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Review article

Computational modeling of pulverized coal fired boilers – A review on the current position

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ABSTRACT

Computational modeling of pulverized coal fired boilers has made considerable advances in the past 5 decades. Modeling the furnace of a coal-fired boiler is a complex task. Even though bulk of the heat transfer to the furnace water walls is by radiation, it is complicated by the presence of ash and other tri-atomic gases that participate in radiation. It is also necessary to accurately capture the kinetics of the devolatilization, char combustion and volatile combustion processes. The phenomenon of fluid flow is equally important since considerable amount of turbulence is involved. Any model developed for the prediction of critical performance parameters like furnace outlet gas temperature and pollutant emission levels will need to capture this multifarious nature of combustion inside a boiler furnace. While computationally expensive CFD codes are available in plenty, researchers have also developed simpler but effective reactor network models. This review explains the current research position in the computational modeling of pulverized coal fired boilers from the following perspectives i) Coal combustion modeling ii) Radiation modeling iii) Overall furnace model development.

1. Introduction

Coal fired power plants contribute to around 60% of the electrical power generation in India. The surge of non-renewable energy implies that these coal fired power plants need to be flexible in handling the considerable variation in load. Also, non-availability of a constant source of coal has pushed operators towards firing a wide range of coal in the boiler. In certain cases, blending of imported coal with Indian coal is also becoming unavoidable. Coupled with the above issues, modern day power plants need to adhere to stricter environmental norms. Hence it becomes critical for the boiler of the power plant to respond positively to these variations in load and coal. The boiler also needs to consistently operate at higher efficiency to ensure lesser pollutant emissions at the chimney. Hence an optimum design of boiler furnace and monitoring of its performance while in operation is essential. From the perspective of a boiler designer and a power plant operator, the critical parameters used to monitor the performance of a boiler furnace are i) Furnace Exit Gas Temperature (FEGT) ii) NO_x levels and iii) Unburnt Carbon. The fact that the boiler furnace is an extremely non-homogeneous and highly non-deterministic component of the power plant makes accurate prediction of these parameters harder.

Traditionally boiler designers used semi-empirical methods that were evolved based on the tests carried out in pilot plants and utility boilers supplied to their customers to predict the above parameters. Most of these models should have been well stirred models and were kept confidential until Soviet standards were divulged by Blokh [1]. One of such methods to compute the FEGT is the Gurvich method [2] used in Russian boiler calculations.

$$\frac{T_e}{T_c} = \frac{B_o^{0.6}}{B_o^{0.6} + M\ a_f^{0.6}} \tag{1}$$

where T_e and T_c are the furnace exit gas temperature and adiabatic flame temperature respectively, M is an empirical factor based on the fuel and gas temperature profile in the boiler furnace as described by Eq. (3), B_o is the Boltzmann number as in Eq. (2) and a_f is the coefficient of thermal radiation (4).

$$B_o = \frac{\varphi W_f V_c}{\sigma \psi A_p T_c^3} \tag{2}$$

where φ is the furnace efficiency (typically around 0.995), W_f is the fuel inputs in kg/s, V_c is the average heat capacity of the flue gas in the furnace in kJ/kg K, σ is the Stefan-Boltzmann constant (5.67×10^{-8} kW/m^2 K^4), A_p is the projected furnace area in m^2 and ψ is an empirical factor (ψ = ζx). Here x is the distance from the bottom of furnace to furnace exit. For coal fired boilers the value of ζ is

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assumed to vary between 0.35 and 0.55.

$$M = A - BX \quad (3)$$

where A = 0.59 and B = 0.5 for coal fired boilers and X is the relative position of the highest temperature in the furnace with respect to the furnace exit, with both quantities measured from the furnace bottom.

The coefficient of thermal radiation (a_f) is given as below:

$$a_f = \frac{1}{[1+\{(1/\epsilon_f)-1\}\psi]} \quad (4)$$

where ϵ_f is the flame emissivity.

However, an empirical relation is not always accurate and cannot be used with confidence every time. The value of FEGT influences the following: i) extent of fouling and slagging of water walls, superheater and reheater ii) level of attemperation required in the superheater and reheater which affects the heat rate of the plant and iii) temperature of the gas at airheater exit which affects the efficiency of the boiler iv) performance of the downstream heat transfer sections of the furnace like superheater and reheater. Hence it becomes essential to monitor the FEGT continuously to ensure efficient operation of the boiler. But constant measurement of the FEGT is extremely difficult since the ash laden flue gas can damage the instrument progressively. FEGT is inversely proportional to the amount of heat absorbed in the waterwalls of the boiler furnace which is in turn dependent on the size of the boiler furnace, the extent of cleanliness of the waterwalls and the type of fuel fired. Hence by measuring the heat absorption at various locations in the furnace, FEGT can be computed. There are methods to measure the heat flux to the waterwalls [3]. However, it is difficult to measure the surface heat flux and surface temperature for a large permutation of operating variables viz. furnace size, operating load, fluid flow in the waterwall, type of coal fired, ash deposition etc. since the experimentation requires meticulous planning and a large number of measurements which will lead to outage of the power plant for longer periods. In a situation where power scarcity prevails in India, large scale experimentation might not be possible. Hence one needs to take the help of numerical methods to complement the results from experimental measurements to give a complete insight into the processes inside a boiler furnace and thereby predict FEGT more accurately.

The next critical parameter in the operation of powerplant is the amount of NO_x emission. Stringent environmental regulations have made it essential to critically monitor the NO_x emission. NO_x emitted depends on various factors like excess air, burner configuration, amount of nitrogen present in the parent coal and staging of combustion air. Availability of a tool that can predict the NO_x emission in a boiler will aid the operators to judiciously control the operating parameters to minimize NO_x emission.

The amount of unburnt carbon in the fly ash of boiler should also be limited to acceptable levels so that the ash is saleable to other industries by the power plant operators. Unburnt carbon is affected by the extent of combustion of coal in the boiler furnace.

Considering the above factors, it is evident that a furnace model that can predict the FEGT, NO_x emission and unburnt carbon will aid both the designers and power plant operators in assisting to arrive at an optimum boiler design and efficient operation of the boiler furnace.

This paper reviews the current position in the area of computational modeling of pulverized coal fired boilers. The purpose of the paper is to acquaint the reader with the basic principles and methods related to modeling of pulverized coal fired boilers. As shown in Fig. 1, the paper is organized to give a systematic approach to the major building blocks of modeling the combustion process in a pulverized coal fired boiler.

Section 2 of the paper explains the concepts related to the modeling of the chemical kinetics of coal combustion in a boiler furnace. Current research position with respect to the modeling of devolatilization, char combustion, homogeneous gas phase combustion, NO_x formation mechanisms and unburnt carbon formation is discussed. Section 3 of the paper introduces the method for solution of radiative heat transfer in a boiler furnace and discusses the methodologies employed by various researchers in computing the radiative properties of gases participating in radiation. Since Indian coal has high ash content (30%–45%), the effect of ash on radiation heat transfer is also discussed in this section. Pulverized coal fired boilers with tangential firing systems introduce considerable amount of swirl to the gas and hence turbulence is an important parameter. Research related to modeling the turbulence and development of overall furnace model are reviewed in Section 4.

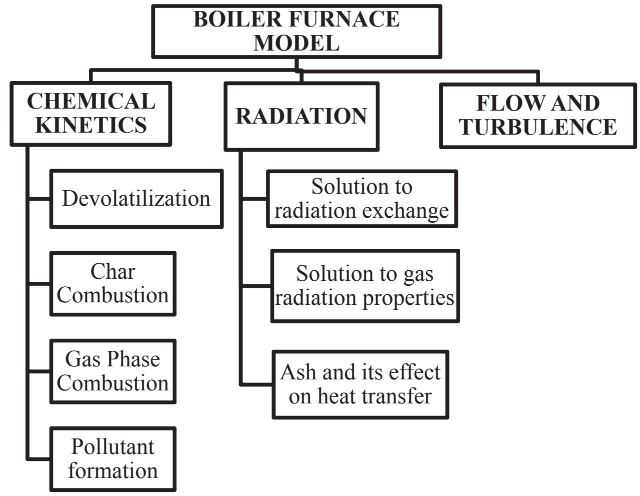

Fig. 1. Components of a coal fired boiler furnace model.

The existence of a very large body of literature relevant to modeling of coal fired boiler furnace is undeniable. A sincere attempt has been made to include most of the work that has happened in this broad research area. However, there exists some arbitrariness in inclusion of the work and hence it is possible that some of the work related to this research area be inadvertently overlooked. Previously a comprehensive review on modeling of coal combustion processes encompassing chemical kinetics, turbulent fluid mechanics, radiation and pollutant formation has been presented by Smoot in 1984 [4] and Eaton et al. [5], after which there is no extensive review work published in the literature. This review attempts to cover progress made in those areas till now.

2. Chemical kinetics

The combustion process of a coal particle inside a pulverized coal fired boiler furnace can be considered to be a two-step process: i) Devolatilization and the subsequent volatile combustion and ii) Char combustion. The major indicators of this combustion process of coal are the NO_x levels at the furnace outlet and unburnt carbon content remaining in the ash particles collected at various hopper locations in the boiler. Hence in order to simulate the combustion process in a boiler furnace accurately, it is imperative to model the devolatilization, char combustion process and the reactions of the homogeneous phase in order to compute accurately the above mentioned indicators. Accordingly, this part of the review is split into six sections namely: i) Devolatilization modeling ii) Char combustion modeling iii) Homogeneous gas phase combustion modeling iv) Overall coal combustion modeling v) Unburnt carbon prediction vi) NO_x prediction. Prior to this review, Smoot [6] in 1984 provided a comprehensive summary of pulverized coal combustion modeling and experimental work carried out at the Brigham Young University. Williams et al. in 2000 [7] and in 2002 [8] authored a review on research in combustion modeling and identified the gaps to be fulfilled in this discipline.

Fig. 2 shows the different alternatives available for the modeling of coal combustion from chemical kinetics perspective. Alternatives available specifically for modeling devolatilization, char combustion