



Full Length Article

Experimental investigation of the effects of cycloparaffins and aromatics on the sooting tendency and the freezing point of soap-derived biokerosene and normal paraffins



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ABSTRACT

The effects of cycloparaffin and aromatic hydrocarbons when blended with soap-derived biokerosene (SBK) and normal paraffins (n-paraffins) on the sooting tendency and the freezing point are quantified to determine a method for improving the properties of SBK and n-paraffin fuels. In this study, SBK was derived from the saponification and decarboxylation of coconut oil, and consists predominantly of n-paraffins with carbon chain lengths from C7 to C17. Dodecane, butylcyclohexane and butylbenzene were chosen as surrogate components for n-paraffins in SBK, cycloparaffins and aromatics, respectively. The total soot volume was measured from the light extinction at ambient conditions in a wick-fed laminar diffusion flame. The measured smoke point of the fuel was correlated with the required sooting tendency according to the jet fuel standard. The freezing point was measured using the JIS K2276 test method. The results show that butylcyclohexane affects the sooting tendency much lesser than butylbenzene when blended with SBK or dodecane. In contrast, butylcyclohexane decreases the freezing point more, as compared to butylbenzene, when blended with dodecane. Butylcyclohexane and butylbenzene have a similar trend of effect on the freezing point when blended with SBK or dodecane. Blending SBK or dodecane with butylcyclohexane matches the requirements of both smoke point and freezing point for jet fuel specified by ASTM D1655. Conversely, blending SBK or dodecane with butylbenzene does not meet these requirements. Therefore, given the tradeoff between sooting tendency and freezing point, cycloparaffins are considered more promising than aromatics for blending with SBK or n-paraffin fuels.

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1. Introduction

Air transportation in the modern world is rapidly growing in popularity due to an increasing demand for business and leisure travel. As a result, the worldwide commercial jet fleet is expected to increase by approximately 102% [1], and the estimated annual average growth rate of world traffic is 4.6% for the next 20 years (2014–2034) [2]. Consequently, the jet fuel demand and the subsequent exhaust gas emissions will increase. Currently, jet fuel prices fluctuate as they depend not only on the availability of crude oil obtained from fossil fuels but also on many societal, economical, and, especially, political factors. These fluctuations in the price of jet fuels create many serious problems for airline companies,

because the fuel cost represents up to 30% of an airline's operating cost and it is expected to increase [3]. In addition, the airline sector is currently responsible for approximately 3% of the total global greenhouse gas (GHG) emissions. Although this value represents a small fraction of the total GHG emissions, aircraft emissions continue to increase and are expected to constitute nearly 5%, even could reach up to 15% of global GHG emissions by 2050 [4]. In an effort to reduce GHG emissions and meet the European environmental goals for 2020 and beyond, the European Union has implemented the Directive 101/2008/EC [5] since 2012. According to this legislation, all aircrafts flying within or into the European Economic Area must either decrease their GHG emissions or purchase CO₂ allowances. Therefore, the commercial aviation industry faces billions of US dollars in cost to pay for the carbon emission tax [6]. To reduce GHG emissions, some efforts have been applied such as improvement of fuel consumption efficiency by increasing engine

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efficiency, aircraft structure designing, and optimizing air traffic management. Along with those methods, using biofuel is increasingly considered by airline companies and governments because biofuel is a renewable resource and significantly reduces the life-cycle CO₂ emissions [7,8]. Besides, using aviation biofuel may reduce the pollutant emissions, such as carbon monoxide, unburned hydrocarbon, nitrogen oxides, and soot emission, from engines [11–15]. Currently, certain types of aviation biofuels have been approved by the American Society for Testing Materials (ASTM) for blending with conventional jet fuel to use in aviation gas turbine engines. These include synthesized paraffinic kerosene from hydroprocessed esters and fatty acids, Fischer–Tropsch hydroprocessed synthesized paraffinic kerosene from biomass, synthesized iso-paraffins from hydroprocessed fermented sugars, synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum resources, and alcohol-to-jet synthesized paraffinic kerosene. The detailed requirements of their composition and properties are presented in ASTM D7566 [9].

Tropical countries, in general, and Indonesia, in particular, are the ideal location for developing ground-used and aviation biofuel because of the abundance of plant oil resources, the vast rural areas, and the low labor cost. Moreover, the Indonesian government approved a plan to use up to 2%, 3%, and 5% by volume of aviation biofuel during flights by 2016, 2018, and 2025, respectively [8]. However, Indonesia faces significant challenges to produce aviation biofuel due to the limitation in technology and investment. Therefore, production of aviation biofuel based on simple technologies at a low cost, and leveraging the available national advantages is a foreseeable solution. The production of soap-derived biokerosene (SBK) meets the above criteria, because it primarily uses a simple production process as shown in Fig. 1. SBK production comprises of two main steps: (1) the saponification process, through which plant oil fatty acids and triglycerides are converted into basic-soap and (2) the subsequent thermal decarboxylation process reacted at 275 °C and ambient pressure, through which the basic-soap is transformed into normal-paraffins (n-paraffins). Thereby, SBK production is simpler and less energy consumption than the hydrotreating processes, which are reacted at high temperature and pressure with the presence of catalyst and hydrogen, in the common aviation biofuel productions (Fig. 2) to convert the plant oils or animal fats into n-paraffins [10]. Furthermore, in common aviation biofuel production pathways [12,30,31], because the fuel used in aviation gas turbine engines is required to have a very low freezing point [16,17], the n-paraffins are generally isomerized into branched paraffins (iso-paraffins), which have a significantly lower freezing point. Besides, in order to improve the other properties of aviation biofuels, especially, distillation, the cracking process is also implemented to break the long carbon chain that exceeds the jet range into shorter chain length paraffins. A typical production process of this type of aviation biofuel is presented in Fig. 2. However, the isomerization and cracking processes are complicated and costly [18–20]. Hence, substitution with other appropriate solutions based on the feedstock conditions, the available technology, and the socioeconomic situation in Indonesia is encouraged. Thereby, to avoid the cracking process in the SBK production, the plant oils that have carbon chain length of fatty acids dominantly in jet range (C8–C16 [16,17]) are selected as feedstock. Besides, mixing SBK with other bio-derived components that have low freezing points is a potential alternative to the isomerization

process to reduce the freezing point of the biofuel. Mixed biofuels with products of different production processes is also promising [21] because it helps to optimize the utilization of flexible feedstock and suitable facilities to produce biofuels, thus maximizing the national potential to develop a sustainable aviation biofuel in each country. Currently, there are many approaches to produce aromatics or cycloparaffins (naphthenes) from bio-feedstocks [23–27]. Because cycloparaffins are commonly produced through hydrogenation of aromatics, their price may be higher than that of aromatics [22]. However, if new production processes or feedstocks are established in the future, then it would be simpler and cheaper to produce cycloparaffins. One promising production process for producing cycloparaffins in Indonesia is the hydrogenation of turpentine oil obtained from pine tree (*Pinus merkusii*), as proposed by Hudaya et al. [28]. Although in their study they proposed a method for producing iso-paraffins, the same method can theoretically be used to produce cycloparaffins.

Cycloparaffins and aromatics can be mixed with SBK to decrease its freezing point since they have a lower freezing point than that of n-paraffins with same carbon number. However, they exhibit a very different sooting tendency. The jet fuel standard (ASTM D1655) specifies that the maximum volume fraction of aromatics present in commercial jet fuels such as Jet A, Jet A-1, and Jet B is 25%, whereas the fraction of cycloparaffins is not limited [17]. Soot formation in a gas turbine combustor is problematic because it generates high radiation heat and deposits, which can damage the combustion chamber or the turbine blade, thus reducing the engine's life [29,32]. In addition, the unburned soot particles emitted with the exhaust gas from a gas turbine engine are dangerous for human health and the environment [33]. Therefore, the sooting tendency plays an important role for evaluating a potential component to mix with SBK.

This research focuses on comparing the effects of cycloparaffins and aromatics on the sooting tendency and the freezing point when mixed with SBK and n-paraffin fuels. Butylcyclohexane and butylbenzene were chosen as the surrogate components for cycloparaffin and aromatic hydrocarbons, respectively. Because dodecane has the same carbon number with the average SBK molecule and with jet fuel [33], it was used to represent for n-paraffins in SBK and jet range n-paraffin fuels. Based on the results of this work, the potential of cycloparaffins and aromatics for mixing with SBK and n-paraffin fuels is assessed with regard to the tradeoffs between the sooting tendency and the decrease of the freezing point.

2. Experimental setup and procedures

2.1. Total soot volume of laminar diffusion wick-fed flame and smoke point measurement

The experimental setup used for determining the total soot volume and measuring the smoke point is shown in Fig. 3. The total soot volume of the laminar diffusion wick-fed flame was determined by employing a light extinction method. As shown in Fig. 3, the burner comprised two closely fitting concentric brass tubes (outer tube diameter = 0.8 cm, inner tube diameter = 0.5 cm) following the methods proposed by Olson et al. [34] and Watson et al. [35]. The outer and inner tubes belonged to the fuel tank



Fig. 1. Soap-derived biokerosene (SBK) production process.

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