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Effects of Aromatic and Cyclo-paraffin on Spray Cone Angle and Liquid Length

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***Abstract*—The lack of aromatic and cyclo-paraffin components in aviation alternative fuels such as hydrotreated biofuels due to different production processes may have influences on fuel performances. This work investigated the effects of aromatic and cyclo-paraffin components on physical properties and spray performances of Chinese jet fuel RP-3. Macroscopic spray performances such as spray cone angle and liquid length were measured downstream a pressure swirl nozzle at injection pressures of 0.3, 0.5, 0.7 and 0.9MPa. The experimental data obtained in this work show that the influence of different kinds of aromatic and cyclo-paraffin on the physical properties of RP-3 is mainly reflected in the kinematic viscosity, which further affects the spray performances. However, under the operating pressure of the nozzle, the effect of various aromatics and cyclo-paraffins added at 10% blending ratio on the fuel performance is very small. This work will be helpful for developing "drop-in" aviation alternative fuels.**

Keywords—component; spray; cone angle; liquid length

I. INTRODUCTION

In recent years, concerns about environmental policy and energy security have led to a continued focus on alternative fuels. In aviation industry, the interest in alternative jet fuels derived from other feed-stocks such as coal, natural gas and biomass is growing rapidly. Among them, bio-based jet fuel, which means the alternative jet fuel made from biomass materials such as jatropha, vegetable oil or algae, is considered as the most promising alternative jet fuel due to its advantages in whole-life carbon emissions[1]. However, there are chemical composition differences between alternative fuel and traditional jet fuel because of the differences in production process[2]. The chemical components of the alternative fuels produced by common processes are mainly chain-paraffin, but lack of aromatic and cyclo-paraffin. Therefore, to be used as a "drop-in" fuel, it is necessary to thoroughly investigate the effects on aromatics and cyclo-paraffin on fuel performances.

Spray performance is one of the most important properties of jet fuel. The atomization process is closely related to the combustion, ignition and emission process of jet fuel in the combustor an aero-engine[3]. Over the years, comparative studies have been made on the spray performances of alternative jet fuels. D.Sivakumar et al. investigated the atomization characteristics of camelina-based alternative aviation fuels discharging from a simplex swirl injector, the results show that the differences in spray characteristics between blends and jet fuel being minor[4]. Sanghoon Kook et al. studied the breakup process of alternative fuels at high temperature and high pressure conditions, the study shows that fuel density has an effect on the liquid length of spray, but it is not significant[5]. Clifford A et al. studied the performances of Sasol fully synthetic jet fuel, the results prove the fuel is approved for unrestricted use in aviation[6]. Kumaran also made a great contribution to the research on atomization performances of alternative fuels[7-9]. However, most of the studies are on the spray performances of an alternative fuel itself or its blends with jet fuel, few researches have directly investigated the effects of fuel components on spray performances.

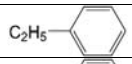
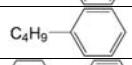
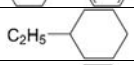
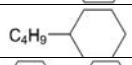
The objective of this work is to investigate the aromatic and cyclo-paraffin component which are commonly absent in alternative fuels on spray performances such as spray cone angle and liquid length. Different kinds of aromatic and cyclo-paraffin were blended with Chinese conventional jet fuel RP-3. The experiment was carried out through a pressure swirl nozzle under different injection pressures.

II. EXPERIMENTAL DETAILS

A. Experimental Materials and Physical Properties

In this study, the Chinese conventional jet fuel RP-3 was purchased from Beijing capital international airport Co., Ltd. The chemical composition of RP-3 was measured using a GC-MS system (Agilent 7890A-5975C) with a HP-5 capillary column ($30m \times 0.25mm \times 0.25\mu m$ i.d.) and a mass selective detector. Aromatic including ethyl-benzene, butyl-benzene and cyclohexyl-benzene, cyclo-paraffin including ethyl-cyclohexane, butyl-cyclohexane and bicyclohexane were blended with RP-3 in a mass fraction of 10% to analyze the effects of different types of monocyclic, dicyclic aromatic and cyclo-paraffin on fuel properties and spray performances. The detailed information of aromatic and cyclo-paraffin selected in this work are shown in Table 1. Physical properties of fuels including density, kinematic viscosity and surface tension were tested according Chinese national standard GB/T 1884-2000 considering that these three properties are closely related to the spray performances of fuels.

TABLE I. AROMATIC AND CYCLO-PARAFFIN SELECTED IN THIS WORK

Fuel	Detailed information of blending component		Physical properties of blending fuel		
	Molecular formula	*Molecular structure*	*Density(kg/m^3)*	*Kinematic viscosity(mm^2/s)*	*Surface tension(mN/m)*
RP-3	-	-	793	1.587	25.69
Ethyl-benzene	C_8H_{10}		799	1.4585	25.87
Butyl-benzene	$C_{10}H_{14}$		799	1.5465	25.87
Cyclohexyl-benzene	$C_{12}H_{16}$		806	1.668	26.14
Ethyl-cyclohexane	C_8H_{16}		792	1.571	25.51
Butyl-cyclohexane	$C_{10}H_{20}$		793.5	1.6555	25.69
Bicyclohexane	$C_{12}H_{22}$		802	1.77	25.85

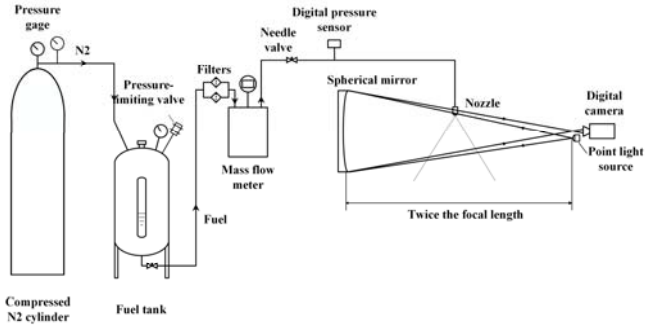


FIGURE I. SCHEMATIC OF THE SPRAY EXPERIMENTAL APPARATUS

B. *Spray Performances*

In this study, the experimental fuels were pressurized by compressed nitrogen and atomized by a pressure swirl nozzle with an exit diameter of 100μm. The nozzle was produced by Danfoss Inc. and have an 80 degree spray cone angle at a working pressure of 0.3MPa. Figure 1 shows a schematic diagram of the experimental set up. Fuels were stored in the fuel tank during the experiment. A digital pressure sensor is installed near the nozzle to measure the true injection pressure during the spray. A mass flow meter was used to measure the mass flow rate of fuels. The spray experiment was carried out at injection pressures of 0.3 MPa, 0.5 MPa, 0.7MPa and 0.9MPa to observe the effects at different injection pressures.

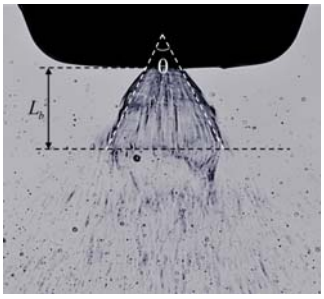


FIGURE II. THE SCHEMATIC OF THE MEASUREMENT METHOD

Macroscopic spray properties of fuels such as spray cone angle and liquid length were measured by shadowgraph method. The shadowgraph devices consists of a light source, a spherical mirror and a Canon 5D digital camera. A T6 LED with power of 150 W is used as the light source of the device. The diameter and the focal length of the spherical mirror are 203mm and 800mm, respectively. The pixel resolution was set as 5472 x 3648 and the focal length of the camera lens was 70-300mm.

In this investigation, the defining of spray cone angle (θ) was the angle formed by two straight lines that start from the nozzle exit and end to the breakup line of the liquid sheet, and the spray liquid length (L_b) was defined as distance from the nozzle exit to the point where the liquid sheet begin to break. The schematic of the measurement method is shown in figure 2.

III. RESULTS AND DISCUSSION

In this section, chemical composition, physical properties and spray performances such as spray cone angle and liquid Furthermore, the effects of fuels properties on spray performances are also discussed.

A. *Chemical Composition and Physical Properties*

Figure 3 shows the detailed information of chemical composition of Chinese jet fuel RP-3. The carbon number distribution of different components is shown in figure 3 (a). The carbon number of different components in RP-3 is mainly distributed in a range of 8 to 15, while in contrast, aromatic and cyclo-paraffin components are mainly distributed in a range of 8 to 11. It means that the aromatics and cyclo-paraffins in RP-3 are predominantly monocyclic. The length of the carbon chain carried on the monocyclic aromatic and cyclo-paraffin molecules determines their carbon number distribution range.

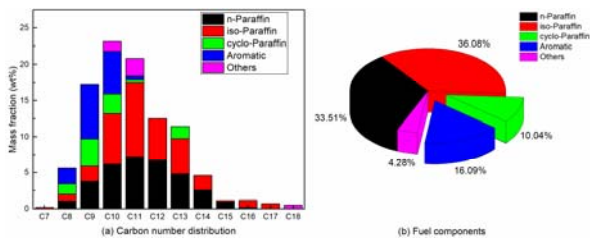


FIGURE III. CARBON NUMBER AND COMPONENTS DISTRIBUTION OF RP-3.

The mass fraction of each component in RP-3 is shown in figure 3 (b). It can be clearly observed that RP-3 is mainly composed of n-paraffin and iso-paraffin, the sum of the mass contents of the two components reached 69.59%. Aromatic and naphthenic hydrocarbons are also important components in PR-3, the mass fraction of two components in RP-3 are 16.09% and 10.04% respectively.

Aromatic and cyclo-paraffin are considered to be closely related to the performances such as lubrication and smoke emission of fuels[10]. This study focuses on the influence of two components on spray performance, as a result, properties closely related to spray performance such as density, kinematic viscosity and surface tension of blending fuels are tested and analyzed. Table 1 shows the properties of blending fuels and RP-3. It can be observed that the blending of ethyl-benzene and butyl-benzene increases the density of RP-3 by 0.76%. In contrast, the effect of monocyclic cyclo-paraffin on fuel density is quite small, the difference between ethyl-cyclohexane and butyl-cyclohexane blends and that of RP-3 is only 0.13% and 0.06%, respectively. With the increase of the carbon chain carried in the molecules, the kinematic viscosity of the monocyclic aromatic and cyclo-paraffin blends increases. The kinematic viscosity of ethyl-benzene and butyl-benzene blending fuel is 8.10% and 2.55% lower than that of RP-3, respectively. The kinematic viscosity of ethyl-cyclohexane blending fuel is only 1.01% lower than that of RP-3, and meanwhile, the kinematic viscosity of butyl-cyclohexane blends is 4.32% higher than that of jet fuel. This means that the presence of benzene ring in the component molecule can significantly reduce the kinematic viscosity of the fuel compared to the carbocyclic ring, thereby improving the fluidity of the fuel. The density and kinematic viscosity of the blending fuel of cyclohexyl-benzene and bicyclohexane are both larger than those of RP-3. The effects of the six selected components on the surface tension are relatively small, the difference between the fuels is only within 2%, which probably means that compared with surface tension and density, the effects of components on kinematic viscosity is a more important reason for the difference in spray performances between their blending fuels and RP-3.

B. *Spray Performances*

Spray performances such as spray cone angle and liquid length of fuels are presented and compared with those of RP-3 in this section. Figure 4 shows the variation of spray cone angle of different blending fuels with injection pressure. For all fuels, the spray cone angle increases with the increase of injection pressure. The maximum difference of cone angle between fuels occurs at 0.3MPa, while that difference becomes smaller with the increase of injection pressure. At 0.3MPa, the spray cone angle of ethyl-benzene blending fuels and butyl-benzene blending fuels are 0.77 and 0.195 degrees higher than that of RP-3, respectively, while the spray cone angle of cyclohexyl-benzene is 0.29 degrees lower than that of RP-3. For cyclo-paraffin, both of butyl-cyclohexane and bicyclohexane blending fuels have a smaller spray cone angle compared with RP-3, in contrast, the spray cone angle of ethyl-cyclohexane blends is 0.53 degrees higher than that of RP-3.

The variation of the difference of liquid length between fuels with injection pressure is similar to that of spray cone angle. For all fuels, the liquid length decreases with the increase of injection pressure, which is a typical liquid length trend with pressure as a result of the higher fuel velocity and weber number at higher pressure. The most obvious difference also appears at 0.3 MPa, as shown in Figure 5. At this condition, the liquid length of ethyl-benzene and butyl-benzene blends is 3.6% and 0.79% lower than that of RP-3, respectively, while the difference between ethyl-cyclohexane and butyl-cyclohexane blending fuel and RP-3 is 0.95% and 1.35%, respectively. The liquid length of the blends of cyclohexyl-benzene and bicyclohexane is higher than that of other fuels. Combining with the experimental results of the spray cone angle and the liquid length, it can be also observed that fuels with a larger spray cone angle tend to have a shorter liquid length downstream a pressure swirl nozzle.

Different atomization angles of fuel at 0.3MPa pressure are believed to be caused by different dynamic viscosities between fuels, which are often used to judge fuel fluidity. Obviously, the fuel with high dynamic viscosity will be subject to greater flow resistance in the process of pressurized flow, which will reduce the fuel velocity at nozzle exit and affect the spray performance. It can be observed from the experimental results that when the atomization injection pressure increases to 0.7mpa or above, the difference in spray cone angle and liquid length between fuels is within 2%, indicating that the influence of fuel properties on spray performances are more obvious under low injection pressure.

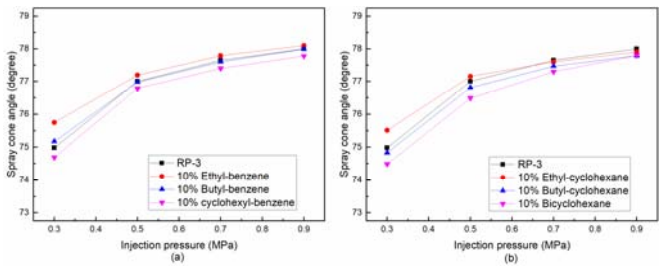


FIGURE IV. SPRAY CONE ANGLE OF BLENDING FUELS

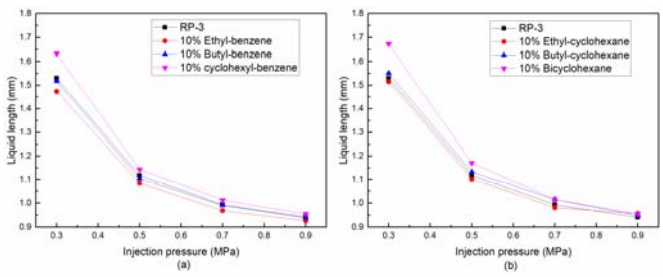


FIGURE V. LIQUID LENGTH OF BLENDING FUELS

IV. CONCLUSIONS

This work presented the effects of different kinds of aromatic and cyclo-paraffin on physical properties and spray performances of Chinese jet fuel RP-3 downstream a pressure

swirl nozzle at injection pressures of 0.3, 0.5, 0.7 and 0.9MPa. The results of this work show that the influence of additional components on fuel physical properties is mainly reflected in the kinematic viscosity, which in turn affects the spray performances of the fuels. The difference of spray cone angle and liquid length between fuels due to the addition of aromatic and cyclo-paraffin is more obvious at lower pressure. The reason for the changes in spray cone angle and liquid length are believed to be that the addition of aromatic and cyclo-paraffin changes the dynamic viscosity of fuels and thus affects the velocity of fuels at nozzle exit. In general, aromatics and cyclo-prarffins added at 10% mass fraction have little influence on the physical properties and spray performances of fuels. Therefore, from the perspective of spray performance, adding the missing aromatic and cyclo-paraffin components to aviation alternative fuels is a possible solution to improve fuel performance to achieve the "drop-in" requirements.

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