Applied Thermal Engineering 131 (2018) 446–454

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Influence of reference temperature on the thermal stress of slag-layer cooling in an atmospheric entrained-flow gasifier with high-speed circulating gasification agent

Haopeng Wang, Zhichao Chen *, Xiaoyan Zhang, Zhengqi Li, Neng Fang, Xiaoying Liu

School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, PR China

HIGHLIGHTS

- The thermal stress of the slag layer in an atmospheric entrained-flow gasifier is studied.
- Creep relaxation is taken into consideration in the numerical model.
- A continuous reference temperature is set to acquire a stress-free state at cooling onset.
- A more reasonable outcome is obtained with a continuous reference temperature.

ARTICLE INFO

Article history:
Received 11 July 2017
Revised 20 November 2017
Accepted 2 December 2017
Available online 5 December 2017

Keywords:
Atmospheric entrained-flow gasifier
High-speed circulating gasification agent
Membrane wall
Slag layer
Thermal stress

ABSTRACT

A slag slayer can protect the membrane wall in an entrained-flow gasifier. Maintaining a certain thickness of slag layer is particularly important for allowing an entrained-flow gasifier to operate steadily. Thermal stress is a major cause for a slag layer to break. This study aims to provide a numerical model that accurately represents the variation of thermal stress in the cooling slag layer in a novel entrained-flow gasifier. Based on experimental data from an industrial-sized atmospheric entrained-flow gasifier with high-speed circulating gasification agent, the thermal stresses owing to cooling are simulated numerically using transient thermal analysis. Creep relaxation is taken into consideration in the model. A continuous distribution of reference temperature based on that at the onset of cooling is applied to the numerical model. The results indicate that the thermal stresses in the slag layer are tensile during cooling, and that the von Mises stress increases. The von Mises stress appears to peak (at 72 MPa) near the initial liquid–solid interface at the end of the cooling process, which is therefore where the slag layer is most likely to crack or even be shed. The numerical model is also calculated with a fixed distribution of reference temperature by way of comparison. In that case, the von Mises stress in the initial solid slag layer decreases during cooling, which is contrary to common sense. The results show that the reference temperature used in the numerical model is crucial to the calculated thermal stress.

1. Introduction

Entrained-flow gasification technology forms part of clean coal technology. Because of its high carbon conversion rate, tar-free raw gas production, and low sensitivity to coal type, it is widely applicable in industrial technology [1–4]. Because an entrained-flow gasifier operates at high temperature (~1500 °C), the coal ash melts into liquid slag, most of which is deposited at the membrane wall to form a slag layer that can be divided into two parts: solid slag in contact with the colder refractory, and liquid slag facing the hot syngas [5]. For the slag layer to protect the membrane wall from syngas radiation and liquid-slag erosion, and thereby to allow the gasifier to operate steadily, a certain thickness of slag layer must be maintained [6].

However, many factors can cause the slag layer to crack or even be shed, such as erosion, gravity shedding, or thermal shock [7–9]. Of these, thermal shock is a major source of slag-layer damage in an entrained-flow coal gasifier. Thermal stress occurs because of an uneven thermal expansion between the deposit and the tube metal, or between different layers [7]. Sudden heating or cooling may cause thermal shock of the slag layer, and sudden shrinking caused by the latter can decrease the adhesion force between the slag layer and a tube, causing the slag layer to crack. This is most

* Corresponding author.
E-mail address: chenzc@hit.edu.cn (Z. Chen).

https://doi.org/10.1016/j.applthermaleng.2017.12.013
1359-4311/

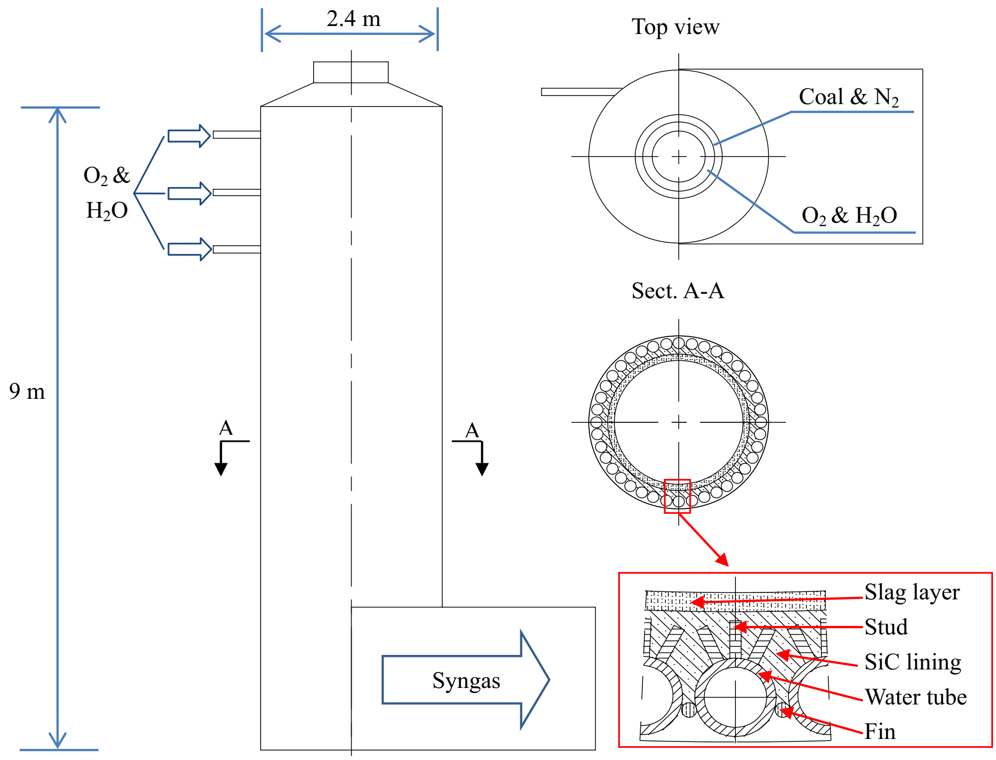

Fig. 1. Schematic of atmospheric entrained-flow gasifier with high-speed circulating gasification agent. (The membrane wall contains 160 water tubes, here only for illustration purpose).

Table 1
Fusion temperature of Saimengteer Coal Ash.

Fusion temperature (°C)			
DT	ST	HT	FT
1130	1140	1150	1180

DT, deformation temperature; ST, softening temperature; HT, hemispherical temperature; FT, flow temperature.

likely to happen during cooling, and so thermal stress analysis of this stage is a major research topic [6,10,11].

Much research has been conducted on the thermal and mechanical properties of the slag layer [6,7,10–12]. Because of the high temperatures and pressures in an actual gasifier and the associated limitations of test instruments, numerical simulation is a common way to gain a better understanding of the thermal stress in the slag layer. Using a laboratory-scale gasifier, Lin et al. [6,10,12] investigated the influence of the thickness and porosity of the slag layer on its thermal stress while cooling. Zhou et al. [11] developed a two-dimensional model for simulating the thermal stress in boiler slag under different temperature conditions with static analysis. Because the gasifier geometry and operating conditions dramatically affect the flow and deposition of slag or ash particles [13], different gasifiers results in different thermal stresses in the slag layer.

As the temperature of the material when it is free of stress, the reference temperature (T_{ref}) is one of the most important parameters in any numerical simulation to calculate thermal stress. In many reported numerical simulations of slag-layer thermal stress, the value of T_{ref} for the membrane wall and the initial solid slag layer was fixed, for example to 25 °C [6,10]. However, an entrained-flow gasifier is typically run for 6–18 months [6] at high temperature (~1500 °C) [14,15], which means that high-temperature creep relaxation of the material becomes an important factor in determining the stress state. Creep during the high-temperature phase can relax the stress as the material layers grow, resulting in a stress-free state at the end. This phenomenon is usually seen in thermal barrier coatings [16–18] that, like gasifier slag layers, are multilayer structures. Hence, during typical operation of an entrained-flow gasifier, the thermal stress in the membrane goes through three stages:

(1) During heating, the thermal stress in the membrane wall increases from zero. To simulate the thermal stress during this process, the whole model can have a fixed value of T_{ref} (i.e., the temperature at the onset of heating, which could be ambient temperature, e.g., 25 °C).
(2) During stead operation, creep relaxation of the material gradually dissipates the thermal stress of the membrane wall. After a long time, the membrane wall returns to a stress-free state.
(3) During cooling, the thermal stress in the membrane wall again increases from zero. To simulate the thermal stress during this process, the model must somehow acquire a stress-free state at the beginning of the cooling process. Given the physical meaning of T_{ref}, it is necessary to set the temperature distribution of the membrane wall and solid slag layer at the beginning of cooling as a continuous T_{ref} on the model.

Hence, a fixed T_{ref} (e.g., ambient temperature, say 25 °C) is unlikely to be suitable for the thermal stress in the membrane wall during cooling after the gasifier has been in operation for a long time. Such an approach would lead to unreasonably exaggerated thermal stress because of the substantial difference between the imposed T_{ref} and the actual temperature.

Although entrained-flow gasifiers tend to operate at higher pressures [19,20], atmospheric gasification technology (such as