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Research article

Ignition of promising coal-water slurry containing petrochemicals: Analysis of key aspects

Dmitrii O. Glushkov, Semen V. Syrodoy, Arkadiy V. Zhakharevich, Pavel A. Strizhak *

National Research Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk 634050, Russia

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ABSTRACT

An experimental study of the macroscopic laws of the ignition of coal-water slurry containing petrochemicals (CWSPs) based on coal and flammable liquids processing waste is presented. Investigations have been performed to determine the prospects for burning such fuel mixtures prepared from raw materials in power plants at temperatures ranging from minimal (700–800 K) to high (not $<$1000 K). Oxidizer flow velocities varied between 0.5 and 5 m/s. The study specifies the main stages of the processes at different heating rates and heat flows through a fuel surface element (a droplet or a particle). Investigations have been conducted on a single droplet (radius from 0.25 mm to 1.5 mm) of a specified fuel composition (we have considered over 20 different compositions). With the use of cross-correlation and high-speed video cameras coupled with software applications Tema Automotive, Actual Flow, we have examined the interactions of oxidizer flow with a fuel droplet surface. The ignition delay time and durations up to complete combustion of CWSP droplets have been measured. The experimental results allowed us to elaborate the heat and mass transfer mathematical model including phase transitions and chemical reactions in the main stages of the processes under study, which are: the inert heating up of the sample, the evaporation of moisture from a superficial layer (water and flammable liquid), the thermal decomposition of coal in the superficial layer of a droplet, the mixing of volatiles with an oxidizer, the combustion initiation of the emerging gas mixture, the heating up of coke, and its heterogeneous ignition. From the mathematical model and experimental data, we have defined the necessary and sufficient conditions for the ignition of CWSP.

1. Introduction

Numerous results of theoretical and experimental studies over the past 25 years (see e.g. [1–7]) in the field of coal-water technologies (the structure and characteristics of fuels, peculiarities of their preparation, transportation and spraying in furnaces, combustion in power plants and other industrial plants) characterize their high interest. At the same time, as a rule, it is noted that key issues are the definition of necessary and sufficient conditions for ignition of coal-water slurry (CWS).

Reports [4,5] present such conditions for particular CWS of given composition. In these studies, an interesting approach was applied. A droplet of CWS was placed on a thermocouple junction and was inserted to a cylindrical chamber (with an observation window made of quartz). The temperatures in the droplet, near its surface, and oxidizer temperatures in the chamber were measured. The experimental values of these temperatures obtained at the ignition of CWS allowed elaborating a theoretical model that is considered as one of the most complete; it takes into account the basic processes, phase transitions and chemical reactions.

An experimental approach described in studies [4,5], based on hanging a CWS droplet on the thermocouple junction, can be considered as the most optimal in terms of collecting information about the test processes and minimizing the impact of the junction on the conditions of droplet's heating up and ignition. Preliminary experiments using this setup demonstrated that in the case of mixing CWS droplets in an oxidizer flow, it is difficult to monitor the characteristic change in their size, ignition stages, dispersion and other features, even using high-speed video recording complexes and specialized software applications with continuous tracking functions. To process the results of experiments, the authors used rather limited (by functions) software and did not focus on the patterns of changes in size, shape and appearance of CWS droplets during heating up. The results of experiments [8,9] show that such features can be identified using Tema Automotive software application. This will complement the theoretical model [5].

One of the promising directions for the development of CWS combustion technologies can be the burning of mixtures of slurry and flammable liquid. Only few research results on coal-water slurry containing petrochemicals (CWSPs) are published (for example, [10–13]). The urgency of improving their burning is very high. The

* Corresponding author.
E-mail address: pavelspa@tpu.ru (P.A. Strizhak).

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Nomenclature

C	heat capacity, J/(kg·K)
E	activation energy, J/(mol·K)
k	pre-exponential factor, 1/s
K_P	permeability of porous structure, m^2
M	molar mass, kg/mol
m	porosity
p	pressure, Pa
p_l^s	pressure of saturated vapor, Pa
Q	enthalpy of process/reaction, J/kg
q_c	conductive heat flux, W/m^2
q_k	convective heat flux, W/m^2
q_r	radiative heat flux, W/m^2
R	radius, m
R_t	perfect gas constant, J/(mol·K)
S	surface area, m^2
T	temperature, K
T_s	surface temperature, K
u	filtration rate of gas mixture (water vapor + flammable liquid vapor + volatile), m/s
V	velocity, m/s
W	mass rate of process/reaction, kg/(m^2·s)
Z	degree of compressibility of water vapor, 1/Pa

Greek symbols

α	convective heat transfer coefficient, W/(m^2·K^4)
ε	emissivity
η	burnout parameter
λ	thermal conductivity, W/(m·K)
ν	viscosity, Pa·s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, W/(m^2·K^4)
τ	time, s
τ_c	complete combustion time, s
τ_d	ignition delay time, s
φ	mass fraction

Subscripts

0	initial conditions
4	gas mixture (water vapor + flammable liquid vapor + volatile)
c	coal
d	droplet
dec	thermal decomposition
f	freezing point
g	heated gas flow (air)
l	flammable liquid
ox	oxidation
p	particle
rev	reversible reaction
v	vapor/volatile
vap	evaporation
w	water

main components of CWSP can be: low quality coal dust, waste water, coal processing and oil refining waste, waste oils and various flammable liquids. The most important issue is the possibility of using filter cakes in CWSP (the volumes of such low-quality coal processing residues are estimated in millions tons in the world [14–17]). Filter cake is coal flotation waste. In accordance with this method of enrichment, a coal rock is washed with water and surfactants. Further, coals are sorted on sieving to separate size fractions. Water used for washing the rock is fed into special tanks, in which coal particles are sedimenting. This suspension is pumped out and sent to press filters, in which the suspension is filtered through a special membrane – extraction takes place. The resulting wet residue of coal particles is filter cake.

Solving the problems of producing CWSP will significantly expand a resource base for large and small power industries. Thus, there will be an alternative to high quality energy fuels based on coal, oil and gas. This is a major economic issue for many countries, where particularly oil and gas are the main sources of economic growth.

CWS and CWSP are of great interest due to their high environmental and economic performance compared to conventional solid fuel (coal dust) [10–13]. Since CWS and CWSP have low calorific value, one can assume that their burning in power plants should be provided at much lower oxidizer temperatures than that at present time (as a rule, over 1200 K). The research results have not been published yet on the low-temperature combustion of CWS and CWSP droplets. Therefore, it is of interest to develop an approach [4,5] targeting lower oxidizer temperatures aiming at low-temperature regimes around 600–800 K [18,19] to study the ignition processes of CWSP. This will allow developing a heat and mass transfer model, which takes into account the main stages of the ignition of CWSP droplets with phase transitions and chemical reactions.

The aim of this work is to study the macroscopic laws of the ignition of promising coal-water slurry based on typical waste of coal processing and oil refining.

2. Experimental methods

We have studied the ignition of CWSP droplets of a unique composition using the setup described in Fig. 1. The main recording tools of the facility are similar to those used in experiments [20,21]. A CWSP droplet *1* was heated in the air flowing inside a glass (quartz) cylinder *2*. By using a blower *3* and a heater *4*, the oxidizer temperature T_g can be varied in the range of 600–1100 K, the air flow velocity V_g is in the range of 0.5–5 m/s. These parameters allow us to examine

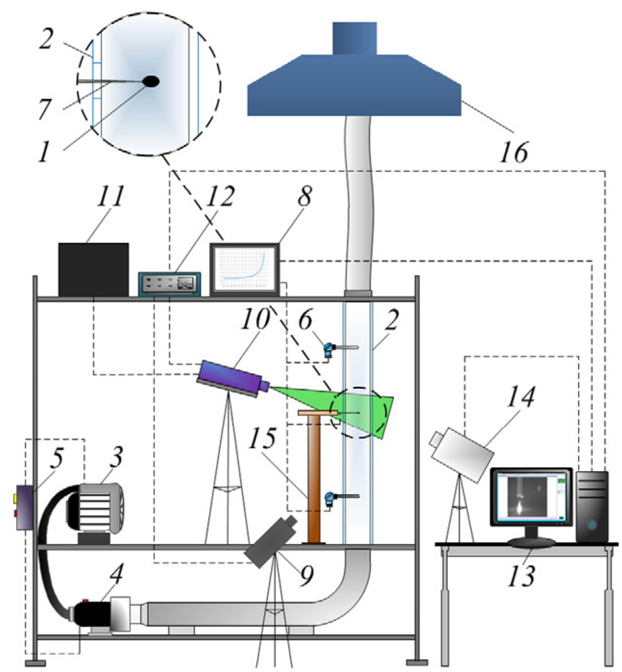

Fig. 1. Scheme of experimental setup: *1* — droplet; *2* — hollow glass cylinder; *3* — blower; *4* — heater; *5* — remote control; *6* — thermocouples; *7* — low-inertia thermocouple; *8* — registrar; *9* — cross-correlation video camera; *10* — two-pulse solid-state laser; *11* — laser generator; *12* — synchronizer; *13* — computer; *14* — high speed video camera; *15* — positioning mechanism; *16* — exhaust ventilation.