PAPER • OPEN ACCESS

Review of simulation research on pulverized coal combustion in industrial boilers

To cite this article: Xuemin Liu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **295** 052028

IOP Conf. Series: Earth and Environmental Science **295** (2019) 052028 doi:10.1088/1755-1315/295/5/052028

Review of simulation research on pulverized coal combustion in industrial boilers

Xuemin Liu[1*], Yajun Ge[2], Guoli Qi[1] and Songsong Zhang[1]

[1] China Special Equipment Inspection and Research Institute, Beijing, 100029, China

[2] Harbin University of Science and Technology, Harbin, Heilongjiang, 150080, China

[*]Corresponding author's e-mail: liuxuemin@csei.org.cn

Abstract. The development of pulverized coal industrial boilers was briefly introduced in this work. The numerical research on PC industrial boiler in recent years was summarized. Due to the limited space in the furnace of PC industrial boiler, calculation of flow and temperature distribution in the burner is the focus of numerical simulation. With the increasingly strict environmental protection regulations, NO_x emission characteristics under different design and operating conditions have attracted more and more attention. The calculation models adopted by different scholars were analyzed, based on which the common models suitable for simulation of PC industrial boiler were concluded.

1. Background

By the end of 2015, there were about 565,000 industrial boilers in China, of which about 464,000 were coal-fired industrial boilers. The annual energy consumption and pollutant discharge of coal-fired industrial boilers were in the second place. The annual energy consumption was about 0.6 billion tons, accounting for 17% of the total coal consumption in China. The annual emission of dust, SO_2 and NO_x accounted for about 40%, 27% and 9% of the total emission in China, respectively. Because of the large quantity, low operating efficiency and high pollutant emission, coal-fired industrial boilers have always been the focus of energy conservation and environment protection.

According to the basic principles and characteristics of the combustion process, the coal-fired industrial boilers can be classified into three technical forms. 1) Stoker boiler: coal particles are spread into a layer on the grate and air is mainly sent from under the grate, flowing through the coal layer and reacting. 2) Fluidized bed boiler: coal particles are fluidized by primary air, which is sent into the furnace from wind chamber through air distributer. Circulating fluidized bed (CFB) boiler has been widely commercialized due to the advantages in fuel flexibility and low cost of emission control. 3) Pulverized coal (PC) boiler: fuel is sprayed into the furnace with air and reacts in suspension. With the characteristics of fine particles and high combustion efficiency, PC boiler is mainly used for power generation. In recent years, it has also been popularized in the field of industrial boilers.

In this work, the development history of PC industrial boilers is briefly introduced and the simulation progress of pulverized coal combustion is reviewed. Then the numerical simulation method is summarized, providing important reference for simulation research on PC industrial boilers.

2. Development overview of pulverized coal industrial boilers

The developed countries began to study the PC industrial boilers from the 1980s. In the mid and late 1990s, the technology had been developed maturely. In particular, Germany, as a country lacking oil and gas but rich in coal resources, has been committed to the research on PC combustion technology for a long time. The PC industrial boilers have been widely commercialized and the technology level is in the leading position in the world. By 2009, more than 80% of coal fired industrial boilers are PC boilers. The main technical categories include Dr. Schoppe, HM, Pillard and Saacke, etc.[1] In order to meet the special requirements of industrial boiler users, such as variable load and frequent start-stop, all the technical categories adopt the concept of dense phase combustion. Taking the Dr. Schoppe technology[2] as an example, the feeder is a porous rotary disk with concentrated and volumetric integral fluidization, which can realize the secondary activation of pulverized coal, no-pulsating feed and sealed delivery. The burner adopts the central reverse fuel injection and forced reflux technology, combined with the unique structure of stable combustion chamber with front double cone and the principle of accelerated injection flame, to enhance ignition and combustion. The boiler proper belongs to the shell and fire tube type, the double cone combustion chamber is in the shell and the back combustion chamber uses the full membrane wall structure. The boiler efficiency is very high, generally up to 92%. The capacity of single furnace boiler is up to 20 t/h. If more than 20 t/h, double furnaces are usually used, with the boiler load adjustment range of 30%-110%. By adding limestone to the pulverized coal particles, the sulfur retention rate in the furnace is not less than 50%. The NO_x emission concentration is 250-350 mg/Nm^3 by using air staging. In general, the development purpose of PC industrial boilers in Germany is to replace oil (gas) fired boilers. There is no historical relationship with utility boilers.

In the 1970s and 1980s, with the rapid development of PC utility boilers, the application of pulverized coal combustion in industrial boilers was tried in China, but failed. Many institutions restarted the research and development of PC industrial boilers around 2000. The technical concept of China Coal Research Institute is similar to that of Germany. The feeding technology is dense phase feeding and the burner adopts the central reverse fuel injection and forced reflux technology. The boiler proper can be classified into three structure types according to capacity. Desulphurization in furnace is combined with flue gas desulphurization by high rate ash-calcium circulation. More than 50% of SO_2 can be removed during combustion. After the flue gas enters the desulphurization system, more than 95% of SO_2 can be further removed. NO_x control is achieved by using air staging and flue gas recirculation, with the initial emission concentration of 150-200 mg/Nm^3. PC industrial boiler is a complex system of multi-technology integration. Each subsystem has other different technical branches. There are three main types of feeding technologies: the first is developed based on the utility boiler system, for instance, the impeller feeder; the second is the existing powder conveying equipment, e.g. the screw conveyor; the third is the introduction of foreign products. The first two types are based on dilute supply, so the initial ignition is difficult. The coal powder can burn independently after the heat storage of boiler is completed. For the burner, the dilute phase swirl combustion technology without pre-combustion cone is also popular. For pollutant control, domestic NO_x control technology path is almost the same. Wet flue gas desulfurization (WFGD) is widely used for SO_2 removal, such as the dual-alkali method, Mg-desulfurization and limestone-gypsum method. In other words, the domestic PC industrial boilers can be classified into two categories: the first is the combination of domestic technology and foreign experience in developed countries; the other is the industrial product developed on the basis of utility boilers. At present, more than 500 sets of PC industrial boilers have been built in China, with a total capacity of nearly 10,000 tons, and the thermal efficiency is about 90%.

In summary, the PC industrial boiler technology has been very mature in Germany, while in China it is still at the development stage with many problems to be solved.

3. Review of simulation research

Due to the high cost and difficulty of the field tests, it's not suitable to carry out in large amounts. With the development of computer technology and application of commercial software, the numerical simulation has been developed rapidly in research on boilers[3-4], of which the FLUENT software is the most widely applied. In recent years, a great amount of simulation research on flow field and combustion in large-scale boilers has been carried out[5-6], while the working conditions for industrial boilers are relatively few. As industrial boilers have the characteristics of fast response, wide load operation, frequent start-stop and limited furnace space, the design and operation experience of utility boilers is difficult to draw on. Therefore, it is necessary to carry out simulation and optimization for high combustion efficiency and low pollutant emission of industrial boilers. This section will focus on the research progress of numerical simulation of PC industrial boilers, and simulation work carried out by different scholars will be introduced.

Xu Y. simulated the cold-air aerodynamic field and combustion characteristics of a new-type burner under different swirl intensity by using the FLUENT software. In the simulation, the Realizable k-ε Model was used to calculate the turbulence flow, the Discrete Random Walk Model was used for particle tracking, the P1 Model was used to calculate the radiation heat transfer, the Composition PDF Transport Model was used to calculate gas phase burning and Kinetics/Diffusion Limited Combustion Model was used to calculate the char combustion[7]. In order to extend the applicability of PC industrial boiler in medium volatile bituminous coal, Jiang S. et al. simulated a 14 MW reversed injection burner. The Realizable k-ε Model and Discrete Random Walk Model were adopted. For calculation of radiation, the Discrete Ordinates (DO) Model was used. For calculation of volatile combustion, the Eddy-Dissipation Model was used. Results show that extending high-temperature area, increasing recirculation zone area can improve the combustion performance[8]. Ji R. also used the FLUENT software to conduct numerical simulation of a new type PC industrial boiler. The Non-Premixed Combustion Model and P1 Model were employed to simulate chemical reaction and heat transfer respectively. De-volatilization was described by Two-Competing-Rates Model. Char combustion was simulated by Kinetics/Diffusion Limited Combustion Model. The simulation results show that a better temperature distribution can be obtained by reducing the boiler load[9]. Han L. studied the combustion performance of a swirl burner with secondary air and analyzed the combustion characteristics in the furnace by using the FLUENT software. The Standard k-ε Model and Discrete Random Walk Model were employed. The Finite-Rate/Eddy-Dissipation Model was used for combustion calculation. For simulation of radiation, the Discrete Ordinates (DO) Model was used[10]. Zhu L. and Chi J., et al. studied the influence of the secondary air swirl intensity and load change on combustion characteristics. The results show that the furnace temperature increases with the secondary air swirl intensity and the burner can still maintain stable combustion when the boiler load drops to 40%[11-12]. The RNG k-ε Model was chosen to simulate gas turbulence flow. De-volatilization was described by Two-Competing-Rates Model and volatile combustion by Composition PDF Transport Model. For simulation of char combustion and heat transfer, the Kinetics/Diffusion Limited Combustion Model and P1 Model were used respectively.

In addition to the mature calculation models in commercial software, some scholars also put forward modified models to improve the calculation accuracy. Li Z. et al. proposed a modified k-ε-k_p two-phase turbulence model and a second-order moment (SOM) reactive rate model, which are used to predict the coal combustion and NO formation at the exit of a double air register swirl pulverized-coal burner[13]. Williams A. developed de-volatilization pre-processor code to compute the pyrolysis rate, the yields and composition of volatiles and char, which allows for a more accurate description of the coal de-volatilization stage[14].

Besides, Wang J. et al. studied the influence of primary and secondary air velocity, internal secondary air swirl intensity and blocking rate of blunt body on flow field near the burner outlet, including the size of reflux area and reflux flow rate[15]. Wang Y. et al. simulated the flow field distribution in double-cone chamber with two kinds of blade under different swirl intensity[16]. Effects of three optimized transformation schemes of a double-cone burner, including installing blunt body, the guide vane, the blunt body and guide vane at the same time on temperature and velocity distribution was studied[17]. Mo R. also simulated the double-cone burner, but the research was focused on the combustion characteristics of coal slurry[18].

With the increasingly strict environmental protection regulations, a lot of simulation studies have been focused on NOx emission. Li G. et al. conducted a simulation study on a 30t/h PC industrial boiler with double-drum. The influence of flue gas recirculation ratio on NO_x emission was analyzed. The results show that the circulating flue gas increases the flame size, makes the furnace temperature more uniform and reduces the NO_x emission[19]. Wang P. et al. studied the influence of air classification depth on boiler combustion and NO_x initial emission. With the increase of tertiary air proportion, NO_x emission concentration can be reduced from the maximum of 697 mg/m^3 under the condition of non-air staging to 424 mg/m^3 under the condition of tertiary air proportion of 30%[20]. Ma W. constructed a pre-combustion chamber model. The effects of swirl angle, pre-combustion chamber aspect ratio, pre-combustion air coefficient and the length of central reversed-injection ducts on combustion and NO_x emission were studied. The NO_x concentration can be decreased by about 30% by using center-reverse-jet technology, but the length of the reverse jet has little effect on the outlet NO_x concentration[21]. Chi J. studied the influence of adiabatic area, boiler load and over-fire air rate on combustion characteristics and NO_x emission. The reasonable proportion of the heat shield should be between 20%-40%. The NO_x concentration decreases with the increase of over-fire air rate[22].

In addition to combustion in the furnace, the feeding coal system of PC industrial boiler can also be numerically simulated. For example, aiming at the problems of Venturi pulverized coal mixer, such as positive pressure in breathing cap, low air velocity and feeding instability, Liu Z. simulated and analyzed the velocity field, pressure field, particle trajectory and coal powder concentration by using the FLUENT software. The results show that these problems are caused by downstream resistance, fan operating point deviation, Venturi negative pressure deviation and so on[23].

In all the above studies, the FLUENT software was used. There are also other kinds of CFD software used for PC industrial boiler simulation, e.g. CFX and STAR-CCM+. Kurose R. et al. used STAR-CD code to simulate pulverized coal combustion field in a test furnace equipped with an advanced low- NO_x burner called CI-α burner[24]. The gas-phase turbulence was represented by renormalization group (RNG) k-ε Model[25]. The continuity and momentum equations were solved using the SIMPLE algorithm[26]. Gaseous combustion was calculated using the combined model of kinetics and eddy dissipation models. The char burning rate was calculated using Field et al.'s model[27]. NO_x formation was typically calculated in a post processing way[28]. Qiu X. studied a PC industrial boiler with the burner arranged at the bottom by using the STAR-CCM+ software[29]. Kumar S. et al. used the CFX-Tascflow software to conduct simulation research on a new type burner with high combustion intensity and low emission[30]. Wang Z. used the ANSYS CFX software to simulate the gas-solid two-phase flow field, pressure field, temperature field and concentration field in the furnace with a new type bias combustion swirl burner[31].

In general, different from utility boilers, the PC industrial boilers have limited furnace space. Therefore, the calculation of flow field and temperature field in the burner is the focus of numerical research, especially the combustion and NO_x emission characteristics under different structural and operating conditions. In addition to FLUENT, which is the most widely used software, CFX, STAR-CCM+ and other kinds of software are also used.

4. Summary of numerical simulation methods

In the numerical simulation of PC industrial boiler, the models used mainly include flow model, combustion model and radiation heat transfer model. The flow model includes gas-phase turbulence model and gas-solid two-phase flow model. Turbulence transport coefficient model, also known as eddy viscosity model, is a commonly used gas-phase turbulence model, of which the k-ε Model is the most typical one, including the Standard k-ε Model, Realizable k-ε Model and RNG k-ε Model. For simulation of swirl burner, the Realizable k-ε Model is often used. The Discrete Random Walk Model under Lagrange Coordinate System is generally used to simulate pulverized coal particles. Radiation heat transfer models include P1 Model, Rosseland Model, Discrete Ordinates (DO) Model, Surface to Surface (S2S) Model and Discrete Transfer Model (DTRM), among which the P1 Model has been widely applied due to its simple and effective characteristics. The combustion model includes three parts: de-volatilization, volatile combustion and coke combustion. De-volatilization can be described by Two-Competing-Rates Model. For volatile combustion, the Composition PDF Transport Model has obvious advantages in dealing with detailed chemical reaction mechanism and interaction between chemical reaction and turbulence. The Kinetics/Diffusion Limited Combustion Model can be used for simulation of coke combustion. NO_x formation is calculated in a post processing way.

5. Conclusions

In this work, the development of PC industrial boiler in China and Germany was briefly introduced. Considering the wide application of numerical simulation in research on boiler in recent years, the numerical research on PC industrial boiler carried out by scholars at home and abroad was summarized. It can be seen that, different from utility boiler, due to the limited space in the furnace of PC industrial boiler, calculation of flow field and temperature field in the burner is the focus of numerical simulation, especially the combustion and NO_x emission characteristics under different structural and operating conditions. In addition, the calculation models adopted by different scholars were summarized and analyzed, based on which the common models suitable for simulation of PC industrial boiler were concluded.

Acknowledgments

Financial support of this work by the National Key R&D Program of China (2017YFF0209800) and Science and Technology Planning Project of AQSIQ (2016QK199) are gratefully acknowledged.

References

[1] Wang N., Shang Q., Zhang X., et al. (2016) Practice of pulverized-coal fired industrial boilers in Germany and status of its research, promotion in China. Industrial Boiler, 2: 1-10.
[2] Hatton E. (2009) The present situation of industrial boiler energy-saving and emission reduction in China and Europe. Industrial Boiler, 6: 11-17.
[3] Patankar S.V. (2002) Computational modeling of flow and heat transfer in industrial application. International Journal of Heat and Fluid Flow, 23: 222-231.
[4] Anagnostopoulos J.S., Sargianos N.P. (1993) The prediction of pulverized Greek lignite combustion in axisymmetric furnaces. Combustion and Flame, 92: 209-221.
[5] Belosevic S., Sijercic M., Oka S., et al. (2006) Three-dimensional modeling of utility boiler pulverized coal tangentially fired furnace. International Journal of Heat and Mass Transfer, 49: 3371-3378.
[6] Zhou L., Li L., Li R. (2002) Simulation of 3-D gas-particle f lows and coal combustion in a tangentially fired furnace using a two-fluid-trajectory model. Powder Technology, 125: 226-233.
[7] Xu Y. (2007) Numerical simulation on the combustion process of a new-type pulverized-coal burner. Huazhong University of Science & Technology, Wuhan.
[8] Jiang S., Wang Y., Zhou J., et al. (2014) Numerical simulation on middle volatile coal combustion in reversed injection burner. Journal of China Coal Society, 39: 1147-1153.
[9] Ji R. (2009) Numerical simulation of combustion in the industrial pulverized-coal boiler. Journal of China, 34: 1703-1706.
[10] Han L. (2016) Numerical simulation of burning in pulverized coal fired industrial boiler. North China University of Science and Technology, Tangshan.
[11] Zhu L. (2012) Combustion characteristic testing and numerical simulation study on the burner of high-efficiency pulverized coal industrial boiler. China Jiliang University, Hangzhou.
[12] Chi J., Chi Z., SUN G., et al. (2013) Numerical simulation and experimental study of burner and furnace of pulverized coal-fired industrial boiler. Power System Engineering, 29: 1-4.
[13] Li Z., Wei F., Jin Y. (2003) Numerical simulation of pulverized coal combustion and NO formation. Chemical Engineering Science, 58: 5161-5171.

[14] Williams A., Backreedy R., Habib R., et al. (2002) Modelling coal combustion: the current position. Fuel, 81: 605-618.
[15] Wang J., Chi Z., Sun G., et al. (2009) Study on flow field characteristics of a new burner of industrial pulverized coal fired boiler. Journal of China University of Metrology, 20: 269-273.
[16] Wang Y., Zhang X., Jiang S. (2013) Swirl intensity calculation of double-cone fine coal combustion chamber. Clean Coal Technology, 19: 79-84.
[17] Guo M. (2018) Research on the optimization of swirl inverse-jet combustor based on stable combustion mechanism in the recirculation zone. China Coal Research Institute, Beijing.
[18] Mo R. (2018) Numerical simulation study on ignition characteristics of coal water slurry in dual cone reverse burner. China Coal Research Institute, Beijing.
[19] Li G., Wang N., Xiao C., et al. (2015) Numerical simulation and investigation on flue gas recycle technology in industrial pulverized coal boiler. Clean Coal Technology， 21: 125-128,133.
[20] Wang P., Wang N., Cheng X., et al. (2018) Numerical simulation of deep air-staged technology in pulverized coal industrial boiler. Clean Coal Technology, 24: 68-76.
[21] Ma W. (2018) Numerical simulation of low nitrogen burner for industrial pulverized coal boiler. Shandong University, Jinan.
[22] Chi J. (2014) Research of adjustable furnace temperature and low NOx combustion on high-efficiency pulverized coal industrial boiler. China Jiliang University, Hangzhou.
[23] Liu Z., Wang N., Ji R. (2013) Numerical simulation of Venturi pulverized-coal mixer. Coal Conversion, 36: 52-55.
[24] Kurose R., Makino H., Suzuki A. (2004) Numerical analysis of pulverized coal combustion characteristics using advanced low-NOx burner. Fuel, 83: 693-703.
[25] Yakhot V., Orszag S.A., Thangam S., et al. (1992) Development of turbulence model for shear flows by a double expansion technique. Physics of Fluids A, 4: 1510-1520.
[26] Patankar S.V. (1980) Numerical heat transfer and fluid flow. Hemisphere, New York.
[27] Field M.A. (1969) Rate of combustion of size-graded fractions of char from a low rank coal between 1200K-2000K. Combust Flame, 13: 237-252.
[28] Eaton A.M., Smoot L.D., Hill S.C., Eatough C.N. (1999) Components, formulations, solutions, evaluation, and application of comprehensive combustion models. Progress in Energy and Combustion Science, 25: 387-436.
[29] Qiu X. (2016) Numerical simulation study on one kind of industrial pulverized coal boiler with burner bottom arranged. Shanghai Energy Conservation, 12: 667-673.
[30] Kumar S., Paul P.J., Mukunda H.S. (2002) Studies on a new high-intensity low-emission burner. Proceedings of the Combustion Institute, 29: 1131-1137.
[31] Wang Z. (2015) Design and numerical analyses of a anthracite blended pulverized coal burner. Jimei University, Xiamen.