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Combustion and Emission Study of Ethanol Blended Fuels in IC Engines

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Abstract: As the most attractive heat engines, internal combustion engines are widely applied for various applications worldwide. These engines convert the chemical energy of the fuel to mechanical energy by the combustion phenomenon, which causes fuel to burn through fuel-air interaction and produce exhaust emissions. Spark ignition and compression ignition are two main categories of these engines differing in combustion mechanism. The conventional fuels of the noted engines are gasoline and diesel. With the population increase and the industrialization of societies, the use of internal combustion engines has become dramatically greater, causing several problems. Air pollution resulting from fuel combustion could be stated as one of the challenges that leads to the temperature rise of the earth and climate changes. The other problem is limited fossil fuels consumed by these engines. Additionally, health issues can be threatened by polluted air. Hence, renewable fuels were introduced as a vital key to overcome the obstacles. Biogas, liquefied petroleum gas, hydrogen, and alcohol are of well-known eco-friendly fuels. Among them, alcohol has drawn extensive attention due to its specific physical and chemical properties. Ethanol as alcohol with a high octane number, oxygen content, and low carbon to hydrogen ratio is a proper candidate to be used as an alternative fuel in internal combustion engines. Herein, the effect of ethanol on combustion and emission procedures is briefly reviewed. Moreover, the ethanol blends' effectiveness as a renewable fuel internal combustion engine is discussed. Furthermore, the measure of hydrocarbons, carbon monoxide, and oxides of nitrogen emissions is compared with the values created by pure gasoline/diesel combustion to analyze the emissions produced as pollution using ethanol blends.

Keywords: Internal Combustion Engine, Combustion, Emission, Renewable Fuel, Ethanol Blend

I. INTRODUCTION

Internal combustion (IC) engines are the devices to convert chemical energy to mechanical movement based on heat transfer fundamentals. Some of the features making these engines applicable and popular are high fuel consumption efficiency, functional adaptability, reliability, and cost value. During the energy conversion process, the fuel chemical energy is converted to thermal energy through the combustion phenomenon, incrementing the temperature and gas pressure. The engine output is the rotation of the crankshaft and exhaust emission [1].

The main IC engine components can be considered as the following: Block, which is the main body of the engine; Rotating shaft, known as Camshaft, to press open valves in the engine cycle at suitable times; Carburetor to mix the proper amount of fuel-air ratio; Combustion chamber located at the end of the cylinder where the fuel-air mix is burned; Catalytic converter for reduction of exhaust emissions; Cylinders consisting of pistons and valves; Cooling fins to cool the engine; Crankshaft to supply the produced work to the out of the engine as it is rotating; Fuel injector; Fuel pump for transmission of fuel from the fuel tank to the engine; Exhaust system to exhaust emissions from the cylinders to the surroundings; and Exhaust manifold for gathering exhaust emissions to a pipe [2].

There are two terms that are widely used for IC engines mechanism, including Top-Dead-Center (TDC) and Bottom-Dead-Center (BDC). TDC is the furthest position where the piston stops, and BDC is the closest to the crankshaft where the piston stops. These engines are employed in various devices such as vehicles, stationary and portable mechanisms, such as an airplane, a generator, and a saw chain [1,3].

Various classifications for IC engines are provided based on different factors like various ignition, thermodynamic cycle, engine cycle, engine design, fuel used, and combustion chamber design. One of the most basic and conventional classifications is based on the types of ignition, which includes Compression Ignition (CI) and Spark Ignition (SI). At CI type, a high compression causes a high temperature leading to the self-ignition of the air-fuel mixture. Meanwhile, in SI engines, the spark plug is used to ignite the air-fuel mixture [1,3].

The combustion process is different in SI and CI engines. The SI combustion can be divided into three phases: ignition and flame development, flame propagation, and flame termination. The combustion starts with the spark ignition leading to a low-pressure rise.

Then, the flame propagates to burn the fuel and air, causing a high-pressure increase when the work produces. Finally, the combustion stops through the pressure decrease. For CI engines, there are six steps, containing atomization, vaporization, mixing, self-ignition, and combustion. In the process, the injector emits a small droplet. The high temperature of the air, made by the engine's high compression, causes the droplet starts to evaporate. Then, the self-ignition of the fuel vapor and the air mixture at multiple locations, made due to the fast fuel injection and cylinder turbulence, leads to the combustion. The gas mixture with a consumable gas-air ratio is consumed due to the created flames propagation. The combustion procedure finishes when the fuel injection stops [1,3].

To analyze the engine efficiency, some parameters such as thermal and energy efficiency, combustion chamber geometry, compression ratio, and exhaust gas recirculation (EGR) are commonly considered. Among them, brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC) factors are mostly assumed [4]. BTE is the ratio of brake power to fuel energy. This parameter specifies the efficiency of converting heat to work, so a larger BTE value means a more efficient engine. Noteworthy, the engine design, the fuel type, and the application could influence BTE value [5]. BSFC is also a ratio of fuel consumption to the produced power by the engine. This value determines the efficiency of converting fuel to the work [6]. As BSFC reduces, a more efficient engine is obtained.

Several parameters are usually discussed, like heat release rate (HRR), ignition delay, and cylinder pressure to study the combustion. HRR is generally defined as the released energy per crank angle for fuel combustion [7-9]. Ignition delay refers to the consuming time to start combustion from ignition initiation. Cylinder pressure is affected by the fuel characteristics such as cetane number and viscosity and has numerous effects on combustion efficiency.

The combustion process creates some exhaust emissions due to chemical reactions between air and fuel, which cause air pollution. The common pollutions of IC engines are hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulates. The HC compound depends on the original fuel components as well as engine design and operating parameters. Some parameters affect the amount of HC emissions. The most important one in SI engines is the air-fuel (AF) ratio, which also affects the CO level. It is worth noting that rich AF results in a higher level of HC and CO. Since there is a lean AF in CI engines, HC emissions are one-fifth of the SI engines. CO is created due to incomplete fuel burning when there is not sufficient oxygen to convert all carbon amounts of CO2. As HC, CI engines emit a much lower CO than the SI engines. Moreover, NOx is produced mostly from the air's nitrogen (N2), and most of its content is NO. The main reason for producing NOx is the high temperature that occurs in lean AF ration. Furthermore, pressure and combustion time are also influential factors. Solid carbon soot particles, seen as smoke, are generated in CI engines because of the reach AF ratio.

With the increase in the number of IC engines globally, air pollution has become a significant issue requiring special attention. On the other side, fossil-based energy sources are limited, and replacing them with renewable fuels is inevitable. Accordingly, several researches have been carried out to introduce and use the alternative fuels and examine their effects on the engine's performance. As the alternative fuels for IC engines, natural gas, liquefied petroleum gas (LPG), hydrogen, biogas, landfill gas, syngas, and alcohols can be mentioned [10,11]. Alcohols are more pleasant because they are more accessible and easier to transport and store among these desires. Besides, alcohol blends make more growth in ignition delay, peak in-cylinder pressure, and maximum heat release rate than conventional diesel fuels.

Ethanol (C2H5OH) and methanol (CH3OH) are two more frequently used alcohol. Whereas, ethanol has received an extensive attention since 19th century as renewable energy for CI and SI engines due to its lower carbon number, higher octane number, oxygen content, and low carbon to hydrogen ratio [12-15]. This approval comes because of its ease of access and fewer effects on climate change.

This fuel can be produced from biomasses and can be used along with diesel, biodiesel, gasoline, and other fuels to make a blend. Different ethanol concentrations cause various engine performances, combustion efficiencies, and exhaust emissions [16]. Although there are experiments to prove the effectiveness of using ethanol blends, this alternative fuel has not been widely employed commercially for several reasons. First, low ethanol concentration can be mixed with other fuels resulting from its low density and viscosity. Second, aluminum and copper corrosion could be occurred resulting from its water-miscibility. Third, fuel pipe banning may occur due to a chemical reaction between ethanol and rubber. This paper aims to review different blends of the ethanol used in CI and SI engines, and its effects on the engines' performance, to give an overview of its current state. Therefore, the following section describes the ethanol and its blend features and applications in CI and SI engines. Then, the effects of ethanol eco-friendly fuel on combustion and emission performances is discussed in the 3rd and 4th sections. In section 5, the experimental and numerical fields of view are briefly explained.

II. ETHANOL APPLICATION IN CI AND SI ENGINES

Several methods can be used to employ ethanol in a CI engine; more common are direct injection, blending, emulsification, and port injection [17,18]. The direct injection technique is not desirable because of ethanol's poor miscibility. Therefore, the port injection procedure is suggested to solve this problem. In this method, the main chamber is used to spray the primary fuel, and ethanol is injected through the intake port.

The port injection can be applied with the least engine adaptation, where the engine can be utilized as either dual fuel or single fuel. In the blending method, a homogenous mixture is created using ethanol and other fuels. Notably, a homogenous blend of ethanol and diesel is not possible due to its poor miscibility [19]. To increase the amount of the ethanol in the mixture, the emulsion method or port injection of ethanol are proposed [12].

In the emulsion process, an emulsifier is applied to decrease carbon chain length leading to the enhancement of ethanol polarity and so the formation of a more homogenous mixture [20,21]. The most level of ethanol as the fuel can be achieved using the port injection method [22].

A higher concentration ethanol blend promotes combustion due to more oxygen content and fuel atomization. It is worth mentioning that an ethanol blend with lower density and surface tension causes better atomization in injected fuel. The addition of ethanol to diesel in CI engines decreases the evaporation temperature leading to lower air-fuel mixture time. The oxygen content of the ethanol leads to improved combustion efficiency and reduces exhaust gases [23].

Ethanol can be employed as a sustainable fuel in SI engines by itself or in a mixture with gasoline because it is fluid and has similar combustion characteristics to gasoline. However, this fuel raises the compression ratio without a knock and leads to fewer exhaust emissions than gasoline resulting from adding oxygen to prohibit incomplete combustion. Moreover, it enhances volumetric efficiency and engine power attributed to its high heat vaporization rate [9,24,25].

The effect of ethanol with various energy fractions on a single-cylinder, four-stroke direct-injection stationary CI engine connected to an AC alternator is studied in the literature [13]. In a direct-injection engine, fuel is sprayed into the main combustion chamber. Four-stroke refers to four pistons traveling along the cylinder. Regarding the CI engines, ethanol-diesel blend with a special proportion is a common fuel [26-28]. The type of considered CI engines by the researchers are a single-cylinder [28], four-stroke, and four-cylinder [27]. Biodiesel-ethanol could be considered another usable blend [29]. Biodiesel/Ethanol in a four-cylinder direct-injection CI engine and a four-stroke single-cylinder CI engine are considered in the studies evaluated by Wei et al. [30] and Gopal et al. [31], respectively.

The blend of acetone–butanol–ethanol (ABE) and diesel/biodiesel or gasoline as an alternative fuel for both CI and SI engines has also been characterized by several researchers [32,33]. In the ABE blend, the ratio of the component is an essential factor affecting the final performance. This mixture has a low cetane number and a high latent heat. The effects of diesel/PODE (polyoxymethylene dimethyl ethers)/ethanol blends on a six-cylinder heavy duty CI engine are declared by Liu et al. [34]. PODE is proposed as an agent of ether fuel to be mixed with diesel/ethanol because of its key role in diminishing soot emissions [35,36]. PODE has a higher cetane number than diesel of the mixture, high oxygen content, and low vaporization temperature, leading to a better fuel-air combination and improving the combustion efficiency.

Its high miscibility with diesel/ethanol and high cetane number could balance the low cetane number of ethanol, making it a potential candidate to be mixed with diesel/ethanol fuel [37]. One of the modification methods for ethanol blend fuel to enhance engine performance and air-fuel burning and diminish emissions is using catalysts. Metal-based additives can be considered effective catalysts specially when they are used in the form of nanoparticles instead of bulk form, because of their higher surface area [38,39]. Venu et al. [29] figured out the effect of loading Alumina (Al_2O_3) nanoparticles in diesel-biodiesel-ethanol fuel in a single-cylinder direct-injection CI engine.

Based on the obtained results, exploiting this nanoparticle in the blend causes a further progress in combustion and emission performances.

The studies related to the influence of using ethanol blend in SI engines are not as many as in CI engines. The effect of ethanol and ethanol-gasoline combination in a four-cylinder, four-stroke SI engine performance is discussed in the literature [25, 40, 41]. A mixture of ABE and hydroxy for the dual fuel SI engine is also investigated by Estrada and coworkers [9]. In addition, Costa et al. [42] studied biogas/ethanol for dual fuel SI engines. The effect of gasoline-ethanol-hydrogen blend on a Ford MVH418 1.8 L SI engine is discussed in the study performed by Akansu et al. [43]. Based on this evaluation, introducing hydrogen into the ethanol blend prevents cold starting and reduces the fuel consumption due to its high self-ignition temperature and extending the lean combustion.

III. ETHANOL EFFECTS ON COMBUSTION PERFORMANCE

The addition of ethanol into diesel fuel causes a reduction in BTE and energy efficiency at low engine loads and an increment at high engine loads [13]. BTE reduction could be assigned to lean ethanol-air mixture and high concealed vaporization. Meanwhile, BTE increase at high loads is associated with a homogenous air-ethanol mixture. Increment of the ethanol energy ratio results in a rise in the peak pressure, ignition delay, and HRR, and decrement in the combustion duration. According to the studies on the ethanol-diesel blend, an increase in the maximum combustion pressure, ignition delay, HRR, and BSFC and a decrease in the combustion duration and BTE are observable [26-28]. Ignition delay rises due to low cetane number, high latent vaporization heat of ethanol, and lower combustion temperature associated with the ethanol quenching effect. This resulted in higher HRR and combustion pressure as well as lower BTE. The biodiesel/ethanol mixture could cause a longer ignition delay, an increase in maximum in-cylinder pressure, maximum HHR, and BSFC [44]. In contrast, there are no noticeable changes in BTE [30]. Gopal et al. [31] implied some different results in which biodiesel/ethanol reduces HRR and BTE at any load while causing an enhancement in BSFC and in-cylinder pressure compared to biodiesel. Using ABE for CI engines increases indicated thermal efficiency (ITE) [45], BTE, and BSFC, especially when a small amount of water is added to it compared with diesel [46] and biodiesel [47]. ABE gives a longer ignition delay and shorter combustion duration [48], whereas an ignition delay similar to diesel fuel could be achieved by adding an acetone ratio [49]. Diesel/PODE/ethanol combination improves BSFC and has no effect on BTE [34]. For the in-cylinder pressure and HRR, there is no overall result.

It can be concluded that their incline or decline depends on the brake mean effective pressure (BMEP), engine load, and the fuel injection method. Embedding Al_2O_3 nanoparticles to ternary fuel proved to enhance BTE, cylinder pressure, HRR, and cumulative heat release rate (CHRR) and reduce brake specific energy consumption (BSEC) [29]. The outstanding result is associated with the nanoparticles' catalyst role effect in improving fuel droplets explosion, thereby better fuel-air interaction. Ethanol results in a lower HRR and superior BTE and BSFC than gasoline [25,40,50].

ABE for SI engines causes growth in BSFC because of its low heating values compared with the gasoline, but the reduction in BSFC in comparison to ethanol [51]. It also increases BTE and ITE compared with gasoline [52], especially using a higher acetone ratio due to having more oxygen in the blend [53].

It is illustrated that in-cylinder pressure reduces whereas fuel consumption rises. Heat release rate and combustion temperature have no changes [9]. Using ABE decreases ignition delay [54] where lower ABE ratio causes increase in ignition delay [55]. Biogas/ethanol dual fuel also gives shorter ignition delay, less HRR, and greater peak cylinder pressure compared with single biogas and ethanol fuels [42]. The thermal efficiency and maximum pressure values decline through addition of ethanol to gasoline, while loading hydrogen to the combination leads to a growth in thermal efficiency [43].

IV. ETHANOL EFFECTS ON EMISSION PERFORMANCE

It is widely shown that applying ethanol substitution could cause a decrement in NOx and smoke and a rise in CO and HC [13]. Based on the literature, ethanol-diesel blends can cause NOx growth or decline and the reduction of CO, HC, and smoke emissions [26,27,56,57]. However, as declared by Shanmugam et al. [28], CO and HC could enhance by increasing the amount of ethanol concentration. Biodiesel/ethanol improves CO and HC, while reducing NOx [30]. Meanwhile, a contrariwise result has been reported by Gopal and coworkers [31].

ABE for CI engines raises the amount of CO [46], HC [46, 48], and NOx [45, 48] compared to diesel fuel. In addition, the introduction of water leads to a decrease in NOx compared with biodiesel [47]. It has been displayed that Diesel/PODE/ethanol combination leads to the NOx enhancement while decreasing CO and HC compared to diesel [34]. According to the research performed by Venu et al. [29], the incorporation of Al_2O_3 nano additive into ternary fuel for the CI engines decreases the amount of HC, CO, NOx, and smoke emissions by 5.69, 11.24, 9.39, and 6.48 %, respectively. Moreover, it is shown that using ethanol instead of gasoline in SI engines declines HC [30] and CO emissions [40]. Ethanol-gasoline blend gives a reduction in CO and NOx and a growth in HC [41]. In 2018, Iodice et al. [25] represented lower CO and HC for a particular ethanol concentration in the blend and fewer NOx for all examined ethanol concentration. Using ABE and dual hydroxy fuel similar to ABE blend for SI engines [58, 59] decreases CO, HC, and smoke emissions [9], while enhancing NOx emissions in SI engines [9]. Previous researches confirmed that ABE gives the same NOx as gasoline [53-55,59]. Meanwhile, several approaches declared a reduction in NOx for special ABE ratios [52,58,60]. Biogas/ethanol dual fuel is shown to inhibit CO and HC comparing to biogas and NOx comparing to ethanol [42]. The amount of HC and CO enhances through incorporation of ethanol into gasoline, whereas NOx decreases. A vice versa scenario is exhibited for addition of hydrogen [43].

V. EXPERIMENTAL AND NUMERICAL APPROACH

Most of the research in this area has been performed using experiments to study the engine's performance by using various ethanol-based combinations. Three important factors are mentioned to explain the experiment, including the blend type and proportion of components, the type engine, and the investigated performance parameters. The applied blends and the considered engines are described in section 3. The parameters for SI engines are usually in-cylinder pressure, heat release rate, combustion temperature, fuel properties, energy distribution, and emissions levels [9]. Cylinder pressure, HRR, CHRR, BTE, BSEC, and exhaust emissions are the common factors analyzed for CI engines [29]. The numerical studies are referred to evaluations carried out using simulation to model engine, combustion, and so on to investigate the performance of the engine and combustion phenomenon [61]. The main aim of such a model is to analyze pressure and temperature changes in the engine cylinder [62]. Three popular models for combustion simulation are zero-dimensional, multi-zone, and multi-dimensional [63-65]. The multi-zone model is usually employed for dual-fuel engines. Multi-dimensional models are defined by exploiting a set of coupled partial differential equations related to the geometric mesh of the combustion chamber space. The cylinder space is divided into several zones based on the combustion occurrence in the multi-zone model. For example, Papagiannakis et al. [66] proposed a two-zone model to discuss the influence of a pilot fuel quantity and its injection on combustion parameters in a dual-fuel engine. A two-zone model consists of the burned and the unburned zones that should be able to predict HHR in SI engines [65].

VI. CONCLUSIONS

In recent decades, the concerns about the consequences of using fossil fuels have increased with the growth of applying internal combustion engines globally. To deal with this issue, the alternative fuel in IC engines has drawn extensive attention. An ideal alternative fuel should increase the engine efficiency and improve thermal and combustion parameters, including BTE, BSFC or BSEC, ignition delay, HRR, and in-cylinder pressure. In addition, it is preferable to cause a reduction in exhaust emissions like HC, CO, NOx, and soot. Various alternative fuels are introduced by the researchers, such as natural gas, liquefied petroleum gas, hydrogen, biogas, and alcohols. Among all, alcohols are more interested due to more feasible reservation, carrying out, and accessibility. As the alcohol fuel, ethanol blends, the renewable and eco-friendly fuels are known as one the most appealing alternative fuel candidates for replacing the pure fossil fuels in internal combustion engines. This could be linked to the unique chemical properties of ethanol such as its oxygen content that leads to higher combustion and lower exhaust emissions. So, a higher ethanol percentage in the blend results in a better combustion efficiency and a drop in emissions. Nevertheless, low density and viscosity of ethanol prohibit applying its high concentration in the combinations. Therefore, emulsion and port injection methods are employed to deal with this obstacle. Moreover, the low density and surface tension of the ethanol cause the fuel atomization, which increases the complete combustion and diminishes the emissions. Ethanol's low vaporization temperature reduces the air-fuel mixture time leading to better combustion. In SI engines, ethanol raises the compression ratio without adding knock. This feature encourages the use of ethanol instead of gasoline or a gasoline/ethanol blend. It can be inferred from the literature that ethanol's low cetane number, high latent vaporization heat, and lower combustion pressure, attributed to the ethanol quenching effect, increase the ignition delay because of a growth in HRR, combustion pressure, and BSFC, as well as a drop in BTE. However, it is shown that a BTE increase in a high load of the engine is associated with the homogenous mixture of air-fuel. Additionally, compared to pure diesel and gasoline, ethanol could cause increasing NOx emissions and decrease HC and CO.

To approach better combustion performance and lower emissions, incorporation of other substances into ethanol blends is proposed by the scientists. PODE is one of the well-known additives with a high cetane number, high oxygen, and low vaporization temperature leading to a better air-fuel mixture. The main reason for using this substance is to inhibit soot emission. The other parameter changes are the function of BMEP, engine load, and the fuel injection method. Using PODE increases NOx emission and decreases HC and CO. Evaluation of the ABE features has implied not a more achievement than blending ethanol with pure fossil fuels. Al2O3 nanofiller is another proposed additive that has the catalyst effects resulting in a more fuel particle explosion, thereby a more air-fuel interaction. This superiority causes an increase in BTE, CHRR, and HRR, and a drop in BSFC. It also causes a reduction in NOx HC, CO, and smoke. Introduction of hydrogen to ethanol/gasoline proceeds to higher thermal efficiency because hydrogen can prevent cool starting. It also has effects on reducing CO and HO while rising NOx.

To sum up the studies on ethanol prosperity to be used as an alternative fuel in CI and SI engines, several parameters should be considered to investigate ethanol effects on combustion and emission. The engine type, engine load, crank angle, ethanol percentage in the blend, and the engine pressure are the parameters that should be considered in further researches. Researchers should focus on the new ethanol blends to decrease NOx and BSFC. Furthermore, it is vital to investigate the effects of proper nanoparticles regarding the great potential of these fillers in performance improvement.

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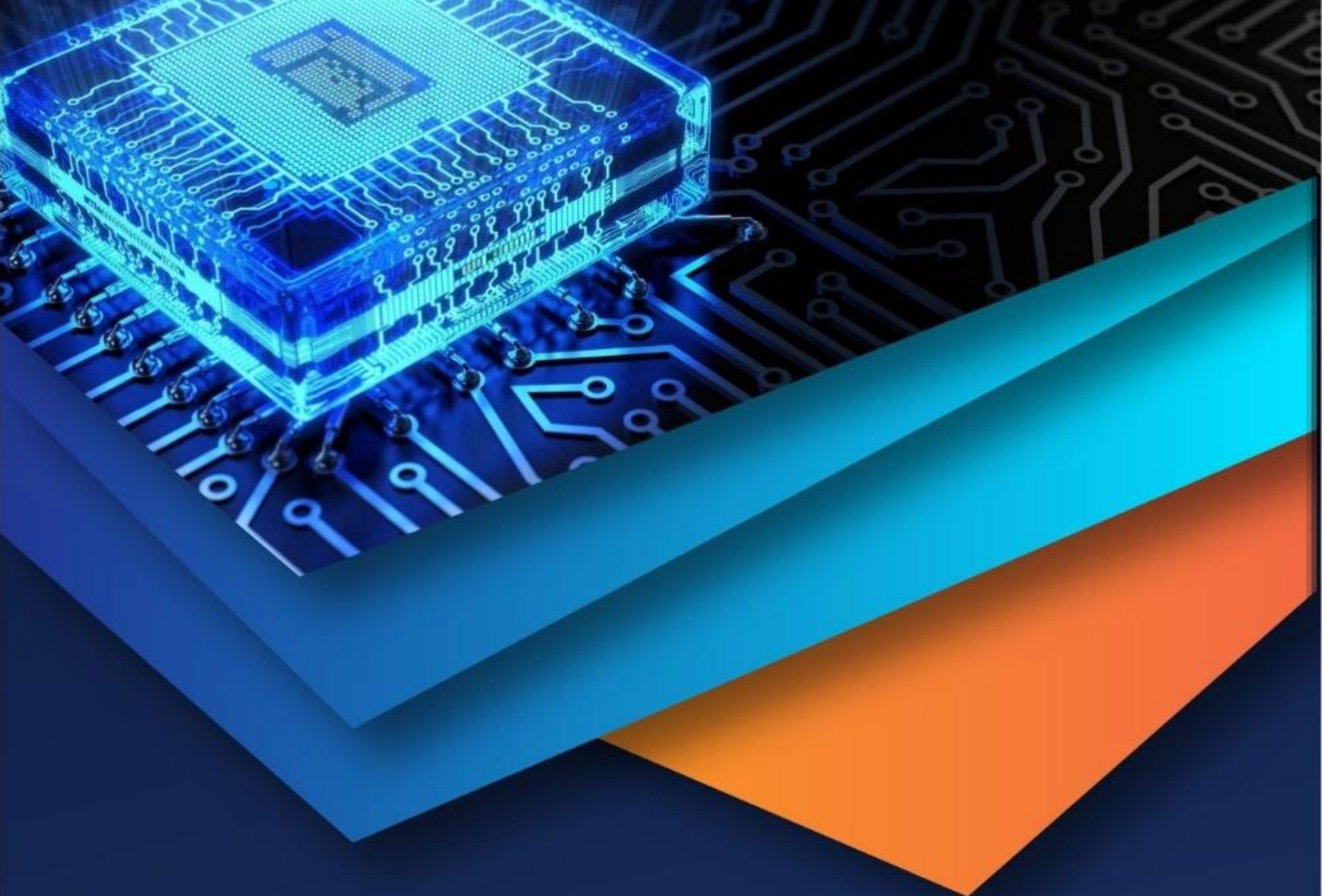

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