Combustion and Flame 180 (2017) 196–206

Contents lists available at ScienceDirect

Combustion and Flame

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

The influence of the structure heterogeneity on the characteristics and conditions of the coal–water fuel particles ignition in high temperature environment

Samen V. Syrodoy[a,*], Genii V. Kuznetsov[a], Arkadiy V. Zhakharevich[a], Nadezhda Y. Gutareva[a], Vladimir V. Salomatov[b]

[a] National Research Tomsk Polytechnic University, 30 Lenin Avenue, Housing 4, Audience 203, Tomsk 634050, Russia
[b] S.S. Kutateladze Institute of Thermophysics, Siberian Division of the Russian Academy of Sciences, Lavrent'eva Avenue 1, Novosibirsk 630090, Russia

ARTICLE INFO

Article history:
Received 17 August 2016
Revised 2 February 2017
Accepted 3 February 2017
Available online 27 March 2017

Keywords:
Water–coal fuel
Ignition
Heterogeneous structure
Porosity

ABSTRACT

The results of the experimental and numerical study of the coal–water fuel particles ignition (CWF) have been given, where the thermal properties (thermal conductivity (λ), heat capacity (C), density (ρ)) have been calculated using the different mathematical models. The heterogeneity and porosity of the structure of CWF have been taken into account in calculating λ, C and ρ. The influence of the shape, configuration and size of the pores on the thermal characteristics of coal–water fuel has been analyzed. It has been established that the effective thermal conductivity (λ_{eff}) is changed when there are the different ways of describing the thermophysical properties. It has been shown that increasing porosity (m_p) of fuel during thermal decomposition affects λ_{eff} (or leads to the higher values of the effective coefficient of thermal conductivity, or to its decrease).

The set of the core processes of heat and mass transfer (thermal conductivity, filtration of water vapor, ignition) has been taken into account when conducting mathematical modeling. It has been carried out with taking into account the intense physicochemical (thermal decomposition of the organic part of the fuel, thermochemical interaction of water vapor and carbon coke) and phase (evaporation of water) transformations together in the WCF particle in the conditions of high temperature heating.

According to the results of the mathematical modeling the delay time of ignition of the coal–water fuel particles has been calculated. The "influence" of the ways of describing the thermal characteristics of CWF has been shown, which can be changed in the process of temperature increase on the delay time of ignition. It has been established that even if the maximum possible change of the coefficient of thermal conductivity (depending on the model λ_{eff}) deviation of the ignition delay time from the average values does not exceed 13%.

1. Introduction

1.1. The economic practicability of the use of the coal–water fuel technology

The application of coal–water fuels (WCF) is one of the promising directions of the power system development [1–7]. The analysis [8] of the current state of the power system (including in the USA) shows that the hydrocarbon fuel can be used as a basic raw material for the thermal power stations. At the same time some characteristics [9] (primarily environmental) WCF is significantly superior to the traditional solid (coal, peat) and liquid (fuel oil) energy carriers. It is also worth noting that the hydrocarbon fuel is more economically profitable in many respects than coal. This is explained by the fact that WCF can be moved over the long distances by pipelines [10]. There is no need in the construction of the large coal depots and the fuel equipment. It saves significantly the interior space of the thermal electric power station, due to the lack of the basic and the transitionary intermediate dust hoppers and the mill equipment.

The use of WCF reduces significantly the cost of the electricity production and as a result reduces it to the end user (e.g. steel production). The latter is one of the factors increasing the competitiveness of the finished products. For example, the Chinese (the WCF technology is spread in China) steel companies have ousted practically the American companies from the USA market. This fact becomes a subject of the political debates [11]. As a result, the USA

* Corresponding author.
E-mail address: ssyrodoy@yandex.ru (S.V. Syrodoy).

http://dx.doi.org/10.1016/j.combustflame.2017.02.003

Nomenclature

T	the temperature, K
σ	the constant of radiation of a black body, W/(m^2 K^4)
ε	integrated emissivity
α	convective of heat transfer coefficient, W/(m^2 K)
p	pressure, Pa
η	the proportion of the thermally decomposed substance
k	preexponent, heterogeneous (m/s) or homogenous (1/s) of the reaction
U	velocity of water vapor in the radial direction, m/s
V	velocity of water vapor in the azimuthal direction, m/s
m_p	porosity
Z	compressibility of water vapor, 1/Pa
K_P	the degree of permeability of the porous structure, m^2
ν	dynamic viscosity, Pa s
Q	thermal effect, J/kg
λ	coefficient of thermal conductivity, W/(m K)
C	heat capacity, J/(kg K)
ρ	density, kg/m^3
r	radius, m
θ	the azimuth angle, radian
h	step of difference grid in space, m
t	time, s
τ	the time step, s
N	the number of nodes of the difference grid

Subscripts

0	is the initial moment of time
1	the area of the original "wet" fuel
2	area of the "dry" fuel
F	evaporation front
g	high temperature gas
i	number of the reaction
s	steam
ev	the interface of the "wet fuel — dehydrated part"
fr	the state of water in freezing temperatures
atm	the atmosphere
eff	effective
etd	end thermal decomposition
ign	ignition
out	outer
std	start thermal decomposition
sur	surface
wat	liquid water

government even had to impose anti-dumping duties [12]. It is also worth noting that the hydrocarbon fuel is advantageous to use as the primary due to the fact that the combustion of WCF produces very little ash (due to the lower combustion temperature), respectively, saving money on cleaning the heat exchange surfaces [13].

1.2. The mathematical models of coal–water fuel particle ignition

Despite all the above advantages of the technology of coal–water fuels the objective conditions for their widespread use have not been created yet. There is no general theory of ignition and combustion of such substantially inhomogeneous heterogeneous fuels. Designed to date, the mathematical models and methods for solving the problems of the WCF particles ignition can be divided into three groups.

The first are the so-called "balanced" or "zero-dimensional" models [14–16], due to the development of which it is assumed that the temperature field of the fuel particle is uniformly, and the evaporation process is focused directly on its surface. These models are the simplest and allow to obtain the approximate analytical expressions for the calculation of the ignition characteristics.

The second group includes the models [17–19], in which the process of the WCF ignition is divided into a number of the serial stages corresponding to the particular physical processes (inert heating, evaporation of water, thermal decomposition of the organic part of the fuel, ignition).

However, the most common is the third group of the WCF ignition models [20–23]. The latter describe the process of ignition by the system of the nonstationary differential equations in partial derivatives. At the same time [20–23] the basic physical and chemical processes in the induction period are taken into account. But while using the technique [20–23] the effect of only a small group of important factors (thermal radiation [21] and particle shape [22]) on the conditions and characteristics of the WCF ignition has been investigated.

1.3. About the essential heterogeneity of the fuel in the ignition

It is known [23] that the WCF in the combustion process is substantially non-uniform with a large enough group of the components (carbon, water, water vapor, gaseous and solid products of the thermal decomposition of the organic part of the fuel, the reaction products of water vapor and carbon "coke", etc.) fuel. It is worth noting that the main stage of the thermal preparation of the WCF drops to the ignition—water evaporation. It is known that evaporation occurs in a very narrow zone (its thickness $\delta \to 0$), called the evaporation front from the work of Heinrich Hertz in 1882 [24]. This is confirmed by the modern researches [25,26]. Accordingly, it is reasonable to assume that in the process of ignition the coal–water particle represents a significantly heterogeneous structure, the thermal and physical characteristics of which depend greatly on the localization of the phase transition front and can be changed abruptly when crossing the boundary of the system "wet fuel—dry coal". It should be noted that both parts of this system—the inhomogeneous heterogeneous structure, consisting of the coal frame and water (the wet part of the fuel) or a mixture of water vapor and the pyrolysis products (dry area of the particle). Accordingly, it is reasonable to assume that the characteristics of heat and mass transfer in such heterogeneous systems will be different significantly from the thermal conductivity in the monolithic coals. For this reason, the use of the simplified models of the coal ignition [16] can lead to significant errors in the calculation of the delay times of ignition. At the same time, it has been established [27,28] that the characteristics of ignition of any condensed substance are substantially dependent on its thermophysical properties. But the analysis for the hydrocarbon fuels of the impact of these characteristics in a possible quite wide range of their changes to the conditions of WCF ignition has not been conducted. It should be noted that the theory of the thermo-physical properties of the disperse and porous media is a system of several dozen [29–38] of the mathematical expressions for the thermal conductivity (λ) and heat capacity (C), corresponding to a particular range of variation of the volume fraction of the component and the conditions of their mutual arrangement. The important aspect of the theory of WCF ignition is reasonable theoretically, the choice of the specific expressions to compute the values of λ and C in the mathematical modeling. The determination of these characteristics in the temperature range from the initial state of the coal–water fuel (when dispersed at the inlet to the furnace of the boiler unit of the thermal power station) to the conditions of the sustained ignition experimentally, is not possible yet.