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Phenomenological characterization and investigation of the mechanism of flame spread over butanol-diesel blended fuel

Manhou Li[a], Kazui Fukumoto[a], Changjian Wang[a], Xiyu Zhang[a], Shenlin Yang[a,*], Xuanya Liu[b,*]

[a] School of Civil Engineering, Hefei University of Technology, Hefei 230009, China
[b] Key Laboratory of Building Fire Protection Engineering and Technology of MPS, Tianjin 300381, China

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ABSTRACT

The butanol-diesel blended fuel possesses broad application prospects in energy industry owing to its excellent properties; thus, studying on flame spread over the blended fuel is of great significance for both scientific meanings and practical guidelines. Several fundamental parameters of flame spread, including the flame spread rate, frequency of flame oscillation, temperature distribution, and velocity of subsurface flow are characterized. Prior to analyzing the experimental data, a blended fuel flashpoint-prediction model is developed based upon Le Chatelier's rule, Antoine's principle, and the ideal liquid evaporation theory. For low ratio of butanol, the calculated values of the butanol-diesel blended fuel flashpoints agree well with those achieved through experimental methodology. The flame spread characteristics of the blended fuel approach those of diesel fuel as the ratio of butanol is less than 17.5%, whereas they resemble those of pure butanol fuel with the ratio of butanol beyond 17.5%. Further, an increase in the ratio of butanol leads to an increase in the flame spread rate as well as the velocity of subsurface flow. The findings of the present work are useful to provide the basic data for butanol-diesel blended fuel spilling fire, and also to develop some fire prevention measures.

1. Introduction

Over the past decades, the rapid economic development of China has greatly improved people's living standards. An increasing number of Chinese people's household vehicles and engineering application vehicles continue to lead to a prominent domestic fossil fuel shortage problem. At the same time, the air pollution problem originated from fossil fuel combustion has attracted considerable attention. In order to solve the shortage of fossil fuels and reduce the emissions of combustion pollutants, scientists have endeavored to develop some clean and eco-friendly fuels [1].

Ethanol-gasoline and ethanol-diesel blended fuels are the most popular alternative fuels used in automotive vehicle, which contain a large proportion of hydrocarbon fuel and a small proportion of ethanol. However, the use of ethanol-gasoline or ethanol-diesel blended fuel generates some disadvantages, such as low combustion heat, low corrosion resistance, poor intersolubility and strong water imbibition [2]. Butanol is a transparent liquid which is the representative second generation biofuel. The source of butanol is very broad, i.e., agricultural residues, corn fiber and some types of lignin. The energy density of butanol approaches that of gasoline; thus it has the excellent fuel economy, high combustion efficiency and the increasing driving distance of the vehicle [3]. Meanwhile, the mutual solubility of butanol and diesel fuel is good, so that no extra chaotropic agent is necessary for mixing the two components [4]. The butanol-diesel blended fuel is currently gradually used to substitute the ethanol and fossil blended fuels. To date, researchers have put emphasis on the combustion efficiency of engine and exhaust emission [5]; however, less work has been conducted to reveal the fire safety issue of this fuel.

Flame spread over liquid fuels is an unavoidable process in the development of fire caused by a fuel leak. Although the occurrence of flame spread is merely the short process, it determines the direction and speed of the development of fire, and the available escape time. Therefore, studying on the phenomenological characterization and internal mechanisms of flame spread over liquid fuel is of great significance to approximate the fire risk. The combustion and flame spread characteristics are considerably influenced by the type of the liquid fuel, especially for alcoholic fuels and hydrocarbon fuels. For alcoholic fuels, flame spread was divided into gas phase- and liquid phase-controlled regimes according to the relationship of initial temperature and flashpoint. The flame always propagated in a steady manner under various initial fuel temperatures except for a small range of liquid temperatures. The non-uniform flame spread stage was defined as the oscillation regime, whereas the uniform flame spread stages were

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* Corresponding authors.
E-mail addresses: yangshl@hfut.edu.cn (S. Yang), liuxuanya@tfri.com.cn (X. Liu).

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Nomenclature

A	Antoine's coefficient, a constant
B	Antoine's coefficient, a constant
C	Antoine's coefficient, a constant
h_*	thermal boundary layer thickness (mm)
L_*	length of subsurface flow (cm)
P	saturated vapor pressure (kPa)
P_B^{f0}	saturated partial pressure of butanol at flashpoint (kPa)
P_D^{f0}	saturated partial pressure of diesel at flashpoint (kPa)
P_B^{flash}	partial pressure of butanol at blend's flashpoint (kPa)
P_D^{flash}	partial pressure of diesel at blend's flashpoint (kPa)
P_B^{mix}	vapor pressure of butanol at 57.2 °C (kPa)
P_D^{mix}	vapor pressure of diesel at 57.2 °C (kPa)
P_B^{sat}	saturated partial pressure of butanol in gas-phase mixture (kPa)
P_D^{sat}	saturated partial pressure of diesel in gas-phase mixture (kPa)
P_m^{sat}	saturated vapor pressure of gas-phase mixture (kPa)
T	liquid temperature (°C)
T_0	initial pool temperature(°C)
T_c	oil surface temperature beneath flame (°C)
T_{Cr}	critical transition temperature of gas phase- and liquid phase-controlled flame spread
u_s	velocity of subsurface flow (cm/s)
x_B	mole fraction of butanol fuel in liquid-phase blend
x_D	mole fraction of diesel fuel in liquid-phase blend
x_D	mole fraction of butanol fuel in gas-phase mixture
y_D	mole fraction of diesel fuel in gas-phase mixture

Greek symbols

Φ	diameter of thermocouple
γ	volume ratio of butanol (%)
σ_T	surface tension coefficient (N/m·°C)
μ	dynamic viscosity (mPa·s)
α_{DB}	relative volatility

Subscripts

D	component of diesel fuel
B	component of butanol

labeled as the pseudo-uniform, uniform and premixed regimes respectively, with the increase of initial fuel temperature [6]. Higuera [7] proposed that heat and mass transfer through the liquid-fuel thermocapillary flow occurred ahead of a propanol flame tip was imperative for the spreading flame. The thermocapillary flow resulted from surface tension in the liquid surface and it determined the velocity of the flame front. Schiller et al. [8] studied the flame propagation above alcohol pools on the basis of two-dimensional unsteady Navier-Stokes computations. Sasaki et al. [9] found that the flame height and the flame spread rate were proportional to the total vapor concentration of the binary mixed liquid fuels of methanol and ethanol.

For hydrocarbon fuels, White et al. [10] investigated the flame spread on multi-component JP-5, JP-8 and mixtures of these fuels. Liquid phase-controlled flame spread was characterized at the initial fuel temperature < 15 °C above the flashpoint of the aviation fuels, while gas phase-controlled flame spread was observed at the initial temperature < 15 °C above the flashpoint. Later, the critical transition temperature of gas phase- and liquid phase-controlled flame spread of hydrocarbon fuel was specified as the fire point [11]. Ji et al. [12] focused on the influence of initial fuel temperature on the flame spread characteristics of diesel and gasoline-diesel blended fuels. The oscillation wavelength of flame spread increased with initial pool temperature for diesel fuel, whereas it varied non-uniformly for gasoline-diesel blended fuel. The oscillation wavelength of gasoline-diesel blended fuel decreased initially and then increased with initial temperature. Bai et al. [13] verified that the flame spread was in a low-speed oscillatory way when the ratio of ethanol inside diesel fuel was less than 10% whereas it was in the uniform regime as the ratio of ethanol was larger than 10%.

In the process of flame spread across the liquid surface, the oscillatory behavior of the flame front is a unique phenomenon which is never observed in flame spread over solid fuels [14]. The oscillatory spreading represents that the velocity of flame spread is non-uniform during the whole spreading process, i.e., the flame propagation in a way of jumping-crawling/stopping-jumping for alcohols or forward-backward-forward for hydrocarbons. Some explanations were proposed to account for this oscillatory behavior. For instance, Glassman [17] believed that the oscillation merely occurred in a condition of a subsurface flow, and Konishi [15] supposed that the flame-induced liquid surface wave was imperative for this behavior. Di Blasi [16] developed a computational fluid dynamics (CFD) code to predict that the gas-phase recirculation cell ahead of flame tip which was a key factor for flame oscillation. Later, the influence of forced air flow, initial fuel temperature, and tray depth on the flame oscillations was studied by using a three-dimensional CFD code that solved the coupled expressions of both the gas and the liquid phases [17].

In summary, the previous investigations principally focused on flame spread over single component alcoholic or high-flashpoint hydrocarbon fuels, while few investigators endeavored to characterize the phenomenology and to reveal the mechanism of flame spread over blended fuels. Considering the excellent properties and broad application prospects of the butanol-diesel blended fuel, studying on flame

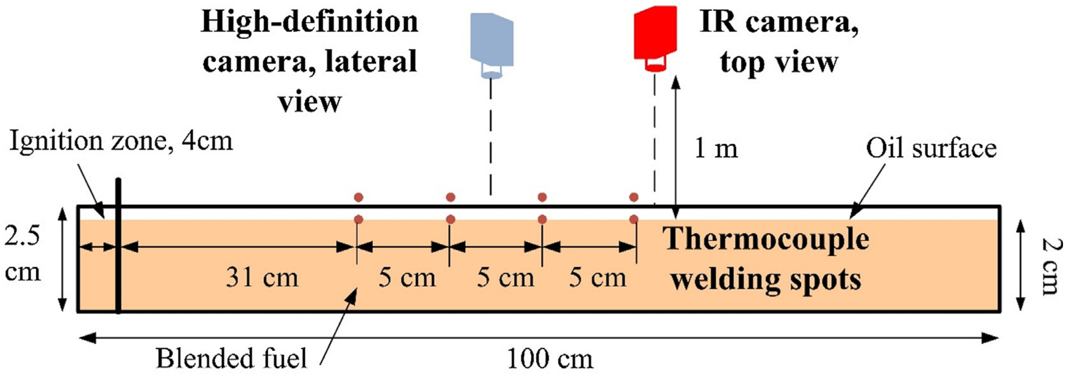

Fig. 1. Schematic diagram of the flame spread experiments.