Chemical Engineering Science 66 (2011) 448–459

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Modeling and comparison of different syngas cooling types for entrained-flow gasifier

Jianjun Ni, Guangsuo Yu*, Qinghua Guo, Zhenghua Dai, Fuchen Wang

Key Laboratory of Coal Gasification of Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

ARTICLE INFO

Article history:
Received 7 April 2010
Received in revised form
13 July 2010
Accepted 3 November 2010
Available online 12 November 2010

Keywords:
Syngas cooler
Energy utilization
Heat transfer
Turbulence
Multiphase flow
Entrained-flow gasifier

ABSTRACT

A three-dimensional numerical model has been developed for studying the multiphase flow and heat transfer process in the syngas cooler. The realizable $k-\varepsilon$ turbulent model and discrete random walk (DRW) model were adopted to simulate the gas phase and particle phase flow fields, respectively. The discrete ordinate model (DOM) was applied to solve the radiative heat transfer equation, and the gas radiative properties were calculated by weight-sum-of-gray-gases model (WSGGM). The ash particle radiative properties were also considered in the radiative heat transfer calculation. The convection heat-transfer between the gas phase and discrete phase is also considered. The flow field and temperature distribution results are in good agreement with the experimental data. Firstly, the results indicate that the RSC should be the better choice for integrated gasification combined cycle (IGCC) power plant. For cooling-syngas quenching cooler, the outlet region has higher risk of fouling and slagging because the outlet gas and particle temperature are about 940 °C, and exceed the criteria temperature 760 °C (suggested in the literature). Secondly, when the inlet velocity and flow rate of the quenching gas are fixed, the more the quenching gas inlets are, the better the flow field and temperature field are. A recirculation region with the diameter about 1.5–2.0 m is formed in the center of the cooler under the quenching gas profile, and the intensity of the reflux flow increases with the number of quenching gas inlets. The particles are rapidly quenched when the particle flow through the quenching gas profile. Furthermore, the temperature of the quenching gas, and the temperature of the water in the tubes of membrane wall also have important effect on the temperature field in the RSC.

1. Introduction

The high-temperature syngas from gasifier must be cooled before its final use. The design of the high-temperature syngas cooling process depends on the type of gasifier used. The highest-temperature gasification process is the entrained-flow slagging process. The gas cooling requirements for entrained-flow gasification system are much higher than other gasification systems. Typically, the gas cooling process in the entrained-flow gasification systems use either heat exchanger to recover the sensible heat of syngas and generate steam or water quenching. The former design may be radiant syngas cooler (RSC), RSC with cooling-syngas quenching and total cooling-syngas quenching, the latter is known as water scrubbing cooling chamber (WSCC). Although the cost of the RSC and convection syngas cooler (CSC) design is higher than that of WSCC design, it has advantage over total water quenching with higher plant efficiency. And it is necessary to recover the sensible heat of gasification products for integrated gasification combined cycle (IGCC) power plant. On the other hand, in a water quenching system, a large amount of water are used and thus contaminated by the slag, requiring complex primary and secondary treatment facilities. Hence WSCC design has additional operating problems such as added water treating facilities, discharge water permitting issues, and increased operating and maintenance costs compared to RSC and CSC design. The typical cooling system types are shown in Fig. 1. Fig. 1a shows the WSCC design, and it is mainly applied by GE Energy gasifier (Higman and Burgt, 2008) and Opposed Multi-Burner (OMB) gasifier (Wang et al., 2007; Dai et al., 2008). Fig. 1b shows the cooling-syngas quenching with CSC cooling type, and it is mainly adopted by Shell gasifier (Heidenreich and Wolters, 2004) and Prenflo gasifier (Seggiani, 1998; Thompson and Argent, 2002). Fig. 1c shows the cooling type design of RSC and CSC, and it is mainly employed by GE Energy gasifier and OMB gasifier. Fig. 1d shows the RSC use syngas quenching in the middle of the cooler and the adiabatic wall is designed for RSC outer wall. The typical applications of GE gasifier and Shell gasifier in IGCC plant are Tampa power plant in USA and Buggenum IGCC plant in Netherlands, respectively. Two type syngas coolers shown in Fig. 1c and b are designed for Tampa power plant and Buggenum IGCC plant, respectively.

The syngas cooler is often one of the most expensive items in a coal gasification system. However, very little information reported on

---

* Corresponding author. Tel.: +86 21 64252974; fax: +86 21 64251312.
E-mail address: gsyu@ecust.edu.cn (G. Yu).

0009-2509/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2010.11.005

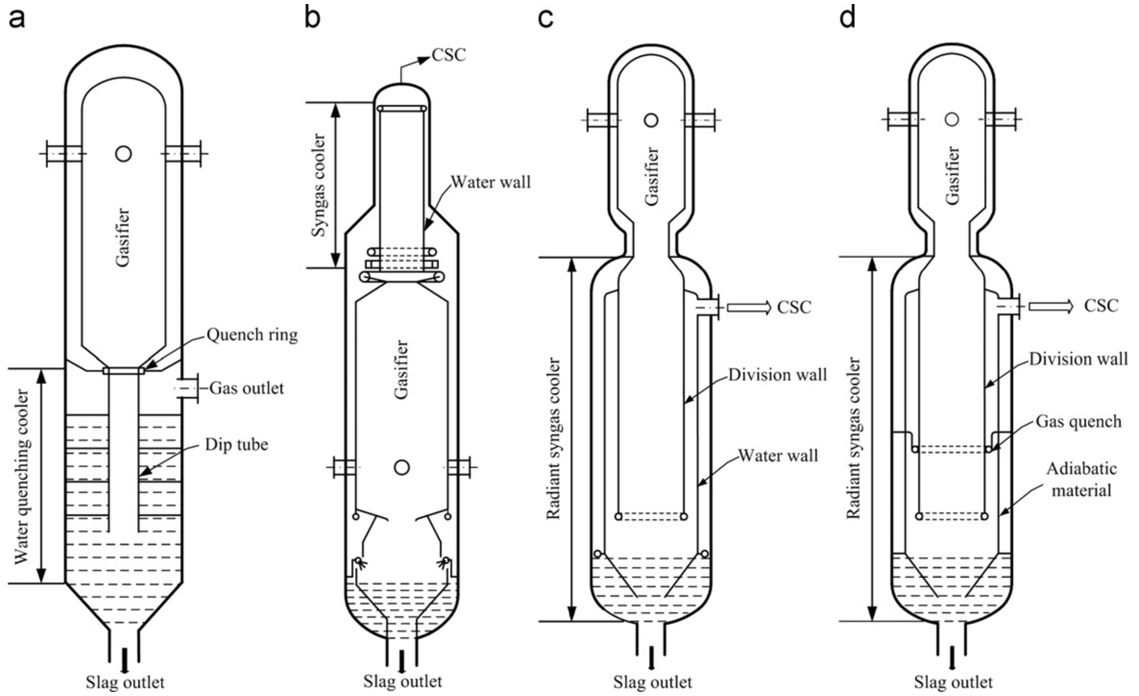

Fig. 1. Schematic diagram of different syngas cooling types for an entrained-flow gasifier.

further improvements of its reliability and availability. Cool Water gasification project is the first commercial IGCC power plant and was successfully demonstrated at Southern California. The third cooling type shown in Fig. 1c was used in Cool Water power plant, and the chemistry properties of the ash deposition in its RSC and gasifier have been studied by Brooker (1993) and Brooker and Oh (1995). It is very difficult to investigate directly the RSC under high temperature and high pressure. Most work since the 1980s have focused on the ash deposition and flow properties of molten slag under reducing environment (Groen et al., 1998; Hurst et al., 1999; Miura et al., 2004; Shannon et al., 2008). All that can help to understand the mechanism of the molten slag phase transformation and ash deposition, but none of which can indicate the gas–particle flow pattern and complex heat-transfer process in the RSC of an entrained-flow coal gasifier. In our original papers (Ni et al., 2009a, b; Yu et al., 2009), attempts have been made to develop a numerical model for predicting the multiphase flow and temperature field of an industrial-scale RSC. It was validated that the numerical model is the best choice for investigating the flow field and temperature field of the RSC under high-temperature and high-pressure conditions.

The main objective of this study is to calculate the gas–particle flow field and temperature field of the different type coolers shown in Fig. 1. The gas flow field of the cold-model RSC and the temperature distribution in the dip tube of bench-scale WSCC have been measured, and the comparison of the measurement and prediction values are performed. A three-dimensional numerical model is developed to consider the effect of the different operating parameters, such as the temperature of the quenching gas and the water temperature in the tube of membrane wall. Furthermore, the particle temperature distribution, particle velocity distribution, and particle diameter distribution in the syngas quenching section have been presented.

2. Model description

2.1. Fluid flow approach

In the present work, an Euler–Lagrangian method has been adopted to describe the flow behavior of the gas and particle phases. A dilute particle concentration was considered according to the mechanism of the entrained-flow coal gasifiers (Ni et al., 2009a, b). The particle was assumed as sphere shape, and the particle volume fraction is about 10^{-4} or lower in syngas cooler, so according to the criteria suggested by Crown (1988), the interactions between the particles were ignored. However, the interaction between the gas and particle phases were considered by the two-way coupling method. The gas flow was simulated as turbulent, described by the realizable k–ε model. Then the gas flow results were used in the simulation of the particle flow described by the discrete random walk (DRW). The key features of these models were briefly described as follows.

2.1.1. Gas phase flow model

The realizable k–ε model (Shih et al., 1995) was used for predicting the steady gas flow. This model has been extensively validated in a wide range of flow, including round confined jet (Shih et al., 1995; Zhang and Li, 2008). The k-equation and ε-equation were shown as follows:

The kinetic energy of turbulence:

$$\frac{\partial(\rho_g k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho_g \varepsilon \tag{1}$$

The dissipation rate of kinetic energy of turbulence:

$$\frac{\partial(\rho_g \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho_g C_1 S_\varepsilon - \rho_g C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} G_b \tag{2}$$

where the standard constants of realizable k–ε model used were given as: $C_{1\varepsilon}=1.44$, $C_2=1.9$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.2$.

The syngas from gasifier is a mixture of many species, and the typical components of syngas for pulverized coal gasification are listed in Table 1. Quenching gas shown in Table 1 is part of high-temperature gas after cooling, but it has been humidified and cleaned through water bath collector, cyclone mixer, and water scrubber. So the mole fraction of water vapor in quenching gas is higher than high-temperature gas. The species transport model