple aim-point array. In the aim-point, either cavity or external receivers can be placed. An advanced configuration, having a hyperboloidal mirror with one of its foci in the aim point of the collector subsystem to reflect the concentrated radiation to the ground, is also a possible optical configuration for a central receiver system [1, 2, 4]. It is therefore economically important to optimize this subsystem and minimize the number of heliostats.