Fuel 189 (2017) 1–7

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

The effect of azeotropic blended fuel on combustion characteristics in a ceiling vented compartment

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HIGHLIGHTS

- Effects of azeotropic blended fuel pool fire are studied in a compartment.
- Four burning stages are divided by the temperature profiles intuitively.
- $Q/A_v^{5/4}$ is applied to consider both the heat release rate and ventilation condition.
- Ghosting flame creates larger high-temperature regions and increases fire hazards.
- Azeotropism can effectively delay the appearance of ghosting flame.

ARTICLE INFO

Article history:
Received 26 June 2016
Received in revised form 17 October 2016
Accepted 19 October 2016
Available online 24 October 2016

Keywords:
Pool fire
Azeotropism
Blended fuel
Compartment fire

ABSTRACT

The effect of azeotropic blended fuel on combustion characteristics was studied experimentally in a ceiling vented compartment. A variety of blended liquid fuels with different mixing ratios was employed to explore the thermal performances by the measurement of fuel mass loss rates, fuel and gas temperatures, etc. Results indicate that azeotropism has a significant effect during the combustion process, resulting in four typical burning stages, especially based on fuel temperature profiles: initial growth, azeotropic burning, single-component burning and decaying. Two significantly different thermal performances appear: steady burning (fuel-limited) and self-extinction (oxygen-limited). When the burning rate reaches a critical value, about 35 g m^{-2} s^{-1}, the confined space cannot entertain enough air, self-extinction followed. A parameter ($Q/A_v^{5/4}$) derived from energy conservation equation is applied to divide the steady burning and self-extinction in consideration of both the heat release rate and ventilation condition, and the critical value is 200 kW/m$^{5/2}$. Moreover, the ghosting flame maybe appears during the self-extinction condition, especially when $Q/A_v^{5/4} > 300$ kW/m$^{5/2}$. The ghosting flame is detached from the fuel pan and goes from place to place with violent oscillation, which creates a larger high-temperature region and thus increases fire hazards. Meanwhile, according to both the fuel temperature profiles and mass loss rate, azeotropism can effectively delay the bulk boiling of the remaining single fuel and the emergence of ghosting flame.

1. Introduction

Ceiling vented compartments are very common in ship industry, underground space, nuclear power plants, etc. The combustion characteristics in such compartments have drawn much attention and researchers have conducted plenty of experiments in the last four decades. The major factors of combustion characteristics in a confined compartment are the heat release rate and ventilation condition. Poulsen and Jomaas [1] explored the burning rate of pool fire and thermal runaway under the room burn conditions with varying heat release rates based on various pool sizes, lining materials and amounts of liquid burning. Takeda and Akita [2] reported four regions about the burning of methanol as vent size increased in a compartment: extinction, stable laminar burning, unstable oscillations, and steady burning. Tu [3] also found similar phenomena by investigating the combustion behavior of ethanol with various ceiling vent sizes. Nasr et al. [4,5] studied the energy

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http://dx.doi.org/10.1016/j.fuel.2016.10.095
0016-2361/

balance at the pool fire surface and classification of burning regime in compartments based on different heat release rates by changing pool size at various ventilation flow rates. Furthermore, He et al. [6] explored the combustion characteristics in a ceiling vented compartment with a typical parameter ($Q/A_v^{5/4}$, where Q is the heat release rate and A_v is the area of ceiling vent) reflecting simultaneously the influences of heat release rate and ventilation condition, which were applied in this paper. In addition, a special thermal performance called ghosting flame should be concerned in the compartment which was first presented by Sugawa et al. [7] in 1991. This phenomenon was observed in full-scale fires by Audouin et al. [8], and subsequent experimental studies [9–14] further explored the thermal characteristics of ghosting flame in under-ventilated condition.

However, most previous studies mainly focused on alcohol and hydrocarbon fuel with a single component. It is worth noted that the widely used fuel is blended fuel (multi-components) whose combustion characteristics is more complex than those of the single-component fuels in real scenarios [15–17], where petroleum products and bioenergy fuel, especially ethanol gasoline in engine [18,19] (E10, E15, E85), are usually used. In the United States, to meet a growing annual target of total gallons blended, the federal Renewable Fuel Standard (RFS) effectively requires refiners and blenders to blend renewable biofuels (mostly ethanol) with gasoline. In Brazil, the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP) requires gasoline for automobile use to have 27.5% of ethanol added to its composition, and even pure hydrated ethanol is available as a fuel [20]. So the fire hazards of blended fuel cannot be ignored in storage and transportation process.

For such blended fuels, a special phenomenon called azeotropism is no doubt a matter of concern since it changes the boiling point of fuel and can result in an enormous impact on the burning process. The azeotropic proportion which is specific for certain blended fuel plays an important role in this situation, whereby the vapor has the same proportion of constituents as the liquid mixture at the azeotropic point [21]. In the recent studies of ethanol/*n*-heptane azeotropic blended fuel pool fires in open space, Ding et al. [22] focused on the phenomenon and divided the combustion process into four typical stages: initial growth, azeotropic burning, single-component burning, and decay stage. However, when the effects of confined compartment are taken into account, the thermal performances and fire hazards should be different from those in open space, and some interesting problems arise. For example, how does the mixing proportion affect combustion parameters, such as burning rate, fuel temperature and gas temperature? Additionally, what special thermal phenomena will occur in confined compartment? Does ghosting flame appear, and what is the critical threshold for such ghosting flame occurrence? In this paper, these questions will be addressed in detail. A series of fire experiments was conducted with ethanol, *n*-heptane and their blended fuels with various mixing ratios. The purpose of this paper is to obtain deep insight into the thermal performances of azeotropic blended fuel in a ceiling vented compartment.

2. Experimental

The experiment was conducted in a reduced-scale ship compartment with an interior dimension of 1 m (L) × 1 m (W) × 0.75 m (H). At least two repeated tests were performed for every case. The ceiling vent was in a corner, with dimension 0.49 m (L) × 0.49 m (W) (Fig. 1). The walls of the compartment were made of stainless steel plates of 0.005 m thick except the front wall, which was made of 0.005 m thick silica glass (a glass withstanding

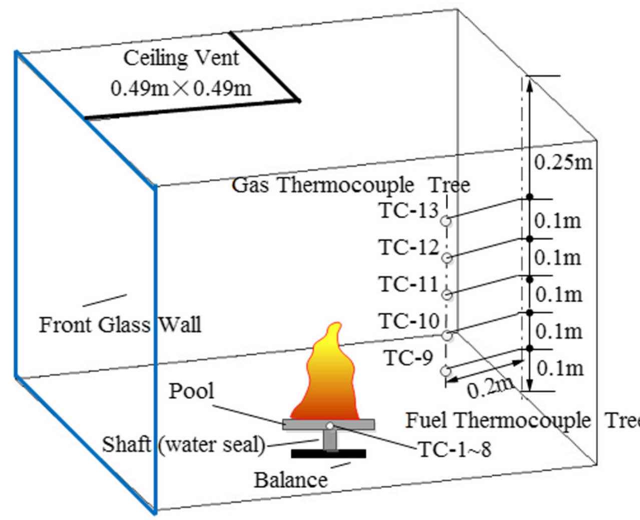

Fig. 1. Schematic of the experimental setup.

temperature up to 950 °C). All joints were sealed using fire resistant sealant to avoid unintended leaks.

An electric spark igniter was used to ignite the fuel and removed from the flame after ignition. All fires originated from a circular fuel pan, 0.2 m in diameter and 0.04 m in height, and the fuel pan was located at the floor center of the compartment. The test fuels were ethanol, *n*-heptane, and their blended fuels with different mixing volume ratios. In every case, the initial volume of blended fuel was 1000 ml, indicating that the initial thickness of the fuel was 0.032 m. Detailed experimental cases and fuel physical properties are shown in Tables 1 and 2.

An electronic balance with 0.1 g precision was attached to fuel pan to measure fuel mass loss. Fuel temperature was measured using eight K-type thermocouples with 1 mm diameter (from the lowermost TC-1 to the uppermost TC-8). These thermocouples were approximately equally spaced in the fuel, wherein, the lowermost and the uppermost thermocouples were 0.004 m and 0.032 m above the bottom of the pan, respectively. Five K-type thermocouples (TC-9 ~ TC-13) had the same horizontal coordinate to measure gas temperatures, at a position of 0.2 m to the nearest wall. Their vertical distance to the compartment floor was 0.1 m, 0.2 m, 0.3 m, 0.4 m and 0.5 m. Meanwhile, the oxygen concentration near the fuel pan was measured by a smoke gas analyzer (Kane® KM9106), with 0.2 m horizontal distance with the pool center [6]. A digital video camera with a maximum capture rate of 50 frames/s, was used in each test, and resultantly the burnout time could be extracted accurately and dynamic burning behaviors were fully monitored.

3. Results and discussion

3.1. Fire behaviors of blended fuel in the ceiling vented compartment

After ignition, the fire spread to the whole pan and the flame height increased gradually. A lot of bubbles appeared near the vessel and then covered the whole pool surface. Then, as the volume fraction of *n*-heptane (η) in the blended fuel increased, two distinct phenomena appeared: (1) Steady burning (fuel-limited), and (2) Self-extinction (oxygen-limited, ghosting flame might occur), as shown in Table 1. In tests when η was less than azeotropic proportion (AP), the burning was stable and the flame was attached to the pan during the whole combustion process. This can be referred as steady burning, fuel-limited. But in tests when η > AP, the combus-