17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-XXXX
NUMERICAL MODELLING OF COAL COMBUSTION IN A DROP TUBE FURNACE (DTF)

Carlos Henrique Lauermann, carloslauermann@hotmail.com
Thamy Cristina Hayashi, thamy.hayashi@mecanica.ufrgs.br
Federal University of Rio Grande do Sul, Dept. of Mechanical Engineering. Combustion Laboratory. R. Sarmento Leite, 425, Centro, CEP 90050-170, Porto Alegre, RS, Brazil

Abstract. *Coal is still widely used as a source of energy and it is main solid fuel used for electricity production. The more abundant it is, the more useful it becomes. However, considering environmental factors, coal may not be the best option due to the products generated through its combustion. However, it is necessary to know the behavior of this fuel in front of the energy production processes to optimize them and minimize pollutants. The objective of this work is to present a model that has been developed in order to allow for the investigation of the kinetic parameters of combustion of coals and biomasses in a drop tube furnaces, which is an equipment capable of resembling actual combustion conditions.*

Keywords: *Coal, coal combustion, modelling, DTF*

1. INTRODUCTION

Combustion has been mankind's major source of heat for either end-use as so or conversion to work. Even though research on alternative energy sources have been reinforced in the past decades, the availability of fossil fuels has made it very difficult for other technologies to prove being more reliable and cost-effective than simply burning coal, oils and natural gas or other hydrocarbon fuels. Particularly interesting in the Brazilian southern states, where its significant reserves are concentrated, coal is still widely used as a source of energy and it is main solid fuel used for electricity production. The more abundant it is, the more useful it becomes. However, considering environmental factors, coal may not be the best option due to the products generated through its combustion. which rises the need for studies to know the behavior of this fuel in front of the energy production processes to optimize them and minimize pollutants.

Enhancing the efficiency of coal combustion, either when used as single fuel or in mixtures with other solid fuels requires the knowledge of the kinetics of the conversion steps. Researchers have mainly used thermogravimetric analysis (TGA) to study the kinetic parameters of the devolatilization and combustion steps, but since the heating conditions in these tests do not resemble the flow and heating conditions that are present within industrial equipments, drop tube furnaces (DTF) have been used to overcome this difficulty.

A DTF consists in a vertical cylindrical reactor, capable of mantaining a homogeneously heated section along which combustion of solid fuel particles take place in similar heating rate and temperature conditions as those that are found in the operation of industrial-scale pulverized coal boilers. Through experiments in DTF it is possible to characterize the efficiency of burning solid fuels, the process of release of volatiles, the emissions generated and deposition of ash on surfaces. It is also possible to study the kinetic effects of different atmospheres by controlling the composition of the gas or to study the interaction effects of different fuel mixtures.

A drop tube furnace was built in the Combustion Laboratory of the Mechanical Engineering Department of the Federal University of Rio Grande do Sul - UFRGS. The reactor measures 1340 mm in testing height and can be heated to provide inner temperatures up to 1200ºC. Combustion of samples of the selected fuels can be evaluated in terms of the evolution of burnout, gas temperature and composition of the gas and of the char collected in a set of positions along the DTF axys.

The objective of this work is to present a model that has been developed in order to allow for the investigation of the kinetic parameters of combustion of coals and biomasses in the DTF. The model is based on the work of Ballester and Jiménez, 2005, and consists of a set of transient balances of momentum, mass and heat transfer in a diluted flow of solid fuel particles. The results of time integration are converted to provide spatial evolution of burnout, particle temperature and particle diameter along the heated length of the furnace as functions of the DTF operating conditions and particle size distribution. Predicted results are compared with experiments conducted by Wang, 2014.

2. MODEL

2.1 Problem formulation

A drop tube furnace similar to the one under study was designed and built at the Combustion Laboratory – LC/UFRGS, as part of the development of the capacity to investigate the kinetics of thermal conversion of Brazilian coals and biomasses. The main characteristics of a typical DTF and probe are shown in Fig.1.

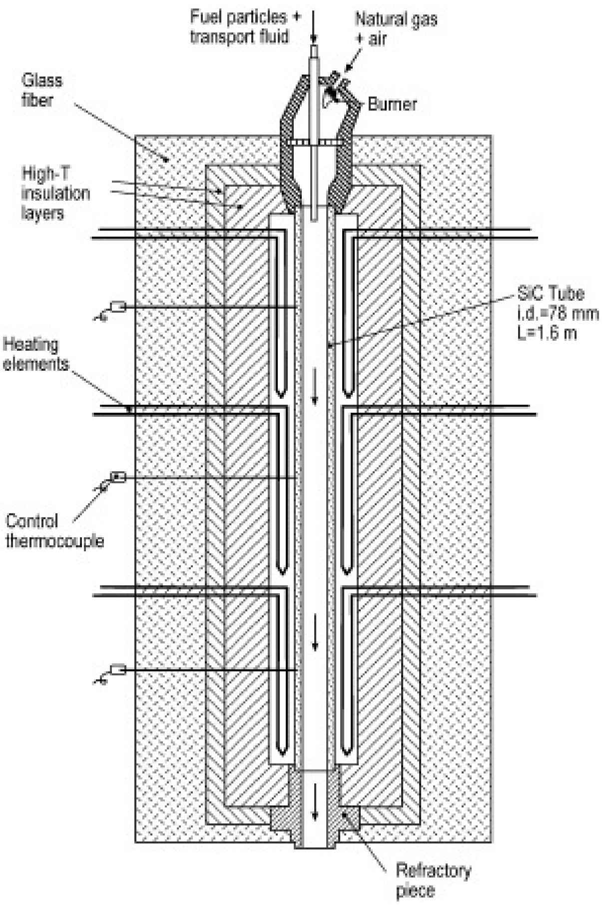

Figure 1. Schematic view of a drop tube furnace (Ballester and Jiménez, 2005).

The reactor is continuously fed with a diluted mixture of the solid fuel in the carrier gas. The gas guides the particles to a moving probe, positioned inside the cylinder for characterization of the fuel along the reactor. The gas can be preheated and the particles collected by the probe are cooled by the same with water and nitrogen in order to stop the devolatilization or combustion reactions at the given moment.

The DTF is able to simulate in laboratory the working conditions of large-scale combustion processes at high temperatures and high heating rates, such as an industrial reactor. It can simulate the burning of coal in boilers. Ovens can be configured using the operational key parameters to produce results similar to those observed on actual burners. Key parameters include gas temperature, gas velocity, particle residence time, air excess, heating rate and particle surface temperature (Zimmer, 2012).

According to Wang, 2014, the DTF of Instituto Superior Técnico, operates at a maximum temperature of 1100 ºC. The combustion chamber measures 0.05 m and 1.3 m in the inner diameter and in the length, respectively, and is made of stainless steel. The temperature control in the kiln wall is performed by eight K type thermocouples, distributed along the reactor. A double thread type volumetric feeder transfers the particles to the cooled injector, from where the fuel is inserted into the combustion chamber. After traversing part of the combustion chamber, the particles are collected by means of a mobile probe which is cooled with water and nitrogen. Combustion is ceased at the moment the particles are collected.

2.2 Numerical model

Following the modelling approach of Ballester and Jiménez, 2005, combustion of coal is divided into two stages, devolatilization and char combustion. In addition to the parameters of operation and geometric characteristics of the DTF, it is necessary to provide the model with the temperatures measured along the reactor.

The conversion (burnout) is defined as the fraction of the initial amount of volatiles and char that is consumed:

$$BND = 1 - \frac{V + C}{V_0 + C_0} \tag{1}$$

The number of particles for the i-th class, N_i depends on the initial particle diameter $d_{p,i}^0$ and density $\rho_{p,i}^0$, as well as on the mass fraction of class i in the coal, ω_i:

$$N_i = \frac{\omega_i}{\frac{1}{6}\pi\left(d_{p,i}^0\right)^3 \rho_{p,i}^0} \tag{2}$$

A balance of the gravity, inertia and drag forces acting on the particle results in a differential equation that relates de particle velocity $v_{p,i}$ with the instantaneous size of the particle $d_{p,i}$, the fluid velocity v_g.

$$\rho_{p,i}\frac{1}{6}\pi\left(d_{p,i}\right)^3 \frac{\mathrm{d}v_{p,i}}{\mathrm{d}t} = \left(\rho_{p,i} - \rho_g\right)\frac{1}{6}\pi\left(d_{p,i}\right)^3 g - 3\pi\mu d_{p,i}\left(v_{p,i} - v_g\right) \tag{3}$$

where $\rho_{p,i}$ is the instant value of the particle density, g is the gravity acceleration, and μ and ρ_g are respectively the gas dynamic viscosity and density.

Knowing the evolution of the particle velocity allows for the coupling of the time-response of the particles with the distance travelled within the DTF. Once the gas temperature distribution is known from experiments, rates of volatile and char conversion are calculated at the position occupied by class i particles at the end of the time step.

Release of volatiles due to heating precedes the combustion of char, which takes place at higher temperature. In accordance with other works the velocity constant in the devolatilization rate (Eq. 4) is modelled as an Ahrrenius-type reaction (Eq. 5).

$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = -k_{V,i}V_i \tag{4}$$

$$k_{V,i} = A_V \exp\left(\frac{-E_V}{R_u T_{p,i}}\right) \tag{5}$$

In Eq.4 and Eq.5, V is the mass of volatile matter per kilogram of fuel, k_V is the velocity constant of the devolatilization reaction, A_V and E_V are respectively the pre-exponential factor and the activation energy, R_u is the universal constant of gases and T_p is the temperature of the particle. The index i is included as to recall that different conversion is reached by each class of particles in the flow along the DTF.

Char combustion is treated analogously to devolatilization. Following Ballester and Jiménez (2005), Ahrrenius-type kinetics of the apparent heterogeneous oxidation of the carbon mass is considered. Both the availability of oxygen at the surface of the particle and the effect of the variation of the superficial area are taken into account.

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = -k_{C,i}N_i\pi d_{p,i}^2 \tag{6}$$

$$k_{C,i} = A_C\, p_{O_2,s} \exp\left(\frac{-E_C}{R_u T_{p,i}}\right) \tag{7}$$

In Eq.6, C is the mass of char per kilogram of fuel. In the expression of the reaction velocity constant, Eq.7, the concentration of oxygen at the particle surface, $p_{O_2,s}$, is assumed to be constant and equal to that in the farfield, which is valid in the case of very diluted particulate flows. Moreover, A_C and E_C are respectively the pre-exponential factor and the activation energy of the char combustion apparent reaction.

As the particle temperature is different from the gas and reactor surface temperatures, it is necessary to perform the energy balance for each class of particles, which considers convective transfer of heat between the particles and gas, radiation heat transfer with the wall and heat release accompanying devolatilization and combustion, and reads:

$$\rho_{p,i}\frac{1}{6}\pi d_{p,i}^3 c_{p,i}\frac{\mathrm{d}T_{p,i}}{\mathrm{d}t} = -\dot{Q}_{dev,i} + \dot{Q}_{comb,i} + \dot{Q}_{conv,i} + \dot{Q}_{rad,i} \quad (8)$$

The dependence of the specific heat capacity, $c_{p,i}$, on the particle temperature is actually not taken into account and a constant value of this property is assumed. The heat rates in Eq.8 are expressed in terms of the heats of reaction Hdev and Hcomb, the gas and wall temperature (Tg and Tw, respectively) as follows.

$$\dot{Q}_{dev,i} = \frac{1}{N_i}\frac{\mathrm{d}V_i}{\mathrm{d}t}H_{dev} \quad (9)$$

$$\dot{Q}_{comb,i} = \frac{1}{N_i}\frac{\mathrm{d}C_i}{\mathrm{d}t}H_{comb} \quad (10)$$

$$\dot{Q}_{conv,i} = hA_{s,i}\left(T_g - T_{p,i}\right) = \pi d_{p,i}\,\mathrm{Nu}\,k_g\left(T_g - T_{p,i}\right) \quad (11)$$

$$\dot{Q}_{rad,i} = \sigma\varepsilon\pi d_{p,i}^2\left(T_w^4 - T_{p,i}^4\right) \quad (12)$$

After integration of the set of equations for each class of particles individually, for a residence time long enough as to obtain total conversion of particles the time evolution of the burnout, particle size and temperature are post-processed in order that the spatial description of the process for each class can be summed to obtain the overall result of conversion in the DTF.

The total unburned fraction is obtained by summing the product of the mass percentage of the class by the unburned fraction of the same group at each position along the reactor.

$$V(x) = \sum_i \omega_i V_i(x) \quad (13)$$

$$C(x) = \sum_i \omega_i C_i(x) \quad (14)$$

$$U(x) = \frac{C(x)+V(x)}{C_0+V_0} \quad (15)$$

3. RESULTS

Simulations of the experiments conducted by Wang (2014) were carried out to assess the ability of the model to reproduce those experimental results. Wang (2014) studied the combustion of European coals in a DTF similar in size to the one that has been built at UFRGS.

Predicted results of burnout are compared to experimental data presented in Wang (2014). It is observed that a better agreement is obtained at higher temperatures, where combustion is the dominating process. In the devolatilization section, the model predicts higher reaction rates.

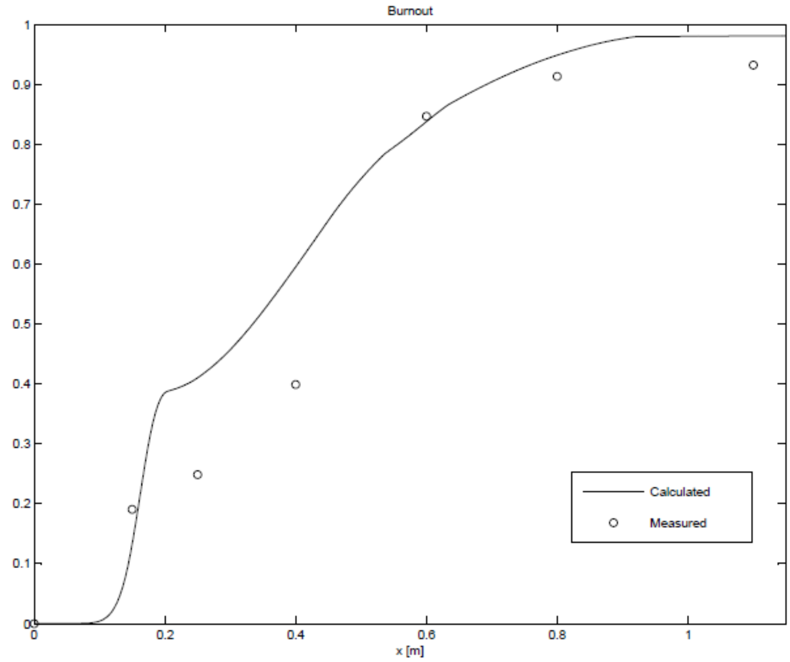

Figure 2. Comparison of predicted results of coal burnout in DTF with experimental data from Wang (2014),

In the continuation of the work, tests of sensibility of the predicted burnout to variations of the kinetic paramenters are being conducted to support the implementation of a procedure to estimate kinetic parameters of the thermal conversion of solid fuels from DTF tests.

4. REFERENCES

Ballester, J., Jiménez, S., 2005. "Kinetic parameters for the oxidation of pulverised coal as measured from drop tube tests". *Combustion and Flame*, Vol. 142, p. 210.

Wang, G., 2014. *(Co-)combustion of solid fuels: experiments and modeling*. PhD Dissertation, Instituto Superior Técnico, Lisbon, Portugal.

Zimmer, L., 2012. *Modelagem da combustão de carvão em um forno de queda livre*. ("Modelling of coal combustion in a drop tube furnace"). MSc dissertation. Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.