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LAMINAR BURNING SPEED AND FLAME HEIGHT OF PREMIXED PERTAMAX-AVGAS BLENDS WITH ETHANOL

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Abstract

An investigation explored the effects of blending aviation gasoline (Avgas) with Pertamax fuel and adding ethanol on laminar burning speed (S_L) and premix flame height at equivalence ratios of 0.8, 1.0, and 1.2. The Bunsen burner method was employed for testing due to its simplicity and relatively accurate results. Ethanol exhibited the highest SL value among the tested fuels. Blending Avgas and Pertamax resulted in lower burning speeds than pure Avgas 100 LL but higher than pure Pertamax. Conversely, flame height results were inversely proportional. The addition of 30% ethanol to the blend increased the burning speed. Comparison with previous research shows that the pattern of ethanol laminar burning speed values at equivalence ratios of 0.8, 1.0, and 1.2 in this study aligns with existing findings. Additionally, the ethanol laminar burning speed values in this study are consistent with results from other studies. Overall, the findings highlight the significant impact of fuel composition on laminar burning speed and flame characteristics. This study demonstrates potential avenues for optimizing combustion efficiency in reciprocating engines by adjusting fuel blends and ethanol content.

Keywords: Avgas 100LL, Aviation fuel, Laminar burning speed, Piston engine aircraft, Renewable energy.

1. Introduction

Aircraft are still the fastest, most efficient, and affordable mode of transportation. However, the aviation industry must remain committed to safety, even amid very high risks. It is because various high technologies support aircraft. In order to work well, an aircraft needs a propulsion engine with supporting capabilities. Aircraft engine types are divided into jet and piston engines. Jet or gas turbine engines are commercial aircraft widely used by airlines to carry passengers and cargo in large quantities over long distances [1]. The fuel used in this engine is generally an aviation turbine.

Meanwhile, aircraft with piston engines or reciprocating are used in general aviation, such as for flight training, or are also often used in the agricultural sector [2]. Aircraft with piston engines operate on the same principles as spark ignition engines in cars but have much higher performance requirements [3]. In addition, piston aircraft engines operate at higher temperatures and produce greater power [4]. The fuel used for this aircraft engine is Aviation Gasoline (Avgas). Avgas fuel has characteristics that can prevent detonation, so it does not affect flight safety and operational reliability of aircraft [5].

Fuel is said to be able to prevent detonation if it meets the requirements for an adequate octane value. It is essential because fuel with a high enough octane value can better avoid the knocking effect, which can damage the engine and interfere with reducing engine performance. Avgas is a fuel with special additives intended for aircraft with piston engines [6]. The additive is TEL or Thetra Ethyl Lead, known for treating engine knock problems [7]. If there is no TEL additive, the octane level of the Avgas will be too low, which will increase the risk of engine failure in obtaining the power required by the aircraft [8]. One type of Avgas that is widely used is Avgas 100 LL (Low Lead); this fuel has passed the ASTM D910 or DEF STAN 91-90 standard test.

As explained, Avgas contains lead or Thetra Ethyl Lead (TEL) to increase the Research Octane Number (RON) value [6]. However, although the significant role of TEL as an additive to prevent knock in piston engine aircraft is no longer in doubt, the reality is that 100 LL Avgas significantly impacts the environment, especially its effect on human health [8]. A certain amount of lead in the blood can be an adult cancer agent. Meanwhile, for children, the impact can decrease IQ and even cause academic disruption at school if it accumulates over several years [8]. Apart from that, economic reasons are also a weakness of 100 LL Avgas fuel. This fuel is twice as expensive as Pertamax. Therefore, a solution to this problem is needed. One alternative to overcome this is to mix Avgas fuel with mogas.

Experiments using mogas as aircraft fuel were first conducted on a Cessna 150-type aircraft in 1982, equipped with a Continental 0-200 engine. The results of this experiment showed positive things, then the Federal Aviation Administration (FAA) appointed the Piston Aircraft Fuel Initiative (PAFI) as an organisation that focuses on finding alternative aircraft fuels without the use of lead as an additive, which is currently used in 100 LL Avgas. Meanwhile, for its application in aviation use, the FAA permits piston engine aircraft users to use mogas as a mixture of Avgas fuel but must first go through approval of the Supplement Type Certificate (STC) issued by the FAA [9].

Researchers have also carried out several studies regarding mixing Avgas fuel to find alternatives to reduce the use of lead, including mixing Avgas and various types of mogas [9], up to variations in MON (Motor Octane Number) values [10], then adding additives in the form of aniline, N-methyl aniline or m-toluidine [11], and isooctane with n-heptane [5]. From the literature mentioned earlier, no research has shown the impact of mixing Avgas fuel with Pertamax in determining the laminar burning speed and flame height. So, with this background, researchers will discuss the impact analysis of mixing 100 LL Avgas and Pertamax fuel using the Bunsen burner method. Mixing Avgas with mogas can cause side effects [12], so to overcome this, ethanol was added as an additive in this study. The decision to choose ethanol as an additive was due to its properties, which can affect the laminar burning speed of several types of gasoline [13].

Laminar burning speed is one of the essential characteristics that must be met by spark ignition engine fuel. The laminar flame speed influences how much the fuel and air mixture will burn in an ideal situation (without turbulence interference). The higher the laminar flame speed, the faster the mixture burns, which directly impacts fuel combustion rates in a variety of applications, including internal combustion engines. Fuel combustion can be more efficient and produce greater power with a higher laminar flame speed [14].

However, the combustion mechanism requires further validation through measurements of laminar burning velocity to ensure accurate predictions of combustion behaviour and optimize engine performance [15]. Next, another parameter that needs to be considered is the flame height. It can also determine the burning speed from the flame's height. Apart from that, the flame height reflects the soot in the combustion process and determines the stability of the combustion process [16].

From the literature reviewed, there is a noticeable gap in research specializing in measuring laminar burning speed and premix flame height for mixtures of Avgas 100 LL, Pertamax RON 92, and ethanol addition. This lack of studies is also reflected in other areas of combustion research. As noted by Eckart et al. Laminar burning speed is a critical property for assessing the application of Diethoxymethane (DEM) in combustion devices [17]. Unfortunately, the literature on laminar burning speed of DEM is limited. This highlights the need for more focused research to better understand the combustion characteristics of such fuel mixtures. Due to this urgency, this research will discuss the laminar burning speed and flame height from variations in fuel mixture composition.

2. Methods

This research uses experimental methods [18]. The test equipment used is a Bunsen burner. The fuel tested consisted of Avgas 100 LL, Pertamax, and ethanol. Previously, the 100 LL Avgas and Pertamax fuels were subjected to a GC-MS (Gas Chromatography-Mass Spectrometry) test to determine the composition of the two fuels, the result is shown in Table 1(a) and (b). Next, the three fuels were mixed with the volume percentages shown in Fig. 1. Figure 1 also illustrates the test equipment for determining laminar burning speed and flame height. The variation of burner tip used is made of copper material. Meanwhile, the central part of the Bunsen burner for air-fuel mixing is made of stainless steel with a Y-Junction geometric shape, and a heater is provided on the burner neck to adjust the initial temperature to obtain a good combustion process to adjust the fuel flash point [19].

Table 1. Components of Avgas 100 LL and Pertamax.

(a) Avgas 100 LL

Compound	Molecular formula	Volume (%)
Ethyl Aziridine	C_4H_8	2.74
Pentamethylheptane	$C_{12}H_{26}$	2.15
Trimethyldecane	$C_{13}H_{28}$	23.32
Toluene	C_7H_8	1.97
n-Octadecane	$C_{18}H_{38}$	1.22
n-Pentadecane	$C_{15}H_{32}$	1.78
tetramethyl	$C_{20}H_{42}$	2.71
dimethyl	C_8H_{10}	14.07
Trimethylbenzene	C_9H_{12}	50.05

(b) Pertamax

Compound	Molecular formula	Volume (%)
Methylcyclopentane	C_6H_{12}	8.36
Dimethylpentane	C_7H_{16}	7.95
Isopropylbenzene	C_9H_{12}	12.66
n-Hexatriacontane	$C_{36}H_{74}$	12.71
Di-n-decylbenzene	$C_{26}H_{46}$	2.77
4,4-Dimethyl-Adamantan-2-OL	$C_{12}H_{20}$	8.26
Methylnaphthalene	$C_{11}H_{10}$	15.82
Phenylcyclohexene	$C_{12}H_{14}$	3.0
heptynyl	$C_{13}H_{16}$	4.61
Dimethylnaphthalene	$C_{12}H_{12}$	9.5
n-Hexadecane	$C_{16}H_{34}$	3.81
Tetramethylhexadecane	$C_{20}H_{42}$	10.54

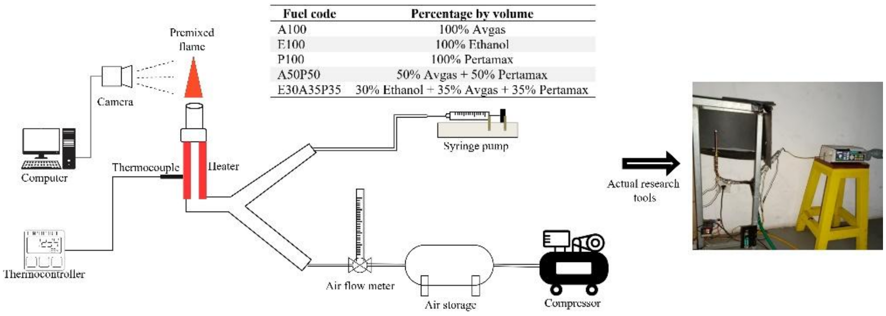

Fig. 1. Schematic of research tools.

2.1. Data measurement

The flames were recorded using a camera positioned parallel to the burner tip at a distance of 18 cm. Each variation was recorded three times to ensure data validity. The resulting video was then converted to image format using AceMovie Video Editor software. From these images, the best flame image was selected, and its height and angle were measured using Image-J software. The flame height was determined by measuring from the base to the tip of the premix flame. The flame angle (α) was measured by fitting a triangular line along the outermost contour of the premix flame, ensuring it encompassed the outer edges of the flame. A clearer illustration of this process can be seen in Fig. 2.

2.2. Data analysis

The recorded flame data were then processed to obtain values for flame height and laminar burning speed. It is necessary to multiply the flame angle (α) produced by the fuel reactant speed [20]. The flame angle (α) value that has been obtained is then calculated using Eq. (1) to determine the laminar burning speed (SL) [18].

$$SL = V.\ \sin\alpha \tag{1}$$

where V is reactant velocity (cm/s), and α is the flame angle value (°).

Meanwhile, the reactant velocity component (V) is obtained using Eq. (2).

$$V = \frac{Q\ air + Q\ fuel}{A} \tag{2}$$

where Q_{air} is Air flow rate (ml/sec), Q_{fuel} is Fuel discharge (ml/sec), and A is the Cross-sectional area (cm^2).

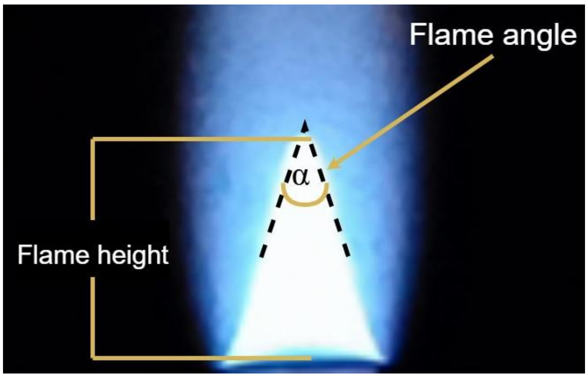

Fig. 2. Flame height and flame angle measurement.

3. Results and Discussion

3.1. Laminar burning speed at various fuel mixture compositions

Comparison of the results of ethanol laminar burning speed in this study with previous research is shown in Fig. 3. From the research that has been conducted, it can be seen in Fig. 3 that the pattern of ethanol laminar burning speed values at an equivalent ratio of 0.8, 1.0, and 1.2 in this study confirms the results of Katoch et al.'s research [21]. Apart from that, The results from this experiment also closely match the pattern observed by Sileghem et al. and Dirrenberger et al. in their tests at an atmospheric temperature of 298 K [22, 23]. In both studies, the graph shows that the highest laminar burning speed occurs at an equivalence ratio (ER) of 1.0, while the lowest speed occurs at an ER of 0.8. Additionally, the graph indicates that at an ER of 1.2, the laminar burning speed is lower than at 1.0 but remains higher than at 0.8.

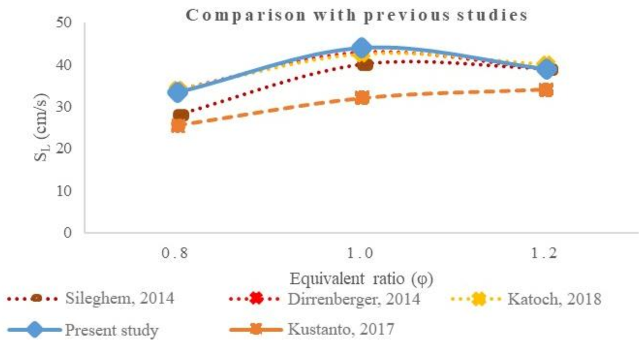

Fig. 3. Ethanol laminar burning speed comparison with previous studies.

In the combustion process, a temperature gradient exists between the products and the reactants, with the products having a higher temperature. According to the laws of thermodynamics, this temperature difference drives heat transfer from the hotter products to the cooler reactants. As heat transfers, the hot products diffuse, leading to a more uniform temperature distribution around the reactants. This heat transfer is accompanied by the diffusion of mass from the products toward the reactants. As the reactants absorb heat, their temperature increases, causing the preheat zone to shift toward the reactant area [18]. As the preheat zone, with its elevated temperature, advances, it eventually reaches the reaction zone, forming what is known as the reaction zone, as shown in Fig. 4.

This process enables the flame front to move steadily toward the reactants, with the rate of flame advancement referred to as the flame propagation speed or burning velocity. The reactant velocity, which is the rate at which the reactants are transported into the combustion zone, plays a crucial role in this process. It directly influences the rate of heat transfer and mass diffusion into the reaction zone. A higher reactant velocity increases the flow of fresh reactants into the combustion region, which can enhance the heat transfer rate and, consequently, the flame propagation speed. Thus, the reactant velocity is closely linked to the overall combustion dynamics and is integral to understanding the behaviour of the flame front and the laminar burning speed.

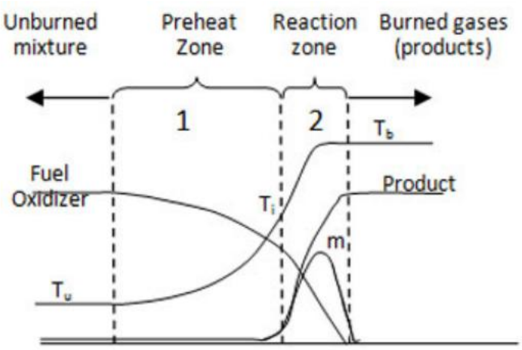

Fig. 4. Zone division in the combustion process [18].

The data on laminar burning speed values are shown in Table 2. It can be seen that the highest laminar burning speed of all the fuels tested was ethanol at φ 1.0, namely with a value of 43.9 cm/sec. This statement is also confirmed by their research [24], which shows that ethanol has the highest laminar burning speed compared to gasoline and mixtures of the two. The possible reason is that ethanol has a relatively short carbon chain, namely C_2H_5OH. Short carbon chains tend to facilitate the combustion process because they break down more easily into combustion products. In addition, ethanol contains oxygen bound in its molecules to reduce the need for outside air used during the combustion process, which ultimately causes the AFR value of ethanol to be lower and causes a higher laminar burning speed [25].

Meanwhile, Pertamax at φ 1.0 has the lowest laminar burning speed value of 25.09 cm/second because this fuel, on average, consists of compounds with a high carbon chain. It can be seen in Table 1(b) that the compound components with a volume above 10% are, respectively, 12% C_9H_{12}, 12% $C_{36}H_{74}$, 15% $C_{11}H_{10}$, and 10% $C_{20}H_{42}$. Some of these components have a high contribution, considering their volume percentage, so they can inhibit the combustion process because it takes longer to release the atomic chains for the combustion process [26].

Meanwhile, at φ 1.0, Avgas 100 LL has a higher speed value than Pertamax, namely 38.62 cm/sec. Due to the chemical compounds listed in Table 1(a), the results of the GC-MS test showed that Avgas 100 LL has several constituent compounds with carbon chains that tend to be smaller than Pertamax. An example of a compound is C_9H_{12}, which has a composition of 50%. It significantly impacts the speed of combustion because, in terms of releasing atoms in the combustion process, it requires a relatively shorter time with a smaller number of C atoms.

However, different results were obtained when combining 100 LL Avgas and Pertamax fuel at 50% volume each. The laminar burning speed value at φ 1.0 decreases compared to pure Avgas 100 LL but is higher than pure Pertamax. These two fuel mixtures' laminar burning speed value is 29.28 cm/sec. It happens because combining the two fuels, the compound components contained in Avgas 100 LL, can help increase the burning speed of Pertamax and vice versa. So, the properties of the compounds tend to adjust. This phenomenon has already been discussed in detail by Kumar et al [6].

Furthermore, the Avgas 100 LL and Pertamax mixture was given additional ethanol. From the test results, adding 30% ethanol proved that it could increase the laminar burning speed significantly, namely at φ 1.0, it was 34.75 cm/sec. It happens because the addition of 30% of a compound with a smaller atomic chain, namely C_2H_5OH, can help in the combustion reaction, causing the laminar burning speed to increase compared to before the addition [27].

Table 2. Fuel Variation impact on laminar burning speed.

Fuel	**Laminar burning speed (cm/second)**		
	φ = 0.8	φ = 1.0	φ = 1.2
A100	30.13	38.62	35.54
E100	33.28	43.95	38.87
P100	21.31	25.09	23.64
A50P50	24.16	29.28	28.01
E30A35P35	27.95	34.76	32.45

3.2. Flame height at various fuel mixture compositions

Apart from the burning speed, flame height values were also recorded to assess the flame structure at each equivalent ratio (φ) [28]. The experimental data show that the lowest flame height occurred at φ 1.0, which is a fuel mixture close to stoichiometric. Research by Zhen et al. indicates that the fuel-to-air mixture ratio significantly influences flame height, with deviations from stoichiometry leading to an increase in flame height [29]. This happens because flame height is directly related to the total consumption of fuel vapor, which reaches its peak when all vaporized fuel is fully combusted [30]. The availability of sufficient oxygen is critical for combustion at the stoichiometric ratio and for determining flame height. The highest flame height for all fuel types tested was observed at φ 0.8 and φ 1.2, while the lowest flame height occurred at φ 1.0. This supports the idea that a balanced fuel-to-oxygen ratio is crucial for determining optimal flame height [31]. As the fuel mixture moves away from the stoichiometric ratio, the flame height increases due to a more efficient combustion process and a higher consumption of vaporized fuel. These trends and the flame height values for each fuel type and equivalent ratio are summarized in Fig. 5.

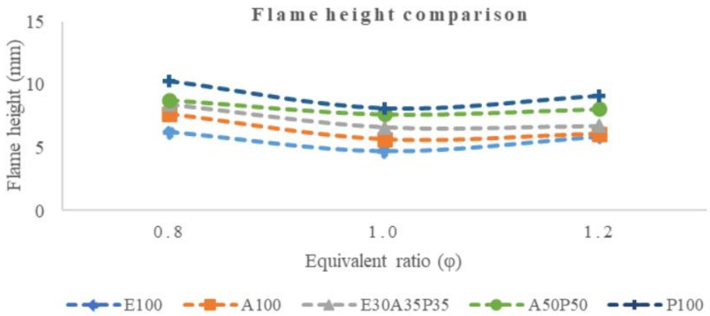

Fig. 5. Flame height comparison for different fuels.

4. Conclusions

From the test results, it can be observed that the highest laminar burning speed occurred with pure ethanol, followed by Avgas, a mixture of Pertamax-Avgas with the addition of 30% ethanol, and then the Pertamax-Avgas mixture. Pertamax showed the lowest laminar burning speed. The addition of 30% ethanol (30 ml per 100 ml of fuel) increased the laminar burning speed of the Pertamax-Avgas mixture from 29.28 cm/sec to 34.76 cm/sec. This result is influenced by the different constituent components of each fuel tested. Shorter atomic chains facilitate the separation of C and H atoms, allowing them to bond more readily with oxygen during combustion process, and vice versa. The type of fuel also influences the height of the flame produced. This flame height represents the efficiency of the combustion process, where the higher the flame indicates that the combustion reaction is taking place optimally and most of the fuel has burned efficiently. Future work could focus on further optimizing the ethanol blend ratio and testing a broader range of ethanol concentrations to better understand combustion behaviour and its impact on engine performance. Additionally, exploring the effects of ethanol blends on emission reduction and long-term engine wear would provide valuable insights for the development of sustainable aviation fuels.

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