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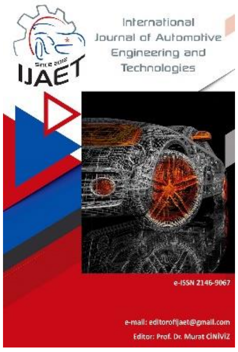

Original Research Article

The effectiveness of iso-alcohols in reducing vapor pressure and enhancing fuel properties of ethanol-gasoline mixtures

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ABSTRACT

Ethanol, with its high octane rating and emissions advantages, is a viable and renewable alternative to gasoline for Spark-Ignition (SI) engines. However, when mixed with gasoline, ethanol forms an azeotropic mixture that increases the fuel's vapor pressure, potentially causing a clogged fuel line, engine stalling, and unstable operation. This study aimed to address the high vapor pressure challenge by adding C3, C4, and C5 iso-alcohols, namely, isopropanol (IP), isobutanol (IB), and isoamyl alcohol (IA), to reduce the vapor pressure of ethanol-gasoline blends. Fuel properties, including Reid vapor pressure (RVP), density, and distillation temperatures, were measured after each iso-alcohol was individually added to ethanol-gasoline blends (E10, E20, and E30) at a 5% volumetric ratio. According to the findings, E10 and E20 behaved as an azeotropic mixture, yielding increased vapor pressure. The highest RVP of 63.2 kPa was measured for E10. However, adding IP, IB, and IA alcohols to E10 reduced the RVP to 61.8 kPa, 61.3 kPa, and 61.1 kPa, respectively. Including iso-alcohols also increased the density of ethanol-gasoline blends, with the highest density of 763.6 kg/m³ was measured for E30+IA5. Furthermore, adding iso-alcohols improved the distillation profiles, octane rating, and heating value of the ethanol-gasoline blends. More importantly, it was found that the measured fuel properties met the requirements of the European Standards for Gasoline (EN 228) except for some gasoline samples' distilled values for E70 and E100. Based on the findings, C3-C5 iso-alcohols effectively reduce the high vapor pressure associated with ethanol-gasoline azeotropic mixtures, allowing a higher volume of renewable ethanol blending.

Keywords: Ethanol-gasoline blends, Reid vapor pressure, Iso-alcohols, Sustainable fuel, Spark-ignition engine

1. Introduction

Environmental, economic, and energy security concerns have driven the growing need for biofuels in engine applications. Biofuels derived from renewable sources can potentially reduce greenhouse gas and pollutant emissions [1]. By decreasing dependence on imported fossil fuels and diversifying energy sources, biofuels can enhance energy security and independence [2]. In addition, biofuels can be produced from waste, supporting sustainable biofuel production and reducing waste's environmental and health impacts [3]. These advantages are helping to make them a more viable energy source for fueling internal combustion engines (ICEs). Bioethanol, biodiesel, methanol, and biogas are the main biofuels suitable for ICEs. Bioethanol and methanol are viable substitutes for conventional gasoline in SI engines as they offer enhanced fuel properties such as high-octane numbers, oxygen content, and high auto-ignition temperature. Due to its renewable nature and high feedstock availability, ethanol is the most widely used biofuel as a substitute or additive to gasoline in SI engines. Many countries have already incorporated ethanol into their fuel supply, intending to upgrade gasoline quality, reduce their dependence on fossil fuels, and lower greenhouse gas emissions. E5 (5% v/v ethanol + 95% v/v gasoline) and E10 (10% v/v ethanol + 90% v/v gasoline) are the most common ethanol-gasoline blends as they do not require engine modifications. As of January 1, 2011, the Fuel Quality Directive 2009/30/EC in Europe permits a maximum of 10% v/v of ethanol in gasoline [4]. In Türkiye, ethanol is added to gasoline at a maximum volumetric ratio of 5% before the distribution stage to improve fuel properties. Ethanol in gasoline serves as an octane booster and provides oxygen content to improve combustion. E15 is becoming more common, particularly in the United States and Europe. E85, with its high ethanol content, further reduces emissions and fossil fuel consumption. E85 is widely adopted in Brazil and used in flex-fuel vehicles operating on pure gasoline or high ethanol-gasoline mixtures. While ethanol plays a crucial role in reducing carbon emissions and transitioning toward clean and sustainable energy, it has significant limitations, particularly the high vapor pressure of ethanol-gasoline mixtures and its low energy density. Although ethanol has a significantly lower vapor pressure than gasoline due to its stronger intermolecular hydrogen bonds, ethanol-gasoline blends exhibit higher vapor pressure than either pure ethanol or pure gasoline [5]. This is because ethanol and gasoline hydrocarbons combine to form near-azeotropic mixtures that alter the blend's vapor pressure in a non-ideal manner [6]. Increased fuel vapor pressure can cause technical problems, such as blockages in the fuel system, unstable engine operation, and high evaporative HC emissions [7]. The vapor pressure of the fuel also affects combustion efficiency, fuel consumption, and exhaust emissions. Additionally, it plays a significant role in safety in storage distribution and refueling activities [8]. However, excessively low vapor pressure can cause cold start difficulties in cold weather. Therefore, gasoline with slightly higher vapor pressure is marketed in cold weather seasons and cold climate regions to facilitate cold engine starting. The EN 228 gasoline specification regulates the vapor pressure of gasoline for the winter and summer periods. According to this standard, the vapor pressure of winter gasoline should be between 60 and 90 kPa, and the vapor pressure of summer gasoline should fall between 45 and 60 kPa. However, the upper vapor pressure value (60 kPa) given for the summer period is increased depending on the ethanol content. It is 68 kPa for gasoline with 5% v/v ethanol content. Adding ethanol to gasoline can lead to a high vapor pressure value, even exceeding the maximum limit specified in the gasoline specification. The approaches to reducing the vapor pressure of ethanol-gasoline mixture include reformulating the gasoline composition, which poses technical challenges and high processing cost, and adding a third component with lower vapor pressure or high boiling point. The latter is preferable as it is cost-effective and helps stabilize the blend while allowing increasing renewable fuel content [7]. The concept of adding higher alcohol in ethanol-gasoline blends offers the final fuel with a Reid vapor pressure (RVP) equivalent to that of the base gasoline or even below. Recent scientific studies have investigated adding oxygenated compounds to ethanol-gasoline blends to modify their vapor pressure characteristics. Amine and Barakat [9] researched the addition of cyclohexanol (CH) at 3%, v/v to hydrous ethanol-gasoline blends (E0, E5, E10, E15, and

E20) to evaluate phase stability and volatility. The results showed that adding CH to hydrous ethanol-gasoline blends improved water tolerance. Furthermore, cyclohexanol did not negatively impact on the volatility properties of the fuel blends. The study also revealed that blending CH into hydrous ethanol blends reduced the vapor lock index (VLI) due to decreased azeotrope formation.

The same team in a different study [10] examined the effects of adding dimethyl carbonate (DMC) with various volumetric concentrations (0, 2, 4, 6, 8, and 10%) to an ethanol-gasoline blend (E10) on octane numbers and volatility features, such as vapor pressure and distillation profile. The changes in front-end and midrange volatility of the fuel were negligible when DMC was added to the blend. However, the tail-end volatility increased slightly due to the formation of an azeotropic mixture between DMC and the higher boiling components of gasoline. The vapor pressure of E10 was reduced by 3 kPa with a DMC concentration of 8%. The research found that adding 10% DMC to E10 increased the research octane number (RON) by 4 points. As a result, DMC was suggested as an environmentally friendly octane booster additive for E10 fuel blends.

Awad et al. [10] investigated the impact of adding polyoxymethylene dimethyl ether (PODE1) to ethanol-gasoline blend (E10) on fuel properties and phase stability. Their findings showed that E10 remained stable across various PODE1 concentrations (0%, 2.5%, 5%, 7.5%, and 10%). However, the addition of PODE1 slightly influenced the fuel's distillation behavior. Due to the low boiling point of PODE1, it reduced the distillation temperatures, ultimately increasing fuel volatility.

Dash and Tamilvendan [11] examined the effects of co-solvent inclusion on ethanol-gasoline blends, focusing on phase stability, vapor pressure, and distillation properties. Results revealed that adding isopropanol as a co-solvent means that it improves stability at low temperatures and reduces vapor pressure. Further, the vapor pressure decreased with an increase in isopropanol concentration. It was concluded that isopropanol offers an effective solution for enhancing ethanol-blended fuel performance.

Shirazi et al. [12] extensively studied dual-alcohol gasoline blends' physiochemical properties and volatility behavior. Dual-alcohol blends, with volumetric ratios ranging from 10% to 80%, consisting of ethanol or methanol combined with isobutanol or 3-methyl-3-pentanol as the higher alcohols. The main aim of this investigation was to obtain a dual-alcohol-gasoline blend with an RVP matching that of the base gasoline, and it was achieved. All dual-alcohol blends had an RVP within 9% of that of the base gasoline. Moreover, the dual-alcohol blends offered satisfactory fuel properties like volatility, kinematic viscosity, and water tolerance.

The literature survey reveals that various additives are available to reduce the vapor pressure of ethanol-gasoline azeotropic mixtures. Furthermore, long-chain alcohols have been noted as more effective in mitigating the hydroxyl group's azeotropic effect. However, their effectiveness remains unclear, emphasizing the need for comparative study.

This study aims to reduce the vapor pressure of ethanol-gasoline blends by adding C3, C4, and C5 iso-alcohols. Its significance lies in comparing the effectiveness of these iso-alcohols in reducing vapor pressure and improving other critical fuel properties of ethanol-gasoline blends. To the authors' knowledge, no previous study has directly compared the impacts of C3-C5 iso-alcohols on vapor pressure reduction in ethanol-gasoline blends, establishing the novelty of this research.

Higher saturated mono-alcohols, namely, isopropanol (C3), isobutanol (C4), and isoamyl alcohol (C5), were selected as blending components for their low vapor pressure and high-octane numbers. This study's outcomes will contribute to bridging the knowledge gap and offer novel insights into the role of C3, C4, and C5 iso-alcohols as additives in ethanol-gasoline blends.

2. Materials and Methods

Commercial summer gasoline, ethanol (E), isopropanol (IP), isobutanol (IB), and isoamyl alcohol (IA) was used to form fuel samples. The purities of all alcohols used were 99.0% or greater. The thermophysical properties of gasoline and alcohol are shown in Table 1. Commercial gasoline with an octane number of 95 was obtained from a local fuel station. Fuel blends were prepared using the splash blending method, combining gasoline and alcohol in specific quantities to achieve the desired blend. Blends were homogenized by agitation during the preparation, and this process was repeated before measurements. Binary blends of ethanol-gasoline were prepared by adding ethanol at volumetric ratios of 10%, 20%, and 30% to gasoline. Subsequently, ternary blends were obtained by separately adding isopropanol, isobutanol, and isoamyl alcohol at a volumetric fraction of 5% to binary blends of ethanol-gasoline. Table 2 lists the fuel samples and their compositions.

Table 1: Some thermophysical properties of gasoline and alcohol [7, 13-16].

Property	Gasoline	E	IP	IB	IA
Formula	≈C_8H_{15}	C_2H_6O	C_3H_8O	$C_4H_{10}O$	$C_5H_{12}O$
Oxygen content (wt, %)	≤2.7	34.8	26.6	21.6	18.1
Density @ 20℃ (kg/m^3)	740	790	786	802	810
Octane number	95	108	112	105	113
LHV (kJ/kg)	43400	26700	30662	33500	35370
Stoichiometric AFR	14.6	9.0	10.1	11.2	11.7
Boiling point (℃)	35-200	78.5	82.3	108	132
Flash Point (℃)	-40	13	12	28	43
Auto-ignition (℃)	~300	434	456	430	340
Heat of vap. @ 25℃ (kJ/kg)	380-500	904	758	686.4	621
RVP (kPa)	65.0	13.8	9	3.3	1.1

Table 2: Fuel samples and their volumetric composition.

Fuel sample	G	E	IP	IB	IA
G	100%	-	-	-	-
E10	90%	10%	-	-	-
E10-IP5	85.5%	9.5%	5%	-	-
E10-IB5	85.5%	9.5%	-	5%	-
E10-IA5	85.5%	9.5%	-	-	5%
E20	80%	20%	-	-	-
E20-IP5	76%	19%	5%	-	-
E20-IB5	76%	19%	-	5%	-
E20-IA5	76%	19%	-	-	5%
E30	70%	30%	-	-	-
E30-IP5	66.5%	28.5%	5%	-	-
E30-IB5	66.5%	28.5%	-	5%	-
E30-IA5	66.5%	28.5%	-	-	5%

RVP, density, and distillation temperature measurements were performed according to the standard test method via equipment given in Table 3.

Table 3: Equipment, test method, and accuracy.

Measurement	Equipment	Method	Accuracy
Density	Mettler Toledo D4	EN ISO 3675	±0.0001 g/cm^3
RVP	Herzog HVP 972	EN 13016	±0.2 kPa
Distillation	Herzog distillation analyzer	EN ISO 3405	±0.1 ℃

RVP is a crucial fuel property for gasoline and other light-liquid petroleum products. The RVP is also an indicator of the front-end volatility of fuels [17]. It represents the absolute vapor pressure of the fuel at 37.8 °C and at a vapor-to-liquid ratio of 4:1. The higher the RVP, the more volatile the fuel, and vice versa. RVP is often used interchangeably with the fuel's dry vapor pressure equivalent (DVPE) [18]. DVPE is calculated based on the total vapor pressure of the fuel sample that was measured. The correlation equation for DVPE is provided below [5]:

$$\text{DVPE (kPa)} = (0.965\,P_{total}) - 3.78\text{ kPa} \quad (1)$$

Where P_{total} is the measured total vapor pressure in kPa. Equations 2 and 3 were used to calculate fuel samples' octane number and lower heating value, respectively.

$$ON_f = \sum_{i=1}^{3} x_i \rho_i ON_i / \sum_{i=1}^{3} x_i \rho_i \quad (2)$$

Here, x, ρ, and ON are the volumetric ratio in the mixture, density, and octane number of the ith component, respectively.

$$LHV_f = \sum_{i=1}^{3} x_i \rho_i LHV_i / \sum_{i=1}^{3} x_i \rho_i \quad (3)$$

Here, LHV_i is the lower heating value of the component in the mixture.

3. Results and Discussions

The results of the measurement RVP for gasoline and ethanol-gasoline blends are presented in Figure 1. The RVP increased as the ethanol content in the blend reached 10% but decreased with further increases in ethanol concentration. E10 and E20 led to higher RVP, while E30 exhibited a lower RVP than that of gasoline. This behavior was due to the formation of the azeotropic ethanol-gasoline mixture. This result aligns with previous findings [11,19], indicating that a higher vapor pressure in gasoline-ethanol blends is observed when ethanol content is between 10% and 30%, compared to neat gasoline. E10 yielded the highest RVP with 63.2 kPa, whereas E30 offered the lowest with 60.9 kPa, even below that of gasoline. However, as seen in Figure 2, the RVP of all gasoline-ethanol mixtures was reduced by adding C3-C5 iso-alcohols. Specifically, considering E10, the RVP was decreased from 63.2 kPa to 61.2 kPa with the addition of isoamyl alcohol (E10-IA5). This value is 2 kPa and 1.3 kPa lower than the RVP of E10 and gasoline, respectively. Similarly, the RVP of E20 and E30 was reduced by adding C3-C5 iso-alcohols. Moreover, the RVP dropped even further when the added alcohol's chain length increased. This confirms that the hydroxyl group azeotropic effect is weakened as the carbon chain length increases [12]. Therefore, the lowest RVP of 58.9 kPa was measured for E30-IA5. More importantly, all fuels met the requirements of the EN 228 standard, which sets the RVP in the range of 45–60 (68) kPa for summer gasoline.

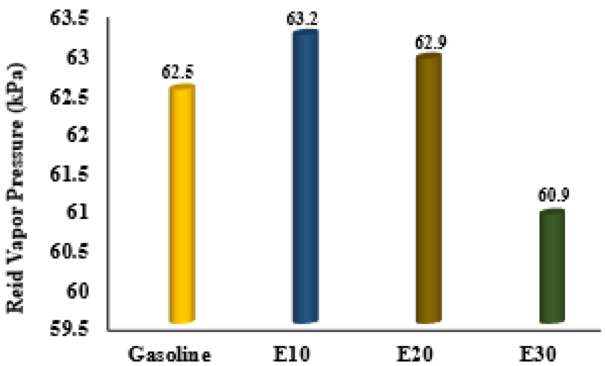

Figure 1. RVP of gasoline and ethanol-gasoline blends.

Adding C3-C5 iso-alcohol to ethanol-gasoline blends also affects other fuel properties. Thus, we determined the fuel samples' density, distillation temperature, lower heating value, and octane number. Figure 3 shows the measured density values for each fuel. The density of ethanol-gasoline blends was higher than that of gasoline, and it increased with the rise in ethanol fraction in the blend as ethanol has a higher density than gasoline. Furthermore, because C3-C5 iso-alcohols have a higher density than ethanol, adding them to ethanol-gasoline blends increased the density further, as expected. Therefore, the highest density of 763.6 kg/m^3 was measured for the E30-IA5. However, it was determined that the density values of all fuel samples were within the range (720-775 kg/m^3) specified in the EN 228 gasoline standard. The analysis shows that the high density of iso-alcohols is a key factor limiting their incorporation into fuel blends. As a result, to comply with EN 228 density regulations, IA can be added to the E30 blend at a maximum volumetric ratio of 7%.

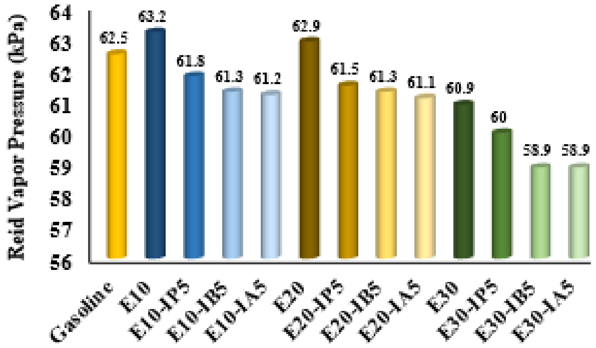

Figure 2. Effect of adding C3-C5 iso-alcohols on the vapor pressure of the ethanol-gasoline mixtures.

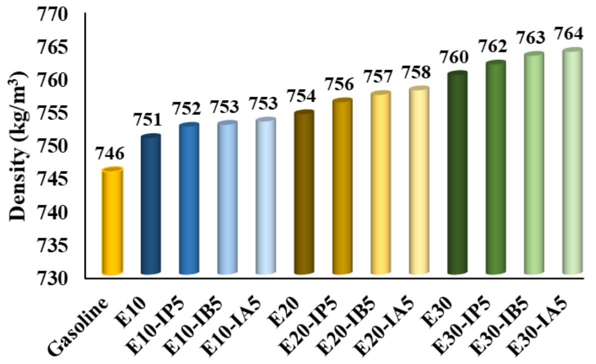

Figure 3. Density of fuel samples.

The lower heating values of fuel samples are given in Figure 4. Due to its oxygenated nature, ethanol has a heating value of 62% lower than gasoline. Therefore, the heating value of gasoline-ethanol mixtures was lower than that of gasoline, and the heating value decreased even more as the ethanol content in the mixture increased. Since C3-C5 iso-alcohols have a higher heating value than ethanol (see Table 1), the heating value of the fuel was increased by adding these alcohols to gasoline-ethanol mixtures. The heating value increases as the chain length of aliphatic alcohols increases [21]. Although the EN 288 gasoline specification does not regulate the lower heating value of engine fuels, a high heating value is a desired feature for engine fuels in terms of fuel economy and performance. Consequently, the addition of C3-C5 iso-alcohols not only reduced the vapor pressure but also increased the heating value of gasoline-ethanol mixtures, eventually reducing fuel consumption. This conclusion is supported by the findings of Bharath and Selvan [22], who demonstrated that the increased fuel consumption associated with lower alcohols can be offset by incorporating higher alcohol additives.

The octane number is a fundamental fuel property for SI engines that characterizes fuel resistance to self-ignition. The higher the octane number, the lower the knock propensity. Figure 5 shows the octane number of fuel samples. Ethanol-gasoline blends and C3-C5 iso-alcohol-added fuels have slightly higher octane numbers than base gasoline. This is an expected result since C3-C5 iso-alcohols have a higher octane rating than gasoline (refer to Table 1). Thus, they offer high anti-knock performance [23]. With a slightly lower octane number than IP and IA, IB yielded only a slight increase or no change in the octane number of the ethanol-gasoline blends. However, IP and IA significantly improved the octane number. It is attributed to their molecular structures. Fuels with extensively branched carbon chains demonstrate enhanced resistance to knocking, leading to higher octane ratings [24]. The octane number analysis result aligns with the findings of Abdellatif et al. [25], who highlighted that isopropanol is a renewable octane booster with excellent physical and chemical properties.

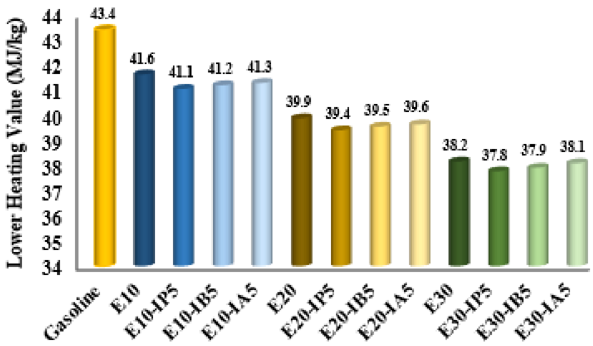

Figure 4: Lower heating value of fuel samples.

RVP is a key indicator of the volatility of the light fractions in gasoline. However, gasoline also contains high hydrocarbon fractions, whose volatility characteristics can be analyzed through distillation tests. Figure 6 displays the distillation curve of gasoline and ethanol-gasoline mixtures. Both gasoline and ethanol-gasoline blends exhibited almost the same distillation behavior from 5% to 30% distilled volume. However, their distillation curve remarkably differed beyond that point.

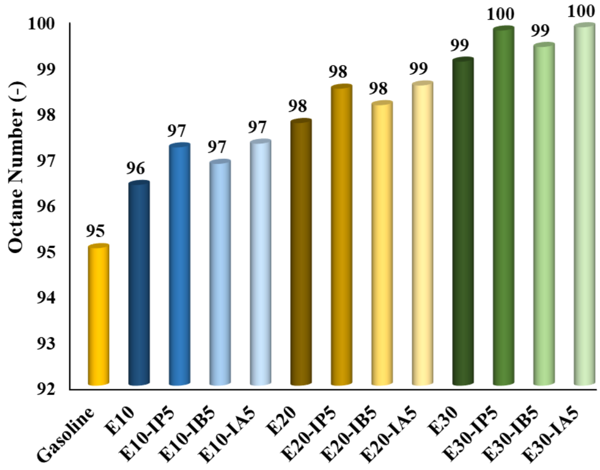

Figure 5: Octane number of fuel samples.

Specifically, the evaporating temperature of gasoline between 40% and 90% was affected by ethanol content. The main reason is that ethanol's boiling point temperature (78.5 °C) is close to the T50 (79.6 °C) and lower than the T90 (155.7 °C) distillation temperature of base gasoline. As the ethanol content in the mixture increases, the distillation curve of the fuel moves further away from the gasoline distillation curve. Similarly, Zhang et al. [26] observed that isobutanol significantly impacts gasoline's 50% evaporation temperature (T50). Such change is undesirable since it may negatively affect engine performance and fuel economy. Overall, ethanol addition to gasoline did not affect the front-end volatility (0-20 %, v/v), but it greatly impacted mid-range (20-80 %, v/v) and tail-end volatility (80-100 %, v/v). However, as seen in Figure 7, distillation curves improved when C3-C5 iso-alcohols with high boiling points were added to ethanol-gasoline mixtures. Among iso-alcohols investigated, isoamyl alcohol has the highest boiling point temperature compared to the others. Thus, it was superior to its counterparts in improving the distillation curve.

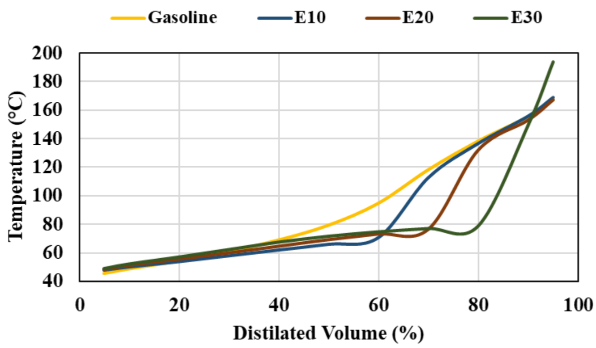

Figure 6: Distillation curve of gasoline and ethanol-gasoline mixtures.

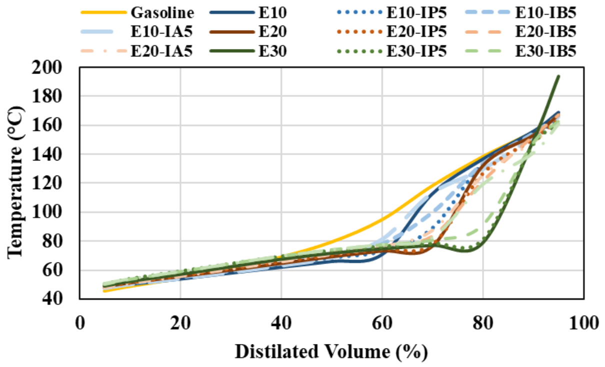

Figure 7: Distillation curve of fuel samples.

The distillation characteristics of the fuel samples were further investigated by analyzing changes in volatility, specifically in the E70, E100, and E150 distillation values. Table 4 lists the distillation values of fuel samples. They are initial boiling point (IBP) temperature in °C, final boiling point (FBP) temperature in °C, distillate fractions at specific temperatures, and residue (%,v/v). E70, E100, and E150 are the distillated volume fractions (%, v/v) at the temperature points of 70°C, 100°C, and 150°C, respectively. The volatility of fuel samples was evaluated considering the distillation values at the current minimum-maximum limits allowed by the EN 228 gasoline specification. The EN 228 regulation does not limit IBP, so the IBP row was colored yellow in Table 4. However, as specified in Table 4, it sets a range for E70 and E100 while limiting the minimum value of E150 and the maximum value of FBP and residue. All fuel samples meet the EN 228 regulation regarding E150, FBP, and residue values. However, some fuel samples exceeded the upper limit and did not comply with EN 228 regulations for E70 and E100 parameters. Due to the high volatility of the azeotropic ethanol-gasoline mixture, E10, E10-IP5, E10-IB5, E10-IA5, and E20 fuels yielded a high evaporated volume at 70°C. Fuel samples except for Gasoline, E10, and E10-IA5 exceeded the maximum limit for E100. The underlying reason for this outcome is the constant boiling point temperature of ethanol (≈78.5°C), which increased the evaporated volume at 100 °C. Since E10 constituted a lower ethanol fraction and E10-IA5 had the highest boiling point (132 °C) component (isoamyl alcohol), they met the E100 criteria. Isoamyl alcohol restricted the increase in volatility at 10% v/v ethanol fraction; however, its effect weakened at higher ethanol fractions. However, ethanol (≈78.5°C), isopropanol (≈82.3°C), and isobutanol (≈108 °C) with boiling points closer to 100 °C caused the blends to exceed the maximum limit set for E100.

Table 4: Distillation values of fuel samples

	IBP	E70	E100	E150	FBP	Residue
Gasoline	36.4	41.5	63.4	87.6	189.2	1% v/v
E10	38.2	60.7	68.1	88.7	189.7	1% v/v
E10-IP5	39.4	53.7	72	89.2	188	1% v/v
E10-IB5	39.2	50.5	71.6	89.5	186.7	1% v/v
E10-IA5	38.8	52.3	66.7	89.7	186.7	1% v/v
E20	39.4	53.6	76.3	90.3	186.9	1% v/v
E20-IP5	38.2	49.2	78.7	90.7	185.5	1% v/v
E20-IB5	38.8	47	77.3	90.5	186.6	1% v/v
E20-IA5	37	48.4	73.2	91	187	1% v/v
E30	37.7	46.6	81.8	91.4	185.6	1% v/v
E30-IP5	39.5	41.4	83.5	91.6	186.1	1% v/v
E30-IB5	39.7	41.2	82.6	91.7	185.7	1% v/v
E30-IA5	39.5	41.2	78.4	92.3	186.6	1% v/v
EN 228 limit	-	22-50% v/v	46-71% v/v	Min. 75% v/v	Max. 210 °C	Max. 2% v/v

Fortunately, the efforts to upgrade EN 228 have been ongoing. For example, the European Automobile Manufacturers' Association (ACEA) members propose revising the current EN 228 regulation. That proposal introduces a carbon/hydrogen ratio limit to help reduce exhaust CO_2 and hydrocarbon (HC) emissions. Similarly, the proposal introduces a C9+ aromatics limit of 10% v/v and a C10+ aromatics limit of 2% v/v while retaining the total aromatics limits at 35% v/v to help reduce ultrafine particle emissions. The proposal lowers the minimum fuel density limit from 720 to 690 kg/m^3 to reduce particulate matter (PM) emissions [27]. This proposal also offers new distillation points and extends the distillation range, as shown in Table 5.

Table 5. The gasoline distillation range outline proposed by ACEA [27].

	Unit	Current EN 228	Proposal
E50	% v/v, min	-	10.0
E100	% v/v, min	46.0	-
E130	% v/v, min	-	70.0
E150	% v/v, min	75.0	-
E170	% v/v, min	-	90.0

4. Conclusion

This study investigated the effects of adding C3-C5 iso-alcohols to ethanol-gasoline blends (E10, E20, and E30) on RVP and other fundamental fuel properties. The essential findings were summarized as follows:

1. E10 and E20 binary blends behaved like an azeotropic mixture, resulting in higher vapor pressure than gasoline and ethanol. However, adding C3-C5 iso-alcohols to ethanol-gasoline blends reduced RVP. The effectiveness of C3-C5 iso-alcohols in reducing RVP follows the order IA > IB > IP, which is related to their respective RVP values.
2. Dual-alcohol (E+C3/C4/C5)-gasoline blends offered enhanced density, heating value, and octane number.
3. Ethanol-gasoline blends resulted in a diverted distillation curve starting from 30% distilled volume compared to gasoline. However, adding C3-C5 alcohols to ethanol-gasoline blends slightly improved the fuel's distillation curve.
4. The determined fuel properties of all C3-C5 iso-alcohol-added ethanol-gasoline blends comply with EN 228 specifications except for some fuel samples' distilled volume at 70 °C (E70) and 100 °C (E100).
5. To comply with EN 228, gasoline regulation with maximum values of E70 and E100 can be relaxed, or the E228 regulation could be modified, including a higher ethanol fraction and C3-C5 alcohols.
6. Additionally, using higher alcohols in ethanol-gasoline blends may be advantageous in increasing the share of renewable/low-carbon fuel.

Although this study highlights a promising approach to reducing the vapor pressure of ethanol-gasoline blends, there are gaps in long-term fuel performance, compatibility with the engine, and broader environmental and economic assessments. Future research should address these limitations for a more complete analysis. Moreover, multi-alcohol blends should be investigated, and their type and concentration should be optimized.

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CRediT authorship contribution statement

Nour Eddın BULBUL: Methodology, Investigation, Writing—Original Draft Preparation, Project Administration.
Abdülvahap ÇAKMAK: Conceptualization, Investigation, Formal Analysis, Writing—Review & Editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

Abbreviations

C3 : Isopropyl alcohol
C4 : Isobutanol
C5 : Isoamyl alcohol
CO_2 : Carbon dioxide
DVPE : Dry vapor pressure equivalent
E : Ethanol
E100 : Distillated vol. (%, v/v) at 100°C
E150 : Distillated vol. (%, v/v) at 150°C
E70 : Distillated vol. (%, v/v) at 70°C
EN 228: European Standards for Gasoline
FBP : Final Boiling Point
G : Gasoline
HC : Hydrocarbon
IA : Isoamyl Alcohol
IB : Isobutanol
IBP : Initial Boiling Point
IP : Isopropanol
LHV : Lover Heating Value
ON : Octane Number
PM : Particulate Number
RVP : Reid Vapor Pressure
T50 : The temperature at which 50% of the fuel evaporates
T90 : The temperature at which 90% of the fuel evaporates

Symbols

ρ : Density (kg/m^3)
x : Volumetric fraction
Subscripts
f : Fuel
i : Fuel component

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