Experimental and numerical study of heat transfer and oxidation reaction during ignition of diesel fuel by a hot particle

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H I G H L I G H T S

- Metal disk with parameters $r_p > 3$ mm, $z_p > 3$ mm, $T_p > 1300$ K can be a diesel fuel igniter.
- Ignition time delay for a ceramic particle is larger than for a metal particle.
- Using a metal particle as a diesel fuel igniter leads to heat transfer enhancement.
- Ignition does not occur at full immersion of a hot particle into the liquid fuel.

A R T I C L E   I N F O

A B S T R A C T

This study is focused on the heat and mass transfer in the complex process of ignition of diesel fuel by a local heat source. The main macroscopic rules governing the ignition of liquid fuel by small steel and ceramic particles heated from 1200 K to 1500 K are established and reported. The investigated parameters are the ignition time delay for different igniters i.e. with different sizes, temperatures, porosities and thermophysical properties. Physical and mathematical models are elaborated. The experimental results are used to describe the interactions between the local heat source and the liquid fuel. Numerical simulations of heat transfer processes are carried out taking into account the vaporization and the heat production by the oxidation reaction. The border line defining the limit of the stable ignition domain is determined for diesel fuel. Possible modes and mechanisms of ignition under laboratory conditions are established.

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1. Introduction

During recent years the increasing utilizations of large amount of liquid fuel concern heavy activities like auto [1–4], aviation [5–7] and shipping [8,9] industries. Large volumes of fuel are also widely stored before being used for heating of apartments [10,11]. On the one hand local heat sources with limited power capacity (e.g. metal and non-metallic scraps like shavers) can be used for energy saving in ignition systems [12,13]. On the other hand, hot particles produced when cutting, welding or disassembling steel and concrete-steel constructions are very often the cause of disastrous accidents. During transportation under overloaded conditions by vehicles with increasing size amplifies the potential danger of these activities involving combustible and volatile flammable liquids [14–16]. This is confirmed by numerous fires in Russia, such as oil sludge processing plant fire in Khanty-Mansiysk (2012), trunk oil pipeline fire in Krasnodar Region (2013), Achinsk oil refining factory fire in Krasnoyarsk Region (2014). A detailed understanding of the critical conditions for ignition of flammable liquids by hot particles is very important for elaborating efficient safety rules, for the development of energy saving ignition system and for fire safety by improving technological processes.

In practice, ignition is a very comprehensive process. When liquid fuel is heated, evaporation from the fuel surface takes place. Flammable vapors are released and mixed with an oxidizer (air) producing a flammable mixture. In case this mixture reaches ignition conditions (concentration and temperature), gas-phase combustion is induced. Interconnected processes of fuel evaporation and oxidation heat release accelerate combustion. In general, the ignition of combustible and volatile flammable liquids is initiated by the ignition of evaporated products.

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Nomenclature

A	accommodation coefficient
a	heat diffusivity coefficient (m^2/s) ($a = \lambda/(C\rho)$)
C	specific heat ($J\,kg^{-1}\,K^{-1}$)
C_f	mass fraction of fuel vapor in air–vapor mixture
C_o	mass fraction of oxidant in air–vapor mixture
D	diffusion coefficient (m^2/s)
E	activation energy (J/mole)
F	surface area (m^2)
g	gravitational acceleration (m/s^2)
k_0	pre-exponential factor (s^{-1})
M	molar mass (kg/kmole)
m_1, m_2	reaction orders ($m_1 = m_2 = 1$)
P	vapor pressure above fuel surface ($N\,m^{-2}$)
P_1	dynamic pressure of fuel vapors ($N\,m^{-2}$)
P_2	pressure of particle gravity ($N\,m^{-2}$)
P_3	pressure of liquid in the direction of the radial coordinate ($N\,m^{-2}$)
P^n	saturated pressure of liquid fuel vapor ($N\,m^{-2}$)
Q_e	fuel enthalpy of vaporization (J/kg)
Q_o	fuel vapor enthalpy of oxidation (J/kg)
Q_r	thermal radiation heat flux ($W\,m^{-2}$)
r, z	coordinates (m)
r_p	radius of hot particle (m), $r_p = r_1$ (see Fig. 2(a))
r_l, z_l	solution domain sizes (m)
r_v, z_v	size of vapor gap between hot particle and diesel fuel (m), $r_v = r_2 - r_1$, $z_v = z_2 - z_1$ (see Fig. 2(b))
R_t	perfect gas constant ($J\,mole^{-1}\,K^{-1}$)
T	temperature (K)
T_b	boiling temperature of liquid fuel (K)
T_e	fuel surface temperature during vaporization (K)
T_p	initial temperature of hot particle (K)
T_0	initial temperature of liquid fuel (K)
t	time (s)
t_d	ignition time delay (s)
u, w	components of combustible gas velocity projected onto the axes r and z (m/s)
V	volume (m^3)
v	kinematic viscosity ($m^2\,s^{-1}$)
W_e	reaction rate of fuel vaporization ($kg\,m^{-2}\,s^{-1}$)
W_o	reaction rate of fuel vapor oxidation in air (s^{-1})
z_i	immersion depth of hot particle at the ignition moment (m), $z_i = z_3 - z_2$ (see Fig. 2(b))
z_p	height of hot particle (m), $z_p = z_2 - z_1$ (see Fig. 2(a)), $z_p = z_4 - z_2$ (see Fig. 2(b))

Greek symbols

α	convection coefficient ($W\,m^{-2}\,K^{-1}$)
β	thermal-expansion coefficient (K^{-1})
ε	emissivity
λ	thermal conduction ($W\,m^{-1}\,K^{-1}$)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
φ	volume fraction
ψ	stream function (m^2/s)
ω	vorticity vector (s^{-1})

Subscripts

1	air
2	hot particle
3	liquid fuel
4	fuel vapor
5	air–vapor mixture

It was established [17,18] that a hot metal particle moving through the vapor of combustible liquid may trigger inflammation of combustible vapors mixed with air at relatively low temperature. However, conditions and characteristics of ignition are depending on many parameters, not only on the temperature of the heat source and combustible vapor mass fraction in the air; but also on parameters as sizes of the igniter, its displacement velocity, air convection intensity, mass transfer conditions. Under these nonstandard conditions the complex physical and chemical processes immediately before the ignition are significantly differed from the voluntary ignition by electrical discharges or other traditional technologies of combustion initializations [19–22].

Some experimental [23–25] and numerical [26–28] studies explained the ignition of liquid fuel droplets or sprays during interaction with a hot plate or hot air. Most of them use different laws governing physical and chemical processes and conditions of the combustion initiation. Concentration of evaporation product or heat source temperature may be less important for ignition conditions, whereas kinetic characteristics of oxidation play significant role. In case of hot spot ignition activation energy and preexponential factor are less important than the heat transfer conditions near liquid fuel – at the hot particle interface to understand the ignition mechanism. The interrelated processes of heating liquid fuel near the surface and the cooling of igniter influence the intensity of formation and heating of combustible gas mixture, with consequences on ignition conditions.

The largest numbers of studies on hot spot ignition are focused on solid combustion of composite propellant [29–32]. In this case, local heat source was often located on the surface or embedded inside the explosives. Ignition occurs in the condensed phase and depends on consumption of solid combustible component and oxidizer during local heating of composite propellant. Gas-phase ignition of liquid fuel is characterized by evaporation, gas diffusion and penetration of solid particle inside liquid phase. These processes can be critical during formation and heating of the combustible gas mixture.

It is important to note that in [33,34] the authors take into account dispersed phase flow as igniter. It consists of a large number of hot solid particles imbedded in gas flow. It means that ignition conditions depend on parameters of hot particles and their concentrations. To determine the lower ignition limit of liquid fuel by local heat source, it is important to identify the particle parameters sufficient to begin the gas phase combustion to get going. For this purpose a model of single particle interaction with a fuel is more suitable.

The experimental and theoretical investigations of the heat and mass transfer shortly before vapor ignition of diesel fuel (it is typical for internal combustion engines) in air by small hot particles drop-out on relatively thin fuel films, are of high interest. The main objective of the present investigation is the determination of the critical conditions for the initiation of the oxidation reaction characterized by the ignition time delay as a leading parameter. The determination of this ignition time delay under laboratory conditions is another important objective.

Thus, our purpose is an experimental investigation of diesel fuel ignition by hot particle and the development of a numerical model for heat and mass transfer processes description. The numerical model takes into account conduction, convection, diffusion, evaporation, and gas-phase ignition for predicting the critical ignition conditions during the interaction of a local heat source with diesel fuel.