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Numerical study on thermal stress and cold startup induced thermal fatigue of a water/steam cavity receiver in concentrated solar power (CSP) plants

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ABSTRACT

The high temperature receivers in CSP plants should startup frequently, so the thermal stress and the fatigue failure are critical important for its safety and stability. In our present study, a computation model is proposed for a water/steam cavity receiver in CSP plant. The model couples the light propagation, the light-heat conversion, the thermo-elasticity and the thermal fatigue analysis together. Monte Carlo ray tracing method (MCRT), finite volume method (FVM) and boiling heat transfer are coupled to get the thermal boundary of the boiling panel. Finite element method (FEM) is adopted to obtain the temperature and stress–strain distribution of the boiling panel. Elastic stress analysis and equivalent stress fatigue assessment method is used to investigate the fatigue failure of the boiling panel. Two different structures of the boiling panel are researched, following results are obtained: The heat flux on the boiling panel is highly non-uniform and it results in the similar non-uniform distributions of temperature and stress-strain as well as the displacement of the boiling panel. The non-uniform stress-strain leads to the warping of the boiling panel and the largest displacement is in the direction normal to the heat absorbing surface toward the cavity internal, the largest displacement range is 17 cm. Fins of the boiling panel at the elbow region (case-1 in the present study) can lead to hot spots of which the temperature is extremely higher than that of boiling tubes, cutting off the fins at the elbow region (case-2 in the present study) can eliminate the hot spots and has no impact on temperature distribution of the boiling panel's main part. The temperature difference on the cross section of the boiling tube is very high (about 130 °C while the heat flux is about 350 kW/m^2) both in radial and circumferential direction, and this high temperature difference results in the high thermal stress on the boiling panel and the maximum thermal stress occurs at the welding region. The welding quality has a significant impact on the fatigue failure of the boiling panel. For a receiver design life of 20 years, membrane wall with cutting off the fins at the elbow region (case-2 in the present study) is a good design and the welding quality level 3 should be ensured at least and only one cold startup for a day is permitted.

1. Introduction

Fossil fuels are still the main energy of our world, but the renewable energy like concentrated solar energy increases greatly in recent years (see in Fig. 1 BP, 2017; IRENA, 2017). For concentrated solar energy, there are four kinds of technology route: the solar power tower (SPT) system, the parabolic trough (PT) system, the parabolic dish system and the linear Fresnel system. The main difference between these systems is the method to collect the sun light, which results in the difference of system efficiency ultimately. Among them, SPT with its high concentration ratio and efficiency can realize the utilization of the solar energy in ways not only thermal power generation (Behar et al., 2013; Reddy et al., 2013) but also thermal chemical (Romero and Steinfeld, 2012; Yadav and Banerjee, 2016; Marxer et al., 2017).

In SPT system, the receiver is the sole component to realize the light-heat conversion. There are mainly two types of receiver while the heat absorbing materials and working fluids are of different kinds: the cavity receiver and the external receiver (Ho and Iverson, 2014; Benoit et al., 2016; Ho, 2017). Due to the cavity effect, the cavity receiver with the heat absorbing panels arranged in a part-closed enclosure is more efficient and has been investigated by numerous scholars. In the past, studies of the cavity receiver focused on its thermal performance. Wu et al. (2010), Tu (2015), Daabo et al. (2016), Wang et al. (2016), Zhang et al. (2017), Deng et al. (2017) and Hu et al. (2017) investigated the influence of the cavity receiver's geometry structure on its thermal performance. Teichel et al. (2012), Tu et al. (2015), Wang et al. (2017)

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Nomenclature

P	working pressure, MPa
T	temperature, °C
T_f	temperature of the working fluid, °C
D	diameter, m
d	thickness, m
h_f	heat transfer coefficient of the working fluid, W/(m^2·K)
u	displacements, m
E	modulus of elasticity, Pa
dr	differential in radical direction, m
Sps	allowable limit on the primary plus secondary stress range, MPa

Subscripts

tth	thermal strain
x, y, z	three coordinates in Cartesian coordinate system, m
tube	the boiling tube
fin	the fin of the boiling panel

Greek symbols

α	thermal expansion coefficient, K^{-1}
λ	thermal conductivity, W/(m^2·K)
μ	Poisson's ratio
κ	absorptance of the boiling panels
σ	normal stress, equivalent stress, Pa
ε	strain

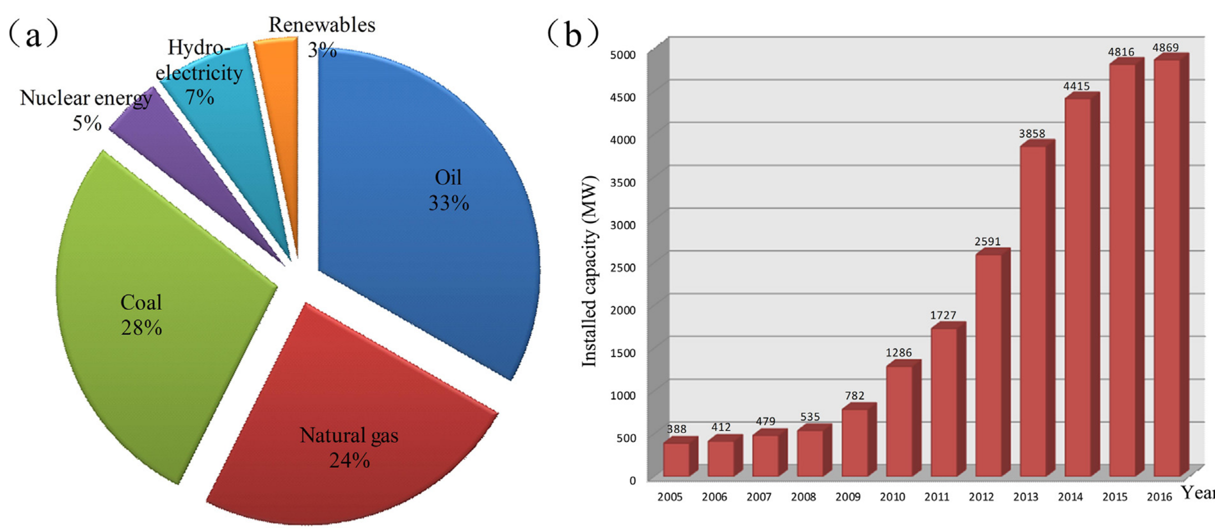

Fig. 1. Global energy consumption in 2016 (a) and the installed capacity of CSP in recent years (b).

and López-Herraiz et al. (2017) did researches on wall's optical property and its effects on the heat losses of the cavity receiver. Salomé et al. (2013), Yu et al. (2014) and Wang et al. (2017) studied the heliostat aiming strategy in order to homogenize the heat flux distribution in the cavity. Fang et al. (2011) and Flesch et al. (2014, 2015) investigated the thermal performance of the receiver under windy conditions.

Due to the fact that the solar energy is the sole source of its normal operation and is always instable, safety and reliability of CSP applications especially receivers where the light-heat conversion takes place are more important. Water/steam leaks of the external receiver in the Solar One system occurred after only eighteen months operation, and tube cracks of the cavity receiver in the CESA-1 system occurred in a few months since April 1983 (Baker et al., 1989). Unfortunately, there is scarcely research published on the safety and reliability of receivers in CSP applications for a long time. It is delightful that this situation is changing with more and more CSP plants coming into operation. Wang et al. (2010, 2012) investigated the thermal stress of absorbing tube in PT system, but the fatigue was not taken into consideration. Du et al. (2016) simulated the thermal stress and fatigue fracture of the molten salt receiver in SPT system. In their model, the safety factor was used to judge whether damage occurs, according to the fatigue curves, there is fatigue limit or endurance limit which is better for evaluating the damage and the fatigue failure can be neglected if the cycling stress amplitude below this limit (Lee et al., 2005). Also, the crack tip opening displacement (CTOD) method was used to get the critical crack length of cracks rather than the fatigue life that is more interesting. Hao et al. (2016) built an electrical heating system to study the hydrodynamic characteristics of cavity receiver tubes with non-uniform heat flux distribution. The results indicated the flow distribution became significantly worse with the increase of heat flux and concentration ratio. Rodríguez-Sánchez et al. (2017) designed a new concept of solar external receiver and studied its mechanical stress, the results indicated that the receiver could improve the thermal efficiency while had negligible effect on tube stress. Sánchez-González et al. (2016) proposed an aiming model for cylindrical molten salt receivers in SPT system, the model adopted allowable flux density criteria to find the optimal aiming strategy, and corrosion and thermal stress constraints were used for determining the allowable flux density.

From the review above, we can find that the thermal performance of the receiver is still very important, but the safety of the receiver has caused extensive concern in recent years. It's important to note that the cycling of thermal stresses originally caused by repeated heating and cooling operation would result in thermal fatigue (Xu, 1988), so fatigue failure of receivers in CSP applications is very important due to the fact that dynamic variation of the concentrated solar energy and receivers need to start-up frequently (at least one time in a day). As far as the author known, fatigue failure in CSP applications has not been studied yet. In our present study, a computation model is developed to evaluate the thermal stress and thermal fatigue failure induced by daily cold startup operation for the cavity receiver in CSP plants. The light