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Research article

Diffusive burning of blended peroxy-fuels: Some experimental results

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ABSTRACT

Dampening of energetic properties and the effects of blending proportions of isododecane on the diffusive burning behaviour of peroxy-fuels are experimentally studied. Blended peorxy-fuels are obtained by adding isododecane in the proportions of 25 wt.%, 50 wt.% and 75 wt.%, respectively, in technical pure peroxy-fuels. The fuels were burned in form of pool fires with diameters 0.02 m ≤ d ≤ 1 m. The mass burning rates and relative flame lengths are found to be weakened with increasing diluent proportions. By measuring the mass burning rates and visible flame lengths of pool fires of different samples of fuel blends an optimum blending criterion is developed. Furthermore, it is shown that the dilution proportions and flame characteristics can be correlated by empirical equations.

1. Introduction

Pool fires are the simplest form of diffusive burning where the fuel vapours have low initial momentum. The schematic of a typical pool fire is shown in Fig. 1. With the increase in pool diameter (d) different modes of flows (laminar, transition and turbulent) and heat transfer (conduction, convection and radiation) to liquid fuel surface control the major characteristics of the fire e.g. mass burning rate, flame lengths, flame temperatures and heat fluxes. There have been significant amount of work done in the past on pool fires of hydrocarbons. However, the knowledge on pool fires of peroxy-fuels was very limited until authors started detailed investigations on fast burning characteristics of five different peroxy-fuels and published important outcomes [1–7]. It is worth mentioning a few interesting results here again i.e., peroxy-fuels burn at a much faster rate (10 to 333 times higher mass burning rates) than a typical hydrocarbon fuel e.g. kerosene or isododecane [1,3,4] as also shown in Fig. 2. The full names of the considered peroxy-fuels are given in Table 1. The reasons for such fast burning were the tendency of peroxy-fuels to undergo thermal decomposition, additional energy release due to decomposition, presence of oxygen atoms in the molecule itself and finally requirement of small air to fuel ratio (for stoichiometric combustion) which helps to accelerate the chemical reactions. For the safe storage and transportation peroxy-fuels are often diluted to minimize the fire and explosion hazards.

Another aspect of this rapid burning and energetic behaviour of peroxy-fuels is that they can be used to enhance the mass burning rates of hydrocarbons by adding them in appropriate proportions [8–15]. Such fuel blends ensured efficient burning and emission reduction properties that can be utilized in a variety of real combustion systems [9,10,12,13,16,17]. With the objective to characterize the burning behaviour of blended peroxy-fuels the present investigations are performed.

2. Background

Peroxy-fuels due to their thermal instabilities possess energetic properties and therefore demand greater safety precautions [3,11,18]. When ignited, they burn at a rapid rate and therefore produce large flames, higher temperature and thermal radiation [1,3,4,6,7]. In Fig. 3 it can be seen that such higher burning rates were largely underpredicted by the conventional equation used for hydrocarbons as written below:

$$\dot{m}''_f \approx 10^{-3}(\mathrm{kg/m^2.s})\frac{Hc}{Hv} \tag{1}$$

where H_c and H_v are enthalpies of combustion and vaporization, respectively. Hence, additional investigations were required to properly characterize the burning behaviour of peroxy-fuels. Authors have shown [3,7] that the mass burning rates of peroxy-fuels can be best correlated with their SADTs (Self-acclerating Decomposition Temperatures, T_{SADT}). These measured T_{SADT} values for investigated peroxy-fuels are given in Table 1 [1,3]. It can be seen that the lower SADT implies peroxy-fuel to burn faster.

Moreover, in previously published works by the authors the possible usage of such distinct characteristics of peroxy-fuels were also outlined

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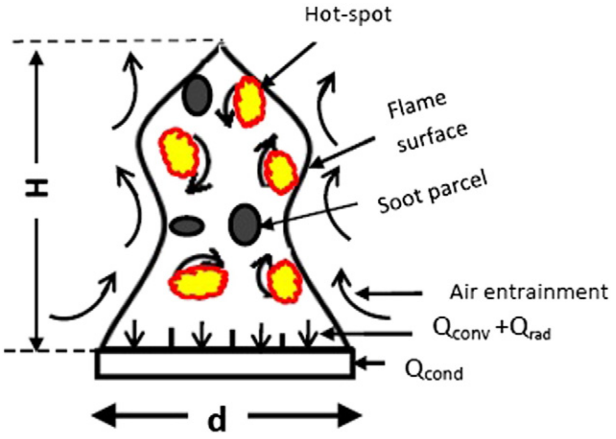

Fig. 1. Schematic of a typical pool fire.

[1,2,8,10]. Alongside various parameters related to safe handling and processing were also discussed.

For fuels having comparable enthalpies of combustion (kerosene and isododecane 43–44 $* 10^3$ kJ/kg) the enthalpy of vaporization plays an important role. Isododecane has a higher heat of vaporization (288 kJ/kg) than kerosene (250 kJ/kg) that is why Mudan eq. predicts comparatively lower burning rate for isododecane. Moreover, Mudan eq. does not contain any corrections for soot blockage effect due to which not sufficient heat reaches to the liquid fuel. Consequently, the burning rate decreases.

The measurements of mass loss (of liquid fuel) versus time of hydrocarbon fuels and peroxy-fuels revealed that a given amount of peroxy-fuel was consumed in much lesser time than in case of hydrocarbons [1].

The dilution/blending increases the burning times for peroxy-fuels and vice versa for hydrocarbons. The burning times for the above three kinds of fuels can be written in ascending order as follows hydrocarbon > blended fuels > peroxy-fuels. Moreover, the faster burning of peroxy-fuels leads to small residence times (the reaction time to convert a given quantity of fuel into products) [8–10] of fuelling elements in the combustion process, smaller air to fuel ratios and available oxygen atoms help to ensure less pollutants and much cleaner combustion [1,8–10,12,14,16].

In the past several studies were performed on the addition of peroxy-fuels in conventional hydrocarbons e.g., diesel, gasoline and others up to ~15% [9,10,12,14]. The important findings were: 1) reduction of total amount of fuel and air required for a given heat flux; 2) considerable reduction in size of chamber/cylinder; and 3) efficient combustion and less pollutants (NOx and COx). Importantly, in [10] a peroxy-fuel (DTBP from 5% to 15%) was added in diesel and burned in Homogeneous Charge Compression Ignition (HCCI) engine. It was found that ≥15% addition of DTBP helps to reduce the fuel consumption and emission. Another study [8] demonstrated that a Spark Ignition (SI) engine can be run in the total absence of air when DTBP was used as a fuel. However, the above studies dealt only with one peroxy-fuel i.e. DTBP and with a fixed range of concentrations for practical applications e.g. in engines. In present study we looked into four different peroxy-fuels (including DTBP) burning behaviour under different proportions of dilution with a hydrocarbon i.e. isododecane which was added in all peroxy-fuels in the range of 25 wt.% to 75 wt.%. These fuel blends were then burned in form of pool fires. Pool fires are diffusion flames where fuel and air mix and combust simultaneously [19–22] as shown in Fig. 1 and discussed before. To the authors best knowledge there are no studies available which describe the burning behaviour of hydrocarbon fuel blends with peroxy-fuels (>15%). Therefore, the present results are novel to the fuel, combustion and energy community.

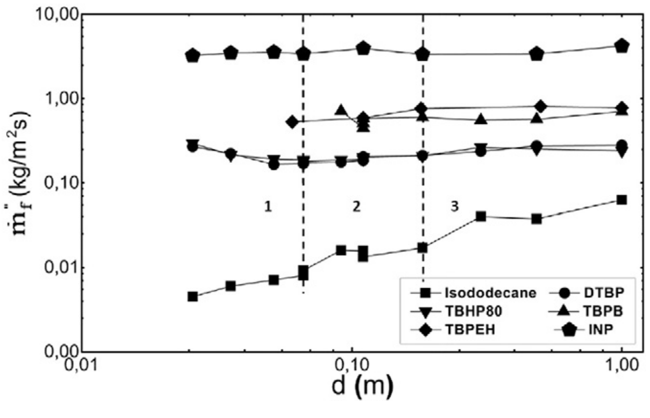

Fig. 2. Mass burning rate vs. pool diameter of different pure peroxy-fuels and isododecane. The three important regimes are also shown as 1: Convective and laminar regime; 2: Convective and turbulent regime and 3: Radiative, turbulent and optically thin regime.

Another important aspect of the present study is to study the effects of dilution on thermal instabilities and burning behaviour of peroxy-fuels to ensure their safety during transportation [3,18]. With these aims and in continuation to [1] this work was undertaken.

3. Fuels

The selected peroxy-fuels were the same as reported in [1]. As a blending agent a pure hydrocarbon fuel isododecane was used. The proportions of isododecane were varied between 25 wt.% and 75 wt.%. The reason behind selecting isododecane as a reference fuel was being a possible surrogate for JetA and other aviation fuels. Because of its inertness and higher boiling point it is also a recommended type A diluent for the safe transportation of peroxy-fuels [18]. The basis for blending weight % was chosen so as to see the proximity of burning behaviour against the dilution % and to verify the options for hazard reductions.

The important properties of peroxy-fuels and isododecane are listed in Table 1. Please refer to [6,7,18–21] regarding details related to fire and explosion safety of peroxy-fuels.

4. Experimental

Experiments were performed in form of pool fire configurations with steel pans of diameters in the range of 2 cm < d < 1 m. Depending on the burning rates measurements up to $d = 18$ cm were carried out at BAM in-house facility whereas tests with larger pans were performed on a concrete plate at BAM Test Site Technical Safety, a large-scale test facility located in 55 km south of Berlin. Mass burning rates were measured by using a precision electronic weighing instrument from Sartorius Ltd. and Labview® was used to record and process the data. The time and mass intervals were set to 0.01 s and 0.01 g, respectively. For obtaining the average mass burning rate initial and final 20% of the time was not taken into account as most part of the peroxy-fuels burns between 20 and 80% of the total mass. At the beginning (after ignition) and at the end (before extinction: pan ran out of fuel) peroxy-fuels burn at a much slower rate showing a small flame for a few seconds. This can amount between 10 and 20% of the total time. Then due to the increased decomposition and vaporization they burned rapidly. In order to establish realistic burning rates 60% of the time was considered when they burn steadily i.e. most part of the fuel burned at this time duration. This is a standard practice which helps to establish precise norm for their safe storage [3,7,8].

For measuring the flame lengths a videographic camera with a resolution of 15 frames per second was used. Images of fully developed flames (steady burning conditions neglecting the small fluctuations) during the 20% to 80% mass loss of fuel were considered and Zukoskís criteria (the length which flame maintains for more than 50% of steady burning time) [22,23] were applied for reporting the average flame lengths. The visible boundary was defined by the luminosity (soot