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Vacuum lifetime and residual gas analysis of parabolic trough receiver

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ABSTRACT

The vacuum characteristics and lifetime are the key problems of parabolic trough receiver. Heat loss of the receiver will greatly increase when the vacuum has been lost. Especially, if hydrogen is inside the annulus space of the receiver, heat loss at a level is approximately a factor of four higher than the loss for a receiver with good vacuum. Suitable vacuum levels and residual gases should be maintained in the receiver to ensure performances during its projected lifetime. In this paper, the variations of composition and partial pressure of residual gases with temperature in the receiver were measured by a high sensitivity quadrupole mass spectrometer gas analyzer. The effects of residual gas and getter on the vacuum lifetime of receiver were analyzed. The results showed that hydrogen was the main residual gas in the annular space of receiver without getter, and the nitrogen was the main gas released in the receiver with getter. It can be confirmed that the residual gas analysis was a very effective way to predict and evaluate the vacuum lifetime of the receiver.

1. Introduction

Parabolic trough solar technology is the most proven, widespread solar thermal power technology today. The majority of parabolic trough plants deployed operate at temperatures up to 391 °C using synthetic oil as heat transfer fluid (HTF) [1]. As the key component of the parabolic trough solar thermal power system, the parabolic trough receiver plays an important role in the energy conversion of concentrated sunlight into thermal energy of HTF [2,3].

The parabolic trough receiver consists of an absorber tube with a selective coating and a glass envelope surrounding the absorber tube to form an annular space between the glass envelope and the absorber tube [4,5]. A glass-metal sealing element is arranged on each free end of the glass envelope, wherein the central absorber tube and the glass-metal transitional element are connected with each other by means of bellows so that the absorber tube and the glass envelope can move relative to each other in a longitudinal direction, as shown in Fig. 1. The vacuum-tight enclosure between the absorber tube and the glass envelope is evacuated, which significantly reduces heat losses at high operating temperatures and protects the solar-selective coating from oxidation. The pressure in the annular space should be kept at or below the Knudsen gas conduction range to mitigate convection losses within the annulus, typically below 10^{-2} Pa to ensure good performance during its expected lifetime 25 years. Getters, which are metallic compounds designed to absorb gas molecules, are installed in the annular space to absorb hydrogen and other gases that permeate into the vacuum annulus over time.

Heat loss of the parabolic trough receiver has an important influence on the thermal and economic performance of the parabolic trough power plant. Recently, researchers found that many parabolic trough plants are experiencing significant heat losses in the receivers, which are so-called "hot tube phenomena" [6–8]. It is confirmed that the heat losses will remarkably increase when the most of vacuum has been lost in the parabolic trough receiver [9,10]. Especially, if the equilibrium pressure of hydrogen is >10 Pa inside the annulus, the heat loss at a level is approximately a factor of 4 higher than the loss for a receiver with good vacuum. The annual plant revenue can then be reduced by as much as 20% by receivers infiltrated with hydrogen [11]. Furthermore, receivers are welded together to form solar collector loops in the parabolic power solar plant, so it is a very complicated and expensive process to replace failed receivers.

It is a significant issue to evaluate the vacuum lifetime of the receiver tube. According to the vacuum principle, the vacuum

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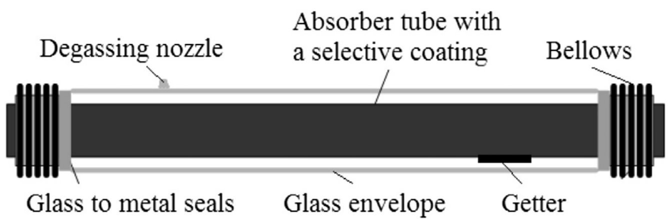

Fig. 1. Schematic of a typical parabolic trough receiver.

degradation of a vacuum device is generally due to the following reasons:

1) Outgassing of the materials in the system.
2) Gas permeation through walls or windows in the vacuum system.
3) Air penetrating into the vacuum system as a result of leaks.

Therefore, the vacuum lifetime of the receiver is not only determined by the amount of hydrogen that permeates from the HTF into the vacuum, but also by the amount of the outgassing and by the air leakage. The getter which can absorb many kinds of gases in the receiver can also affect the vacuum lifetime.

Residual gas analysis is an essential method to test the variation of the gas components and the gas amount with time, and is the most accurate way to verify whether the prediction of vacuum lifetime is correct. According to the residual gas analysis, the amount of the outgassing can be used to estimate whether the outgassing process is reasonable, and to determine which kind of getter and how many getters should be put in the receiver. Therefore, it is inevitable to test the residual gas in the vacuum to control and maintain the receiver vacuum conditions. Li et al. [12] analyzed the gas sources within parabolic trough receiver and absorption characteristics of the getter to evaluate the factors affecting vacuum reliability of parabolic trough receiver. This work also provided the equation of outgassing rate of the receiver which we have used in the paper. Moens et al. [13] studied the mechanism of hydrogen formation in the parabolic trough receiver. They presented that the hydrogen gas was formed during the thermal decomposition of the organic HTF that circulates inside the receiver loop. Wang et al. [14] analyzed different heat transfer mechanisms due to variable residual gas conditions in the annulus. Möllenhoff et al. [15] introduced a new receiver with a capsule containing noble gas, placed in the evacuated annulus to extend the lifetime of receiver by allowing the noble gas filling after a variable period of operation.

However, there are few studies of residual gas analysis and its effects on vacuum lifetime of the parabolic trough receiver, with some works focusing on mechanism of hydrogen formation, using noble gas to extend the lifetime and the effects of residual gases on the thermal performance of the receiver [11–15]. In this paper, the variations of composition and partial pressure of the residual gas in the receiver were measured by a high sensitivity quadrupole mass spectrometer (QMS) gas analyzer. The effects of residual gas and getter on the vacuum lifetime of receiver were analyzed.

2. Vacuum lifetime model

The vacuum characteristics and lifetime are the key problems for parabolic trough receiver. Suitable vacuum levels must be maintained in the parabolic trough receivers to ensure performances during its projected lifetime. Manufactures have taken many ways to maintain vacuum stability, such as increasing the hydrogen capacity of getters, changing the composition of steel tube and using additional hydrogen barrier coatings, etc [16–18]. In order to assess the vacuum lifetime of the receiver, a vacuum lifetime model was developed:

$$V\frac{dP}{dt} = q_l + q_o(T) + q_p(T,\ \Delta P) - q_g(T) \tag{1}$$

where, V and P are respectively the volume and the pressure of the annulus space of the receiver. t is the time, T is the temperature, q_l is the leak rate, q_o is the outgassing rate, q_p is the permeation rate, q_g is the gas absorption rate of getter and ΔP is the pressure difference between inside and outside of the parabolic trough receiver.

As we all know, no vacuum device or system can ever be absolutely vacuum-tight. The leakage mainly occurs at a junction between two materials such as the glass-to-metal seals and the metal-to-metal welds in the parabolic trough receiver. In order to maintain a vacuum lifetime of 25 years, the leak rate should be less than 10^{-10} m^3 Pa/s for the parabolic trough receiver [12]. The leak rate is generally measured by a helium mass spectrometer leak detector. The leak rate q_l was less than 10^{-11} m^3 Pa/s for the receiver measured in this paper. Therefore, the overall amount of the leakage for the receiver, Q_l, can be calculated by:

$$Q_l = \int_0^t q_l dt \tag{2}$$

For the hydrogen permeation, Glatzmaier [19,20] developed a hydrogen occurrence model for parabolic trough plants. This model used a steady-state assumption with the constant hydrogen pressure in the annulus balancing the net permeation rate into the annulus volume from the receiver tube and the permeation rate out of the annulus into the ambient. We developed a hydrogen permeation model for parabolic trough receiver based on measurements of hydrogen permeability of the absorber tube with the solar-selective coating [21]. The effects of the temperature, the hydrogen pressure and the hydrogen barrier coating on the hydrogen permeation into the vacuum annulus were analyzed. The overall amount of the hydrogen permeation, Q_p, can be calculated by:

$$Q_p(T,\ \Delta P) = \int_0^t Aq_o(T,\ \Delta P)dt \tag{3}$$

where, A is the hydrogen permeation area covered on the absorber tube.

Getters are the key components for maintaining the vacuum lifetime of parabolic trough receiver. A getter is a substance that removes molecules from the gas phase by a chemical reaction on its active surface. Both evaporable getters and non-evaporable getters are generally used in receiver. The evaporable getter is just used to indicate whether the vacuum is good or not in the receiver. The non-evaporable getter installed in the receiver is very reactive with a wide variety of gas molecules, such as H_2, CO, CO_2, O_2, H_2O, C_nH_m and N_2 [22]. Because hydrogen is one of the main causes of the “hot tube phenomena”, the non-evaporable getters should have sufficient capacity of hydrogen absorption. Generally, the reactions proceed by dissociative chemisorptions followed by reactions to form oxides, carbides, or nitrides on the surface of the non-evaporable getters, which slowly diffuse into the bulk. However, hydrogen absorption in the non-evaporable getter differs from other gases. A physically adsorbed hydrogen molecule dissociates into atomic hydrogen on the activated surface of the getter.