



A Study of the Effect of Additive Concentration in B40 Biodiesel on the Performance of the Air Preheater in a Steam-Powered Electric Power Plant

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ABSTRACT

The increased use of B40 biodiesel in coal-fired power plants in Indonesia poses challenges related to fuel characteristics, particulate matter content, heat transfer efficiency, and combustion emissions. The present study explores the impact of 2-ethylhexyl nitrate (2-EHN)-based additive concentrations on B40 characteristics, air preheater (APH) performance, and combustion emissions. The additive was subjected to testing at concentrations of 0, 200, 300, 400, 900, 1000, and 1100 ppm. The fuel characteristics evaluated included viscosity, particulate content, cetane number, and Fatty Acid Methyl Ester (FAME). Combustion testing was conducted for a period of eight hours under cold-start boiler conditions, with the exclusion of coal as a fuel source. Operational data were collected at 15-minute intervals via the Distributed Control System (DCS), while SO₂, NO_x, CO, and CO₂ were monitored hourly via the Continuous Emission Monitoring System (CEMS). The study's findings suggest that the incorporation of the additive did not result in substantial alterations to the viscosity of B40 at ambient temperatures. However, it led to a significant reduction in the particulate content. At a concentration of 1000 ppm, the suspended particulate matter decreased from 52.0 mg/L to 1.7 mg/L, representing a 96.7% reduction. Concurrently, the number of particles with sizes ≥ 4 , ≥ 6 , and ≥ 14 μm decreased by 77%, 87%, and 95%, respectively. A concentration of 1000 ppm was found to enhance the thermal performance of the air preheater. An enhancement in the efficiency of the primary air heater (PAH) was observed, with an increase from 75.84% to 78.86%. Furthermore, a rise in efficiency was observed for the secondary air heater (SAH) from 40.49% to 44.12%, and for SAH B, from 38.75% to 42.23%. The incorporation of additive at a concentration of up to 1100 ppm resulted in a 16.40% reduction in CO emissions and a 5.33% reduction in NO_x emissions. Conversely, there were minimal changes observed in SO₂ emissions, while CO₂ emissions exhibited a slight increase. The findings of this study indicate that a concentration of approximately 1000 ppm was conducive to achieving optimal performance in terms of reducing particulate matter and enhancing the efficiency of the air preheater. However, it was observed that higher concentrations did not invariably result in superior performance.

Keywords: 2-ethylhexyl nitrate, additive, air preheater, B40 biodiesel, coal-fired power plant, combustion emissions, particles.

1. INTRODUCTION

Indonesia's energy infrastructure remains heavily dependent on fossil fuels. This dependence raises concerns regarding energy security, foreign-exchange expenditures on fuel imports, and greenhouse gas emissions [1,2]. To address these challenges, Indonesia has promoted energy diversification through renewable energy sources, including biofuels [3,4]. Composed primarily of fatty acid methyl esters derived from vegetable oils, animal fats, or waste lipids, biodiesel offers several advantages over conventional diesel,

including renewability, biodegradability, low sulfur content, a high flash point, improved lubricity, and an inherent oxygen content [5,6]. These benefits have supported the implementation of B40, a blend containing 40% biodiesel and 60% petroleum diesel.

However, increasing the biodiesel content alters important physicochemical properties, such as density, viscosity, heating value, volatility, and oxidation stability [7,8]. These changes can affect fuel delivery, atomization, ignition, flame development, combustion efficiency, fuel consumption, exhaust gas

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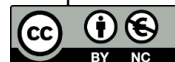
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temperature, deposit formation, and emissions. These effects are particularly important in steam power plants, where combustion performance is closely integrated with downstream thermal processes and heat-recovery systems.

Therefore, recent biodiesel research has explored various additives, including antioxidants, cold-flow improvers, oxygenated compounds, metal-based catalysts, nano-additives, lubricity enhancers, deposit-control agents, and cetane improvers [9,10]. One such additive is 2-ethylhexyl nitrate (2-EHN), which is widely used to improve ignition quality. Its thermal decomposition generates reactive radicals that accelerate hydrocarbon oxidation and chain-branching reaction, thereby increasing autoignition reactivity and shortening ignition delay times [11,12]. Previous studies indicate that 2-EHN can influence cetane number, fuel consumption, thermal efficiency, exhaust gas temperature, and emissions [13–16]. However, these responses depend strongly on fuel composition, additive concentration, combustion-system design, load, air-fuel ratio, and temperature. Consequently, under different combustion conditions, carbon monoxide, unburned hydrocarbons, and smoke may decrease, while nitrogen oxides may either increase or decrease [14–17].

The commercial additive evaluated in this study contains at least 50% 2-EHN combined with 2-ethylhexanol. While 2-EHN primarily enhances ignition, 2-ethylhexanol may modify density, viscosity, volatility, oxygen content, miscibility, spray behavior, and evaporation. Therefore, the additive's effects cannot be attributed solely to pure 2-EHN.

Changes in combustion and flue-gas characteristics may also influence air preheater performance. The air preheater recovers heat from hot flue gas to preheat incoming combustion air. This supports ignition, flame stability, and complete combustion. It also reduces unburned fuel losses and improves boiler efficiency [18,19]. Air preheater performance depends on inlet

temperatures, mass flow rates, heat capacities, fouling, corrosion, and air leakage. Fuel composition can indirectly affect recoverable heat through changes in flue gas temperature, flow rate, moisture, and composition.

Most studies of biodiesel additives have focused on diesel engines, generators, or laboratory combustion systems [13–17], whereas air preheater research has largely examined heat transfer, leakage, fouling, corrosion, and boiler losses [18–21]. Studies of 2-EHN have mainly addressed engine ignition, combustion performance, and emissions [10,12,14,22], while air preheater studies in coal-fired plants have emphasized heat transfer, leakage, corrosion, and ash deposition [18,23]. This leaves an important research gap because findings from engine-scale studies cannot be directly transferred to steam power plants. Accordingly, this study evaluates the effects of different additive concentrations in B40 by considering fuel characteristics, boiler start-up combustion, air preheater thermal efficiency, emissions, and operational stability in a power plant-scale assessment.

2. RESEARCH METHODS

The present experimental study was conducted for the purpose of evaluating the effect of adding an additive to B40 fuel on fuel characteristics, Air Preheater (APH) thermal efficiency, and combustion emission. The additive used contained more than 50% 2-ethylhexyl nitrate, less than 10% 2-ethylhexanol, and approximately 40% other components. The additive dosage variations that were examined encompassed conditions devoid of additives, in addition to dosages of 200, 300, 400, 900, 1000, and 1100 ppm. The testing was conducted in two stages as outlined in the research flowchart (Figure 1). The initial stage comprised laboratory testing of the B40 blend and additives at each dosage variation, with the objective of identifying changes in fuel characteristics. These characteristics included viscosity, particulate matter, and cetane number. The second stage of the research programme involved the

testing of operational boilers with the aim of evaluating the effect of additive dosage on the APH's thermal efficiency and combustion emissions.

The operational testing was conducted during start-up with operating parameters of a main steam temperature of 525°C and a main steam pressure of 104 kg/cm². Subsequent to the introduction of the B40 fuel mixture and additive into the boiler, a 60-minute preparatory and stabilisation period was

undertaken prior to the commencement of data collection. Subsequently, data on operating parameters, APH thermal efficiency (ϵ), and combustion emissions were collected over an 8-hour period for each test condition. The test results for each additive dosage variation were then compared with conditions without additive addition in order to determine the effect of additive use on fuel characteristics and combustion process performance.

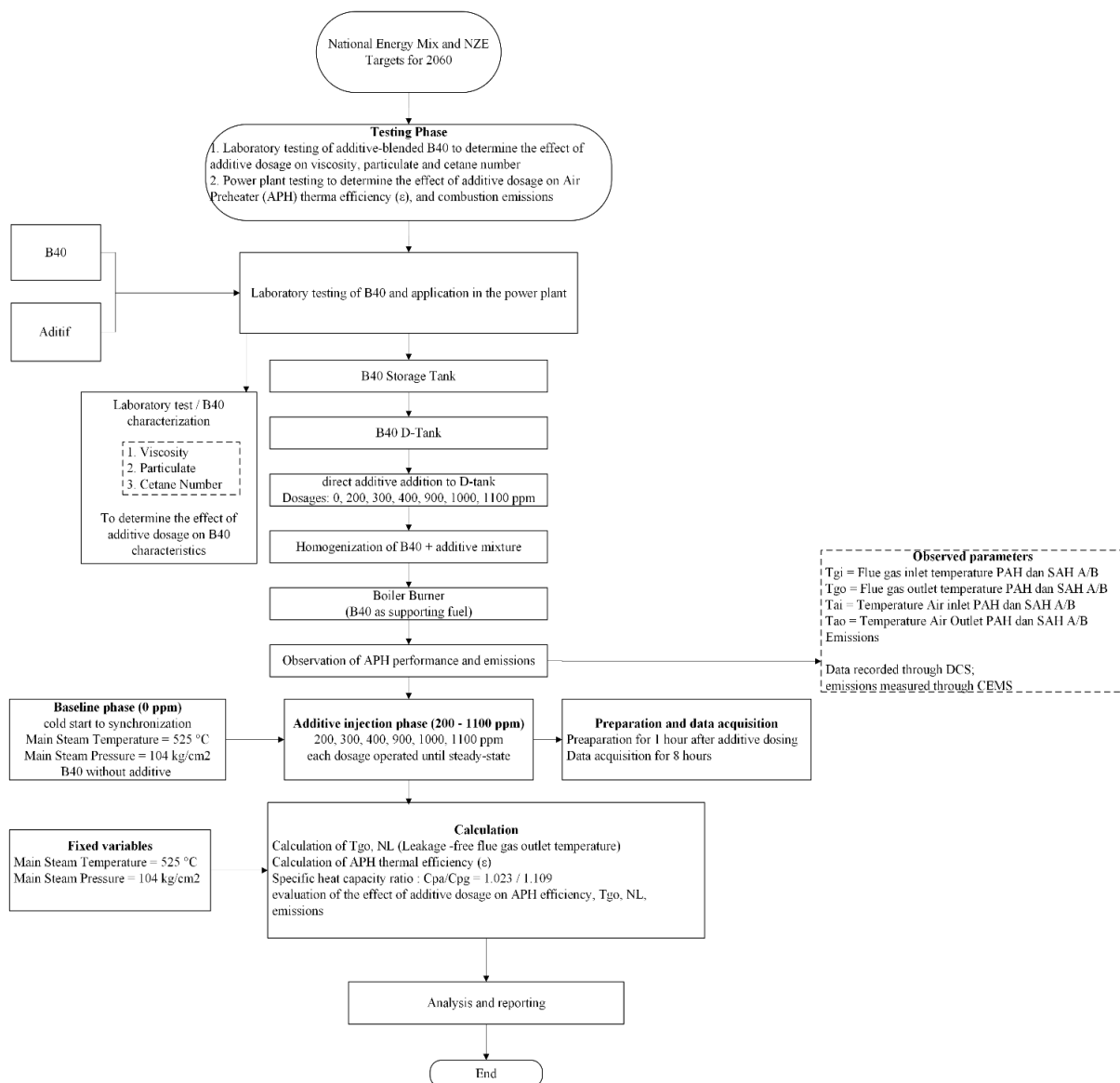


Figure 1. Research flowchart.

The foundational assessment was performed with B40 devoid of any additives. The additive concentrations were subsequently evaluated in a range from 200 to 1100 ppm. Data acquisition commenced once the main steam temperature, main steam pressure, and Air Preheater temperatures attained equilibrium.

The additive concentration was expressed on a volume-to-volume basis (ppm v/v). The requisite additive volume was determined through the application of the following equation (1) :

$$V_{\text{add}} = \frac{C_{\text{add}}}{10^6} \times V_{B40} \quad (1)$$

In this equation, V_{add} represents the required additive volume (L), C_{add} signifies the target additive concentration (ppm v/v), and V_{B40} denotes the actual B40 volume (L). The nominal capacity of the day tank was 527,667 L. At full capacity, the additive volumes required for concentrations of 200, 300, 400, 900, 1000, and 1100 ppm were 105.53,

158.30, 211.07, 474.90, 527.67, and 580.43 L, respectively. However, the additive quantity used in each test was calculated based on the actual B40 volume recorded immediately before dosing.

For the purpose of laboratory characterization, 1 L of B40 was blended with 0, 0.20, 0.30, 0.40, 0.90, 1.00, and 1.10 mL of additive, thereby obtaining concentrations of 0, 200, 300, 400, 900, 1000, and 1100 ppm, respectively. Each formulation was subsequently homogenized using an overhead mechanical stirrer at 500 ± 20 rpm for 30 min at $25 \pm 2^\circ\text{C}$. The samples were allowed to stand for 30 minutes and then subjected to a 5 minute remixing process prior to analysis. The prepared fuels were subsequently analyzed for viscosity, particulate content, and cetane number. The implementation of additive-blended B40 in a power plant context is illustrated in Figure 2. Coal was utilized as the primary fuel source in the power plant, while B40 was employed as a start-up and supporting fuel for the boiler combustion system.

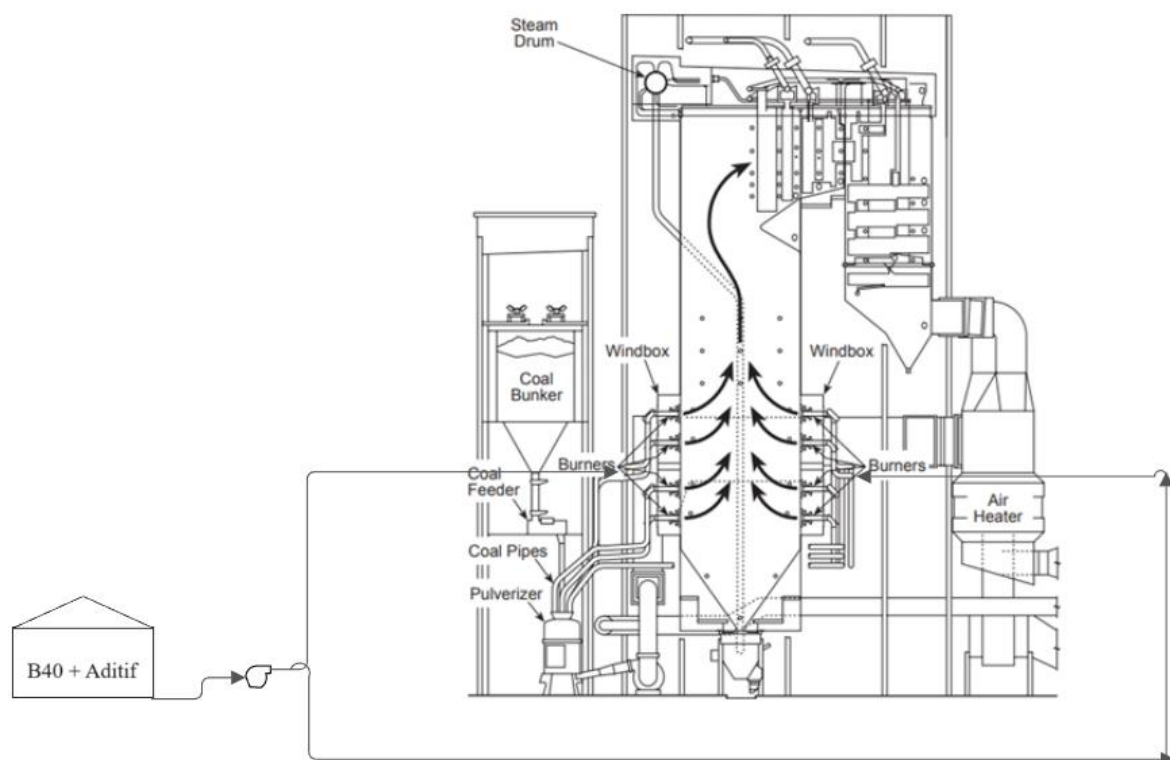


Figure 2. Testing process for B40 and additives at a coal-fired power plant.

The B40 additive was transferred from the primary storage tank to day tank, and the commercial additive was introduced through a closed dosing line at concentrations of 0, 200, 300, 400, 900, 1000, and 1100 parts per million (ppm).

The additive was injected gradually over a period of approximately 30 minutes while the day-tank fuel-recirculation system was operational. The required homogenization time was determined using the following equation (2):

$$t_{\text{mix}} = \frac{NV_{B40}}{Q_{\text{rec}}} \quad (2)$$

Where t_{mix} is the homogenization time (h), (N) is the number of tank volume turnovers, V_{B40} is the actual B40 volume in the day tank (m^3), and Q_{rec} is the fuel-recirculation flow rate (m^3h^{-1}). The homogenization criterion employed a minimum of two tank volume turnovers.

Subsequent to the homogenization process, the additive-blended B40 was introduced into the boiler burner for a 1-hour preparation period, the objective of which was to displace the residual fuel in the pipelines. Subsequently, each additive concentration was subjected to a 8-hour testing period, commencing from the cold start and culminating in synchronization. Subsequent to the attainment of stable operating conditions, the primary steam temperature and pressure were sustained at approximately 525°C and 104 kg/cm^2 , respectively.

The flue gas inlet temperature (T_{gi}), flue gas outlet temperature (T_{go}), air inlet temperature (T_{ai}), and air outlet temperature (T_{ao}) of Primary Air Heater (PAH) A/B and Secondary Air Heater (SAH) A/B were recorded through the Distributed Control System. It also known that C_{pa} : mean specific heat of air (1.023 kJ/kg.K) and C_{pg} : mean specific heat of flue gas (1.109 kJ/kg.K). These data were the utilized to calculate the leakage corrected flue gas outlet temperature ($T_{\text{go,NL}}$) and Air Preheater thermal effectiveness (ϵ) [23]. Subsequently, the following equation is presented:

$$\epsilon = \frac{T_{\text{ao}} - T_{\text{ai}}}{T_{\text{gi}} - T_{\text{ai}}} = \frac{T_{\text{gi}} - T_{\text{go,NL}}}{T_{\text{gi}} - T_{\text{ai}}} \times 100\% \quad (3)$$

In order to calculate the outlet gas temperature, it is necessary to assume that there are no leaks and that all leaks occur on the cold end of the air preheater side ($T_{\text{go,NL}}$) [23]. The following formula can be used for this purpose:

$$T_{\text{go,NL}} = \frac{C_{\text{pa}}}{C_{\text{pg}}} \times (T_{\text{go}} - T_{\text{ai}}) + T_{\text{go}} \quad (4)$$

The combustion emission data were obtained from the Continous Emission Monitoring System (CEMS).

3. RESULTS AND DISCUSSION

Diminished power generation in biodiesel-powered systems may be linked to limited fuel supply due to filter obstruction, particle impurities, and accumulations inside the fuel-injection mechanism. Insoluble impurities, saturated monoglycerides, oxidation by products, gums, and sediments may build up on the filter medium, elevating pressure drop and diminishing fuel flow. Accumulations can also disrupt injector efficacy and fuel atomization [24–26].

In order to tackle these issues, a commercial multicomponent fuel additive was assessed at doses of 0, 200, 300, 400, 900, 1000, and 1100 ppm. In the current operational guidelines, a recovery treatment-

3.1. Effect of Additives on Viscosity

As shown in Figure 3, it has been demonstrated that, at ambient temperature, the incorporation of additives into B40 results in an increase in viscosity following a period of three days storage. This increase is hypothesised to be associated with the oxidative instability of biodiesel, which can result in the formation of gum, sediment, and insoluble compounds [27,28]. The viscosity of biodiesel-diesel blends is also influenced by fuel composition and the temperature during testing [29,30]. Although viscosity increases with the addition of additives, the difference between the 200 ppm and 1100 ppm dosages is relatively small. This

indicates that variations in dosage at room temperature do not yet result in significant changes in viscosity. At 40°C, viscosity demonstrates a temperature and additive concentration-dependent response [31–33]. The 900-ppm dose demonstrated a more stable viscosity profile, while the 300 ppm and 1000 ppm doses exhibited an increase. Concurrently, at a dosage of 200 ppm, contaminants were also detected, which are suspected to be caused by oxidative instability and chemical interactions between the additive and B40 fuel [27,28].

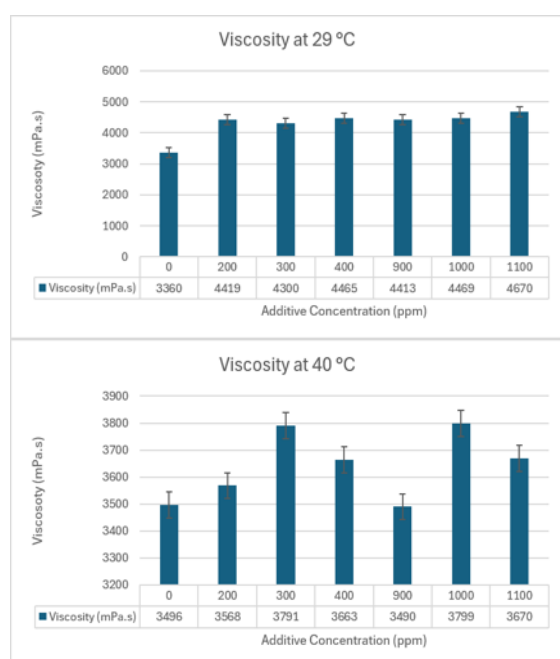


Figure 3. Effect of additive dosage on viscosity.

It appears that the addition of additives did not result in a significant change in the viscosity of B40 at 29°C, but tended to maintain its stability. It has been suggested by Pham et al. [33] that at 40°C, viscosity may decrease as the temperature rises. It is possible that this decrease may also be influenced by the presence of 2-ethylhexyl nitrate (2-EHN), which has low viscosity and acts as a solvent, thereby improving the fuel's flow properties [34]. It is thought that these findings indicate that the additive has the potential to maintain the viscosity stability of B40 at normal temperatures while improving

the fuel's flow properties at higher temperatures.

3.2. Effect of Additives on Particulates

In assessing the quality of B40 fuel, particulate matter is a key parameter, given that blend of diesel and biodiesel may contain insoluble compounds, including monoglycerides, sterol glucosides, free glycerin, way, and sludge. These compounds have the potential to precipitate, leading to filter clogging and disruption of the fuel injection system [25,35]. According to ISO 4406 and detailed in Table 1, B40 without additives contain 28,666 particles/mL of particles $\geq 4 \mu\text{m}$, 26,531 particles/mL of particles $\geq 6 \mu\text{m}$, and 15,860 particles/mL of particles $\geq 14 \mu\text{m}$. The findings of this study suggest the presence of particulate contamination, which has the potential to compromise the functionality of the filtration and fuel injection systems (see visual representation in Figure 4).

Table 1. B40 particle test results at a dose of 1000 ppm.

Particle size (μm)	B40 Particles	With Additive (1000 ppm)	Reduction	% Reduction
≥ 4	28,666	6,562	22,104	77%
≥ 6	26,531	3,550	22,981	87%
≥ 14	15,860	801	15,059	95%

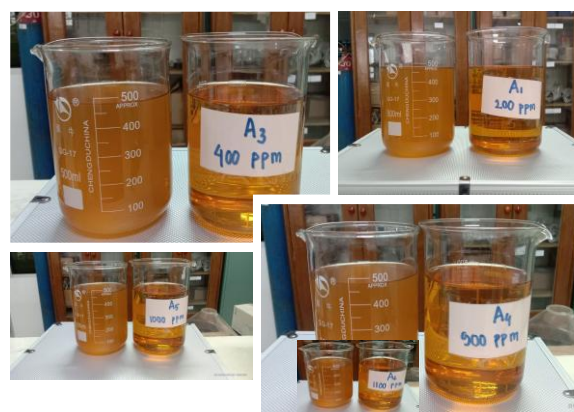


Figure 4. Visualization of the effect of additives on particulates.

In addition to viscosity, the addition of additives also affects the amount of suspended particles in B40 fuel. The formation of these particles can occur during the storage of biofuels in tanks, as a result of interactions between biofuels and fossil fuels. Consequently, B40 fuel, which initially contains approximately 50–60 mg/L of particles, has the potential to cause problems in the fuel system if used without additives, including soot buildup, clogged fuel filters, and injector issues.

At an exposure level of 1000 ppm, the additive demonstrated the capacity to curtail suspended particulate matter in B40 by 90–95% at ambient temperature (Figure 5.A). the effectiveness of the treatment increased to 90–99% when combined with heating to 40°C, even at a low dose of 200 ppm (Figure 5.B). the application of heat has been demonstrated to reduce viscosity, enhance flow properties, and diminish the precipitation of wax and monoglycerides. These findings are consistent with those of Pramudito et al. [25], who demonstrated that temperature, FAME content, monoglycerides, and wax contaminants influence the filtration performance of B30 and B40. However, it is imperative to avoid

excessive heating, as this can accelerate biodiesel oxidation and the formation of gum and deposits. These compounds increase viscosity and reduce fuel quality [27,36,37]. The study results, depicted in Figure 6, show that heating tends to reduce the number of dissolved particles. The number of particles decreased from the starting point (A0) to treatment A1 and then decreased even more in A2. This decrease is thought to be related to changes in the physical properties of the environment due to higher temperatures. These changes include a decrease in viscosity and an increase in particle motion. This increases the frequency of collisions between particles. This makes it easier for the particles to stick together and form bigger clumps. These findings are similar to those of Xiao et al. [38] and Dayarathne et al. [39]. They said that temperature affects how particles clump together, how flocs form, and how things settle. Menkiti et al. [40] also reported that, under certain conditions, an increase in temperature can enhance the removal of dissolved particles through increased aggregation and sedimentation. It is believed that heating helps reduce the number of particles that remain in the dissolved phase.

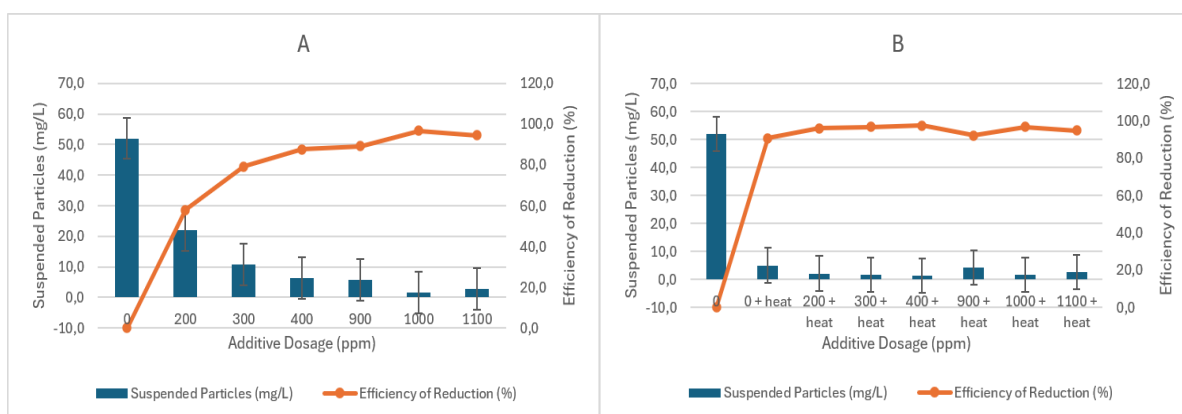


Figure 5. Effect of additives on particulates: (a) without heating and (b) with heating.

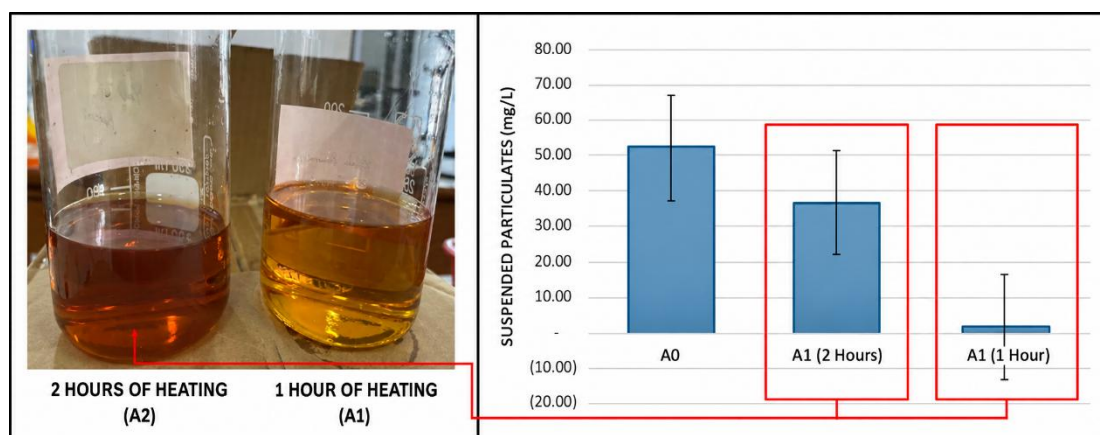


Figure 6. Effect of heating on particulates.

3.3. Effect of Additives on Cetane Number

Ethylhexyl nitrate (2-EHN) is an additive that has been demonstrated to enhance the cetane number, thereby accelerating the formation of primary radicals, reducing ignition delay, and optimizing the combustion performance of diesel and biodiesel fuels. The addition of 2-EHN in the range of 500 to 2,000 ppm has been reported to increase the cetane number (CET/CN). However, the effectiveness of this addition is contingent upon the fuel composition and the engine operating conditions [41–43]. As presented in Table 2, The SHATOX SX-150 instrument revealed alterations in the CN/CET starting from the first day of observation. Notably, doses surpassing 900 ppm resulted in substantial changes in the CET/CN and TFr (temperature freezing) values. The 900-ppm value in this study is a threshold derived from experience and cannot be used as a general standard for all situations. Visual observations revealed a decrease in particulate density in samples to which 200–1100 ppm of 2-EHN was added, consistent with the findings of previous studies examining the effects of 2-EHN on combustion processes and particulate properties [14,44].

The effect of increasing the additive concentration on the fuel's ignition characteristics and low-temperature properties is a subject of interest. The addition of additives has been shown to increase the cetane number, thereby enhancing the fuel's propensity to undergo

spontaneous ignition following injection. This increase is attributable to the activity of the additive's active components, which accelerate the initial oxidation reaction, thereby reducing the ignition delay period. However, the response of the cetane number to additive is influenced by the fuel's inherent characteristics and may exhibit a diminishing response at higher concentrations. This phenomenon aligns with the findings of Gosh [45] and Kuszewski [43], who demonstrated that the efficacy of cetane improvers, notably 2-ethylhexyl nitrate, is substantially influenced by fuel composition and ignition conditions.

Table 2. The effect of additive addition on cetane number and TFr.

Day I			Day II		Day III	
additive dose	CET	TFr	CET	TFr	CET	TFr
0	46.4	-35.3	46.7	-33.3	46.6	-34
200	46.5	-35.2	46.9	-31.5	47	-27.9
300	47	-26.2	47	-25.7	47	-25.2
400	47	-27.6	47	-25.3	49.2	-14.5
900	47	-27.7	48.2	-18.7	49.6	-12.4
1000	47.3	-23.4	48.3	-18.3	49.6	-12.1
1100	48.7	-26.8	48.7	-16.3	49.7	-12.1

Concurrently, the incorporation of additives induces a modification in the TFr value. A decline in the TFr value signifies an enhancement in the fuel's flow properties at

low temperatures. Additives with cold-flow-improving characteristics have been shown to inhibit the growth and agglomeration of paraffin crystals, thereby preventing the formation of waxy structures that can obstruct fuel flow at lower temperatures. These results are consistent with the findings of Gürü et al. [46], who reported that the use of additives can increase the cetane number from 46.22 to 48.24 while lowering the freezing point to approximately 12.4°C, as well as those of Zhao et al. [47], who demonstrated the effectiveness of pour point depressants in lowering the freezing point of diesel fuel.

As demonstrated in Figure 7, the physical appearance of the fuel undergoes changes at varying additive concentration levels. It was observed that both the control sample and the samples to which additives were added exhibited a homogeneous consistency, with no discernible phase separation evident. This finding suggests that the additives mixed effectively with the fuel at the concentrations employed.

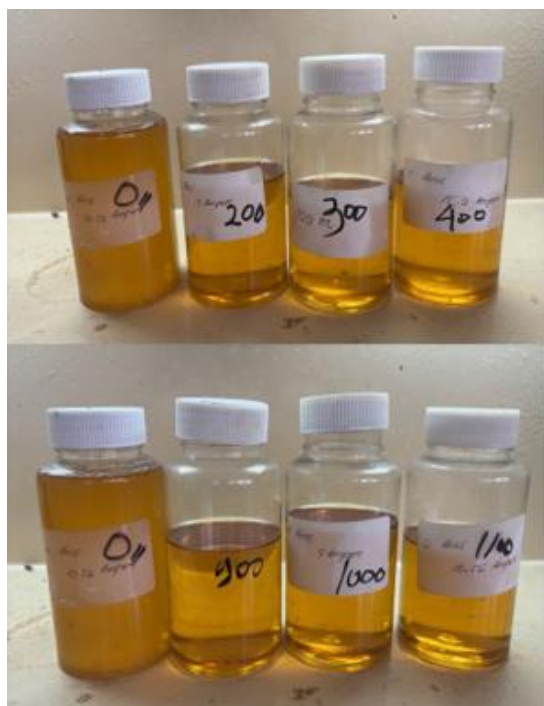


Figure 7. Visualization of fuel samples at various additive concentrations.

3.4. The Effect of Additives on the Efficiency of a Rotary Air Preheater

The incorporation of 2-ethylhexyl nitrate (2-EHN) into the B40 blend has been demonstrated to enhance combustion quality, as indicated by a reduction in the concentration of suspended particles. This decline signifies a reduction in soot formation and solid residues resulting from incomplete combustion, consequently minimising the quantity of particulates conveyed with the exhaust gas to the Rotary Air Preheater. This finding is consistent with Wang et al. [44], who reported that adding 2-EHN at concentrations of 1000–2000 ppm can affect the structure and oxidation characteristics of combustion particulates. The reduced particulate load has the potential to suppress deposit formation and fouling on the elements of the Primary Air Heater (PAH) and Secondary Air Heater (SAH), which can increase thermal resistance and reduce heat transfer efficiency [19,48]. In this study, the most optimal performance was achieved with a dosage of 1000 ppm, as evidenced by a decrease in flue gas temperature at the outlet of the air preheater accompanied by an increase in primary and secondary air temperatures. The findings suggest that the reduction in deposits on the heat transfer surfaces contributes to enhanced heat transfer efficiency in the PAH and SAH. These efficiency improvements across the PAH and SAH are depicted in Figure 8.

3.5. The Effect of Additives Addition on combustion Emissions

Figure 9 demonstrates that an increase in the 2-EHN dose from 0 to 1100 ppm results in a gradual decrease in the concentrations of SO₂, NO_x, and CO, accompanied by a slight increase in the concentration of CO₂. The most significant response was observed in the CO emissions, which decreased from 573.120 mg/Nm³ to 479.133 mg/Nm³, representing a 16.40% reduction. The decline in CO, accompanied by an increase in CO₂ from 9.737% to 9.821%, signifies an enhancement in the carbon oxidation process

and a reduction in incomplete combustion [12,14].

A 5.33% decrease in NO_x emissions was observed, with a reduction from 176.111 mg/Nm^3 to 166.176 mg/Nm^3 . In the range of 0–400 ppm, a decline of approximately 3.30% in NO_x was observed. An increase in dosage from 400 ppm to 900 ppm resulted in a further reduction of 1.76%. However, as the

dosage increased from 900 ppm to 1100 ppm, there was a decrease in NO_x of only approximately 0.34%. this reduction is believed to be related to 2-EHN's ability to shorten the ignition delay, reduce fuel accumulation during the pre-combustion phase, and suppress the intensity of premixed combustion [49].

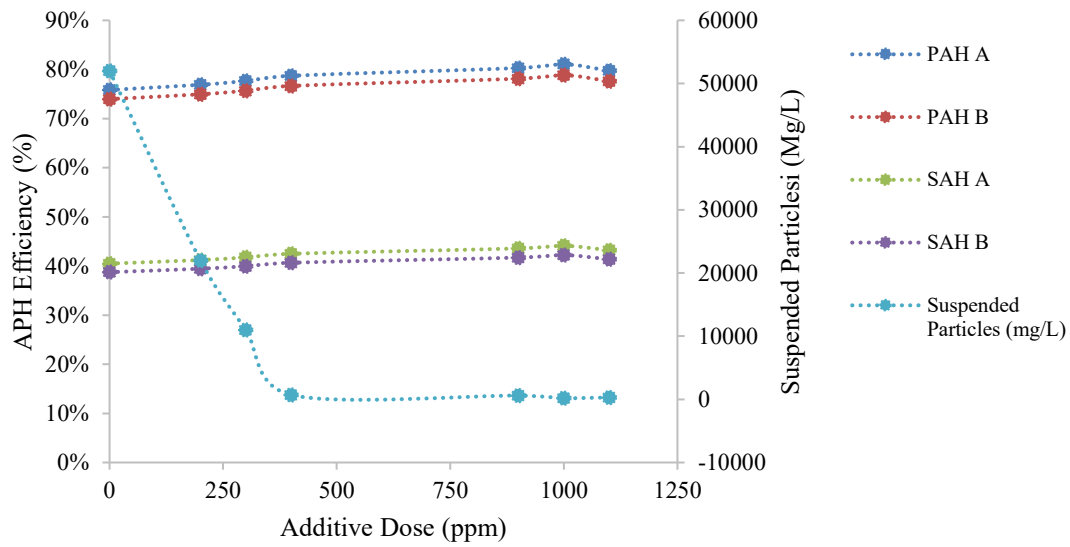


Figure 8. Effect of additives on the efficiency of rotary air preheater.

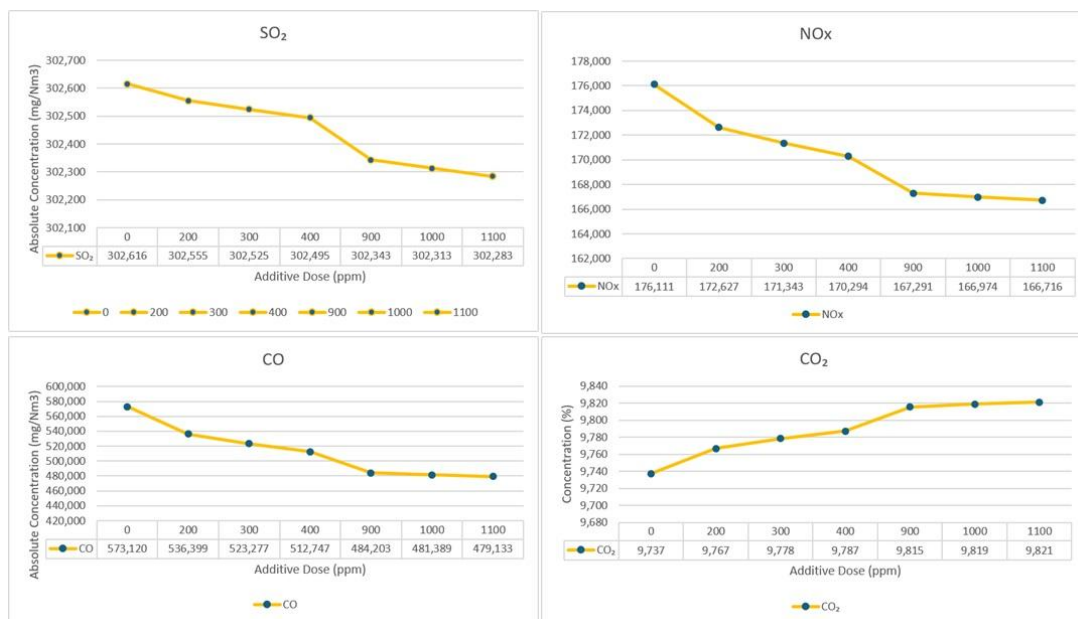


Figure 9. Graph showing the effect of additive addition on combustion emissions.

In contrast, SO₂ levels decreased only from 302.616 mg/Nm³ to 302.283 mg/Nm³ a reduction of about 0.11%. in comparison with the alterations in CO and NO_x, this variation is negligible and can be regarded as relatively stable. The formation of SO₂ is predominantly influenced by the quantity of sulfur present in the fuel. It is evident that 2-EHN functions as a cetane enhancer rather than a desulfurization agent. Consequently, a minor reduction in SO₂ is presumably not a direct chemical consequence of 2-EHN [50]. The emission response exhibited a tendency to stabilise following the administration of a dose 900 ppm; however, the augmentation of the dose to 1100 ppm yielded a modest enhancement. Consequently, the range of 900–1100 ppm can be designated a potential dosage range.

4. CONCLUSION

The findings of the research indicate that the incorporation of a 2-ethylhexyl nitrate (2-EHN)- based additive into B40 fuel typically exerts a favourable influence on fuel characteristics, air preheater performance, and combustion emission, with an optimal concentration of 1000 ppm. The incorporation of 2-EHN did not induce a substantial reduction in viscosity, suggesting that the impact of temperature on viscosity is more substantial than that of additive concentration. At a concentration of 1000 ppm, the suspend particle content exhibited a 96.7% decrease, from 52.0 mg/L to 1.7 mg/L. concurrently, the number of particles sized $\geq 4 \mu\text{m}$, $\geq 6 \mu\text{m}$, and $\geq 14 \mu\text{m}$ decreased by 77%, 87%, and 95%, respectively. The addition of 2-EHN to the B40 blend was found to have a favourable impact on the ignition quality of the fuel. However, the efficacy of this addition was not consistent, and the optimal dosage for fuel characteristics was not identified. With regard to the performance of the air preheater, a concentration of 1000 ppm was found to yield the highest efficiency levels, with 81.08% for PAH A, 78.84% for PAH B, 44.12% for SAH A, and 42.23% for SAH B, in comparison to 75.84%, 73.98%, 40.49%,

and 38.75%, respectively. Increasing the concentration to 1100 ppm led to a decrease in the efficiency of all PAHs and SAHs, indicating an effective concentration limit for enhancing heat transfer. With regard to emissions, the utilisation of additives resulted in a 16.40% reduction in CO emissions and a 5.33% reduction in NO_x emissions. Conversely, SO₂ emissions exhibited a marginal decrease of approximately 0.11%, as its formation is more influenced by the sulphur content in the fuel. Concurrently, the rise in CO₂ from 9.737% to 9.821%, concomitant with the decline in CO, signifies a tendency towards more complete carbon combustion. Consequently, a concentration of 1000 ppm was identified as the concentration that provided the optimal technical performance under the conditions of this study, particularly in reducing particulate matter and enhancing the efficiency of the air preheater. However, the use of concentrations above 1000 ppm requires further investigation because it does not always improve performance and has the potential to affect compositional stability as well as the formation of heavy compounds in the fuel.

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AUTHOR CONTRIBUTIONS

R.S.A.: Writing – original draft, investigation, data curation, formal analysis, visualization, methodology. **W.W.:** Writing – review & editing, supervision, methodology, conceptualization. **A.Y.W.:** Writing – review & editing, supervision, validation, Conceptualization.

CONFLICTS OF INTEREST

The authors declare no competing financial interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the authors used generative AI technologies, including SciSpace and ChatGPT, to support the research and manuscript preparation process. SciSpace was used to assist in preparing the literature review, mapping research themes, identifying potential research gaps, and facilitating the understanding of scientific articles through AI-assisted summaries and question-based text analysis. ChatGPT was used to assist in identifying relevant literature indexed in Scopus, explaining complex concepts, summarizing lengthy texts, and providing suggestions to support the research process. All AI-generated outputs were critically evaluated and verified by the authors, who remain fully responsible for the accuracy, interpretation, and final content of the manuscript.

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