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The effect of azeotropism on combustion characteristics of blended fuel pool fire

Yanming Ding, Changjian Wang*, Shouxiang Lu*

State Key Laboratory of Fire Science, University of Science and Technology of China, Heifei 230027, China

HIGHLIGHTS

- Effects of azeotropism on blended fuel pool fire characteristics are studied.
- Blended fuel burns at special azeotropic ratio when azeotropism appears.
- Four key burning stages of blended fuel pool fire are presented.
- Azeotropic burning leads to higher burning rate and centerline temperature.
- Flame puffing frequency of blended fuel follows the empirical formula for pure fuel.

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ABSTRACT

The effect of azeotropism on combustion characteristics of blended fuel pool fire was experimentally studied in an open fire test space of State Key Laboratory of Fire Science. A 30 cm × 30 cm square pool filled with n-heptane and ethanol blended fuel was employed. Flame images, burning rate and temperature distribution were collected and recorded in the whole combustion process. Results show that azeotropism obviously dominates the combustion behavior of n-heptane/ethanol blended fuel pool fire. The combustion process after ignition exhibits four typical stages: initial development, azeotropic burning, single-component burning and decay stage. Azeotropism appears when temperature of fuel surface reaches azeotropic point and blended fuel burns at azeotropic ratio. Compared with individual pure fuel, the effect of azeotropism on main fire parameters, such as flame height, burning rate, flame puffing frequency and centerline temperature were analyzed. Burning rate and centerline temperature of blended fuel are higher than that of individual pure fuel respectively at azeotropic burning stage, and flame puffing frequency follows the empirical formula between Strouhal and Froude number for pure fuel.

1. Introduction

From the standpoint of fire safety in industrial process or practical energy generation systems, burning behavior of a pool fire has been extensively studied and focused on burning rate, flame height, pulsation, thermal radiation, soot formation, air entrainment, etc. Thereinto, pool fire burning rate is an important parameter in prediction of relative hazards of such fire [1]. It depends on the heat feedback from flame to fuel surface, furthermore is affected by pool diameter, burner material, lip height and so on [2]. Flame height, oscillatory phenomena of diffusion flames and centerline temperature [3–11] are also the crucial parameters in the combustion process.

Previous studies mainly focused on single-component fuel pool fire. However, actual fire process often involves multi-component fuel. For example, usually used petroleum products, such as gasoline and diesel, normally consist of two or more components. But there is little information available from literature on the coexistence of different components in pool fire. For such blended fuels, a special phenomenon called azeotropism [12] cannot be ignored since it changes the boiling point of fuel and might result in an enormous impact on the burning process. As is well known that, in the case of blended fuel with their azeotropic proportion, the composition of the fuel vapor remains constant at azeotropic point. But for those blended fuels without the initial azeotropic composition, whether does the composition of the fuel vapor remain constant or not? If so, can the variation be negligible? If not, how does azeotropism affect the combustion process and the changed composition influence the pool fire heat release rate which is related with flame height, centerline temperature and so on?

* Corresponding authors. Tel.: +86 551 63603141; fax: +86 551 63603141.
E-mail addresses: chjwang@ustc.edu.cn (C. Wang), sxlu@ustc.edu.cn (S. Lu).

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Table 1
Fuel physical properties.

Fuel	Molecular weight	Density (g/cm^3)	Boiling point (K)	Heat of vaporation (kJ/kg)	Heat of combustion (MJ/kg)
n-Heptane	100.2	0.688	371.7	364.9	44.4
Ethanol	46.1	0.789	351.6	836.8	26.8
Azeotrope	63.5	0.734	344.1	596.1	35.8

In this paper, in order to investigate the blended fuel burning behavior and address the above problems, especially the combustion process which might be different with individual pure fuel due to the effect of azeotropic phenomenon, a series of fire experiments was performed for typical blended fuel pool fire with varying mixing ratios of n-heptane and ethanol (negative azeotrope). Several major combustion characteristics are discussed based on experimental data, such as flame height, burning rate and flame puffing frequency as well as centerline temperature.

2. Experimental

In total, 7 pool fire cases were performed in a 22.4 m (L) × 11.9 m (W) × 27.0 m (H) large test hall with ceiling exhaust vents. In each test, doors and windows remained closed so that the wind effect was negligible. Ambient humidity and temperature in the test hall were 55 ± 10% and 14 ± 1 °C, respectively.

Identical square fuel pan, 30 cm × 30 cm in size and 4 cm in height, were used in all experiments. The pan was made out of steel (300 M) whose density, specific heat and thermal conductivity at 293 K were 7.83 g cm^{-3}, 480 J mol^{-1} K^{-1} and 21 W m^{-1} K^{-1}, respectively. The tested fuel was n-heptane and ethanol with different mixing ratios, whose azeotropic point is 344.05 K and azeotropic proportion expressed in mass fraction is 0.51:0.49. Physical properties of fuel are shown in Table 1. Total fuel volume in each test was kept as 1000 ml, so that the initial fuel layer thickness was identical (approximately 11 mm). The volume of n-heptane in each test was 0, 200, 375, 500, 625, 800, and 1000 ml, respectively. When the volume of n-heptane was 500 ml, the mass fraction of n-heptane and ethanol is 0.47:0.53, which is very similar to the azeotropic proportion, and then this composition of blended fuel is regarded as azeotropic proportion approximately.

As shown in Fig. 1, a balance with 0.1 g precision was positioned below the pan to measure fuel mass loss. A digital video camera with a maximum capture rate of 25 frames per second, was used in each test, the horizontal distance from camera to pool centerline is 1.5 m and the vertical distance from camera to pool bottom is 0.5 m. Thereby the burn-out time could be extracted accurately and dynamic burning behavior such as flame height was fully monitored and calculated by referring to the size of pool. Temperature distribution along pan vertical axis was measured by K-type thermocouples of 1.0 mm diameter. Thermocouples were located in every 20 cm above pan surface from the smallest height 0.2 m to the largest height 2.0 m.

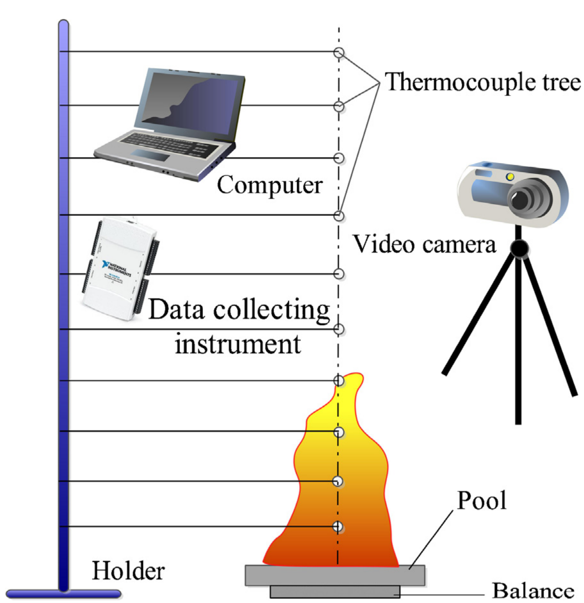

Fig. 1. Schematic of pool fire experiment.

3. Results and discussion

3.1. Flame height

For flames associated with the burning of condensed fuels, the buoyancy plays a leading role in the combustion process [13]. In experiment, flames exhibit turbulent behavior and unstable luminous shape as well as intermittent flame tip. The nondimensional Froude number is approximately applicable to the high-temperature gas in the flames. The geometry of turbulent diffusion flames has been found to scale with the square root of the Froude number. Flame heights can be expressed as a function of pool diameter and energy release rate for a wide range of Froude numbers [14,15].

The mean flame height is defined by averaging the visible flame height over time conveniently. The luminosity of the lower part of the flaming region appears fairly steady and the upper part is intermittent. The height at which the intermittency is 0.5 is defined as the mean flame height [14]. From video record, flame height is obtained by transforming GRB images to pseudo-gray ones and smoothed by Adjacent Averaging method every second (25 frames). Figs. 2–4 present the profiles of fire height for three blended fuels with specific mixing ratios, which are compared with the height of individual pure fuel, respectively.

After ignition, the fire spreads to the whole pool and flame height increases rapidly. The flame height evolution of blended fuel

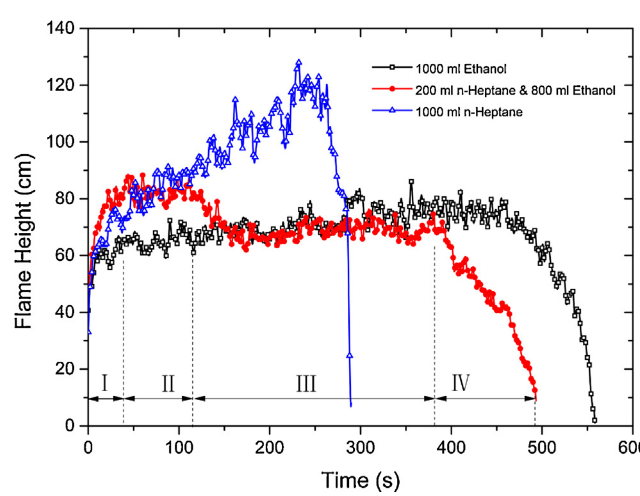

Fig. 2. Flame height for pure fuels (n-heptane and ethanol) and blended fuel (200 ml n-heptane and 800 ml ethanol).