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Modelling of the receiver transient flux distribution due to cloud passages on a solar tower thermal power plant

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Abstract

As more and more solar tower thermal power plants are being operated, built or planned, effort is put both on the development and research to bring costs down and increase the plant efficiency. In those plants, the central receiver is one of the key components, accounting for a large investment share. Receivers have to sustain strong thermal stresses caused by irradiation transients, mainly due to cloud passages. To avoid premature failures, increase the receiver cyclic life, and allow longer daily operation periods, an anticipation of the most likely or the worst situations is required. First the calculation of the receiver incident flux distribution is performed, second the cloud and cloud passage characteristics are identified for a given location, third the most likely case is simulated by covering and uncovering the heliostat field, then a worst case configuration is presented, and finally a strategy for the start-up/shut-down of the heliostats is proposed. The value of terms such as the heat flux peak, the maximal flux gradient, the fastest flux transient and total power transients are needed to choose the control strategies regarding heliostat orientation and the receiver operation, as well as the elimination of some bad plant layouts during the design phase.

Keywords: Solar tower thermal power plant; Central receiver system; Cloud passage; Receiver flux distribution; Transients

1. Introduction

As the list of solar thermal power plants under construction or under planning is growing in sunny regions such as South Spain, North Africa, and California, the assessment and the optimisation of their performance is a continuous process required to further improve competitiveness with both conventional and other renewable-based power plants.

Amidst concentrating solar power (CSP) technologies (mainly trough, Fresnel and dish collectors), solar tower thermal plants are expected to reach levelised electricity costs below 10 USct/kW h_{el} (Sargent & Lundy, 2003) on the long-term. Looking at a solar tower facility, the central receiver is a key component both on the cost issue and on the operation issue: the receiver accounts for about 15% of the total investment costs (Pitz-Paal et al., 2003), while the receiver materials undergo transient irradiation intensity that cause strong thermal stresses and may lead to fatigue and failure before the expected number of thermal cycles.

The most common reason for incident flux transients is the intermittent passage of clouds on the heliostat field, and the available literature divides the analysis into five aspects: the modelling of clouds and their passage on the heliostat field, the control strategy of heliostats, the control strategy of the receiver and its testing, the overall plant dynamic modelling and operation strategy, and the regenerative short-term storage of heat in the primary receiver loop.

Among examples of cloud models study, a shadow model was proposed by Aerospace (1978) in the late

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Nomenclature

Acronyms
CSP concentrating solar power
DNI direct normal irradiation
erf error function

Greek
ϵ efficiency
η transformed y-coordinate
ω angle of incidence
σ standard deviation
ξ transformed x-coordinate

Roman
a transformed heliostat dimension
D distance
H height
t time step
W width
x x-coordinate
y y-coordinate

Superscripts
i heliostat index
$'$ rotated coordinates

Subscripts
1 width
2 height
Aim aim
Atten attenuation
Block blocking
Cos cosine
e effective
el electric
Hel heliostat
Rec receiver
Refl reflection
r on the receiver plane
Shad shadowing
Slope slope (curvature, waviness, alignment, gravity)
Spill spillage
Sun sun
Track tracking
th thermal

seventies: a cloud was defined by its type, area, shape and velocity, and was combined with a cloud-to-cloud spacing, a probability of occurrence, and a worst case situation. Later on Karg et al. (1982) confirmed that these characteristics largely determine the receiver incident power, and stated that increasing the mirror field can make the power station much less sensitive to changes in clouds. More recently, a methodology was proposed by Kroyzer (2011) to define images representative of cloud shadows in order to determine shading parameters and adjust plant operation.

Coming to the control strategy of heliostats, the detection of cloud passage by heliostats groups was presented by Eugene Moeller et al. (1980) in 1980: after detection, heliostats were directed to standby points, and then returned to their original orientation after passage in a controlled manner. More than 20 years later, López-Martínez et al. (2002) submitted the anticipation of cloud presence: after computing a field cover factor, several heliostats are ordered to turn away so that the receiver temperature can decrease before the cloud covers the sun, and in that way prevent from potential rupture by thermal stress.

Moving onto the receiver control strategy and testing, the key factors for the receiver fatigue and creep characteristics were identified even earlier: in 1976 for instance, Sobin et al. (1976) investigated the design of the receiver thermal cyclic life, reaching several hundred thousand cycles. They addressed the receiver irregular shapes due to changes in expected flux by timely sensing and controlling the energy intensity. Subsequently, McDonnell (1978) and Lowrie (1979) performed tests on a pilot plant including intermittent cloud conditions to determine transient characteristics. Six years later, Maffezzoni and Parigi (1982) presented a dynamic analysis and control of the receiver under flux variations, and concluded that the successful operation could only be met by controlling the steam pressure instead of operating with floating steam pressure. Then in the early nineties, Pritzkow (1991) described the quick reaction of the receiver during simulated clouds by opening and closing an attenuator, and similarly almost 20 years later Andrade da Costa and Lemos (2009) established an adaptive temperature control law thanks to a shutter test.

Regarding the plant dynamic modelling and the definition of overall operation strategies taking clouds into account, some theoretical studies date back to the seventies: mathematical models and computer programs comprising time-dependent irradiation and dynamic simulation, such as affected by cloud passages, were presented by Honeywell (1977).

Finally, heat storage within the receiver primary loop turns out to be solving a series of problems during solar transients caused by clouds: as proposed by Fricker (2004) and as already demonstrated in some existing receiver facilities, a regenerative thermal storage unit can supply hot fluid until the solar irradiation returns or a controlled plant shut-down is performed.