

Research Paper

Effect of Moisture Content on Boiling Point Characteristics and Bubble Formation in DOT 4 and 5.1 Brake Fluid

Setya Wijayanta✉, Dzaki Putra Prakosa

Automotive Engineering Technology, Polytechnic of Road Transportation Safety, Tegal 52143, Indonesia

✉ setya_w@pktj.ac.id

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Abstract

The performance of hydraulic braking systems is strongly influenced by the condition of brake fluid, particularly boiling point and tendency to form vapor bubbles that may lead to vapor lock. Glycol-based brake fluid, such as DOT 4 and 5.1, is hygroscopic in nature, causing moisture content to increase during service life. Therefore, this study aimed to examine the effect of moisture percentage on boiling point and bubble formation characteristics of DOT 4 and 5.1 brake fluid. An experimental method was applied by adding distilled water to brake fluid at varying concentrations of 0%, 1%, 2%, 3%, and 4%, followed by gradual heating. Boiling point was recorded using a temperature sensor connected to a data logger, while bubble formation was visually observed during heating process using a high-speed camera with a frame rate of 240 fps. The recorded images during the analysis were subsequently examined using ImageJ processing software. The results showed that increasing moisture content led to a significant reduction in boiling point for both types of brake fluid. At identical temperature levels, fluids with higher moisture content indicated a larger bubble volume formation. These results indicated that moisture content played a critical role in degrading the thermal performance of brake fluid and increased the risk of vapor lock in automotive braking systems.

Keywords: Brake fluid; Moisture content; Boiling point; Vapor lock

1. Introduction

Traffic accidents related to motor vehicles, particularly buses and trucks that are caused by braking system failures, are frequently reported by various media outlets and often associated with high fatality rates as well as severe consequences [1], [2]. The recurrence of these incidents shows that the reliability of braking systems is a critical factor in road safety for heavy-duty vehicles operating under high load conditions and extended travel distances [3]. In Indonesia, accident investigation reports issued by National Transportation Safety Committee (Komite Nasional Keselamatan Transportasi, KNKT) indicate that problems related to braking systems remain a dominant contributing factor to traffic accidents [4].

A primary factor contributing to the degradation of braking system performance is the condition of brake fluid, serving as hydraulic medium that transmits pressure from brake pedal to braking mechanisms at the wheels [5]. A deterioration in brake fluid quality can prevent hydraulic system from operating effectively and significantly increase the risk of braking failure [6]. Moreover, issues frequently encountered in hydraulic braking systems include the increase in moisture content in brake fluid and the reduction of fluid volume in the system [7]. A higher moisture level in brake fluid leads to a lower boiling point, increasing the probability of fluid boiling when braking system operates at elevated temperatures [8], [9].

Brake system failures associated with brake fluid conditions are not limited to Indonesia and



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have been reported in many other countries. Several studies indicate that braking failures are frequently related to excessive heat generation in brake components, insufficient brake fluid volume, and the presence of trapped air or vapor in hydraulic lines [10]. These conditions disrupt the transmission of hydraulic pressure and may lead to sudden and severe loss of braking capability [11].

Glycol-based brake fluid is inherently hygroscopic, signifying the ability to absorb moisture from the surrounding environment during service life [12]. An increase in moisture content directly contributes to a reduction in boiling point of brake fluid [13]. Previous studies showed that even a relatively small amount of absorbed water caused a significant decrease in boiling point, enabling brake fluid more susceptible to boiling under conditions of repeated or prolonged braking [8]. This reduction in boiling point increases the possibility of vapor formation in braking system, often referred to as entrapped air, which can interfere with effective hydraulic pressure transmission [14].

The formation of vapor in brake fluid is frequently called vapor lock and recognized as the primary cause of hydraulic braking system failure [15]. Vapor lock typically occurs under severe operating conditions, such as long-distance driving or continuous braking on downhill roads [16]. Under these conditions, heat generated by friction and high pressure in brake components is transferred to brake fluid. In addition, brake fluid contaminated with moisture reaches boiling point more rapidly and produces compressible vapor bubbles, which impede hydraulic pressure transmission and can eventually lead to an unexpected reduction or complete loss of braking performance [17], [18].

Several previous studies had investigated the effect of moisture content on boiling point of brake fluid, particularly for DOT 3, and consistently reported an inverse relationship between moisture content and boiling point [9]. However, analyses that specifically examine the influence of moisture content on vapor bubble formation characteristics in DOT 4 and 5.1 brake fluid remain limited. The characteristics of bubble formation, such as bubble fraction at various temperature levels, represent critical parameters for understanding the early-stage mechanism of

vapor lock. Currently, limited studies have quantitatively analyzed the effect of moisture content on bubble fraction formation during heating process of DOT 4 and 5.1 brake fluid.

An analytical method that can be applied to investigate bubble formation characteristics is image processing, which enables visual and quantitative measurement of bubble-related parameters [19]. This method has been used by several studies to evaluate bubble diameter, distribution, and fraction in liquid fluids with good accuracy [14]. However, the application to assess the effect of moisture content on bubble fraction formation in brake fluid, particularly DOT 4 and 5.1 types, has scarcely been reported in the literature.

Based on the description above, a visible study gap exists concerning the influence of moisture content on vapor bubble formation characteristics in brake fluid. This study focuses on evaluating the effect of moisture percentage on boiling point behavior and vapor bubble formation characteristics as early indicators of vapor lock occurrence in DOT 4 and 5.1 brake fluid. The results are expected to contribute to a deeper understanding of the early mechanisms of hydraulic braking system failure and to provide a scientific basis for improving the safety as well as reliability of automotive braking systems.

2. Methods

This study was designed to investigate the influence of moisture content on boiling point degradation and vapor bubble formation characteristics in DOT 4 and 5.1 brake fluid under controlled laboratory conditions. An experimental laboratory testing method was adopted, allowing direct control of variables and enabling quantitative observation of both thermal as well as visual changes in the fluid during heating process. Experimental methods were widely applied in studies on brake fluid characteristics because the strategies provided a clear cause-and-effect relationship between moisture content, boiling point, and vapor bubble formation [9], [13], [20]. Unlike the studies of Hunter *et al.* [23], Kao *et al.* [24], and Wijayanta *et al.* [9], which focused mainly on boiling-point degradation in moisture-contaminated DOT 3 brake fluid, the present study investigates both DOT 4 and DOT 5.1 brake fluids and incorporates quantitative bubble-

formation analysis using high-speed video recording and ImageJ-based image processing. This methodological advancement allows simultaneous evaluation of thermal degradation and vapor-bubble growth behavior, providing new experimental evidence regarding the early-stage vapor-lock mechanism in modern glycol-based brake fluids. DOT 4 and 5.1 brake fluid used in this study was new and unused to ensure that the initial condition of the samples was dry as well as free from prior moisture contamination. DOT 4 and 5.1 fluid used were a commercially available NuChem DOT 4 and Brembo DOT 5.1 brake fluid, respectively. According to manufacturer specifications, DOT 4 fluid had a minimum dry and wet boiling point of 230 °C and a minimum wet boiling point of 155 °C, respectively. Meanwhile, DOT 5.1 fluid has a corresponding minimum boiling point of 260 °C and 180 °C. These specifications were used as reference values for comparison with the experimental measurements (Table 1).

Moisture content in brake fluid was varied at 0%, 1%, 2%, 3%, and 4% by volume, based on ranges reported in previous studies on DOT 3 brake fluid that were shown to significantly reduce boiling point and increase the risk of vapor lock [9]. Moisture contamination levels were prepared using a volumetric mixing method. Fresh and previously unopened DOT 4 and 5.1 brake fluid was applied as reference samples. During the process, distilled water was added using a calibrated syringe to obtain nominal moisture contents of 1%, 2%, 3%, and 4% by volume. Concerning each 200 mL brake fluid sample, the corresponding volume of distilled water was added and mixed using a magnetic stirrer for 15 min to ensure homogeneous distribution in the fluid. The reference sample without additional water was designated as the nominally dry condition. Additionally, distilled water was used as the mixing medium to

eliminate the influence of dissolved substances on the thermophysical properties of the fluid. The use of magnetic stirring was intended to minimize concentration gradients and improve mixture homogeneity before testing.

All samples were prepared immediately before heating experiments to reduce additional moisture absorption from ambient air. Brake fluid samples were additionally evaluated using a commercial brake fluid tester after the mixing process to verify the consistency of the prepared contamination levels. The tester was applied as a supplementary assessment tool to confirm the relative increase in moisture contamination among the prepared samples. The results showed a progressive increase in moisture indication corresponding to the nominal moisture contents introduced into brake fluid. Therefore, the volumetric preparation method combined with magnetic stirring and brake fluid tester evaluation was considered sufficient to establish controlled contamination levels for comparative laboratory testing.

Each brake fluid sample was gradually heated using an electric heater pending the boiling conditions were reached. During heating process, the fluid temperature was continuously monitored using a digital thermometer equipped with a thermocouple sensor. The temperature sensor had a measurement resolution of 0.1 °C and a tolerance of ± 0.5 °C, as specified by the manufacturer, allowing the measurement uncertainty to be visibly identified and reported [21]. Boiling point was defined as the temperature at which continuous vapor generation occupied more than 50% of the observation area for a minimum duration of 10s without interruption. This criterion was established to provide a quantitative and repeatable threshold for boiling point determination and to minimize observer-dependent interpretation. Boiling event was simultaneously verified using temperature

Table 1. Manufacturer specifications of brake fluid

Parameter	DOT 4	DOT 5.1
Commercial product	NuChem DOT 4	Brembo DOT 5.1
Brake fluid type	Glycol-based	Glycol-based
Dry boiling point specification of the manufacturer	≥ 230 °C	≥ 260 °C
Wet boiling point specification of the manufacturer	≥ 155 °C	≥ 180 °C
FMVSS No. 116 minimum dry boiling point requirement	≥ 230 °C	≥ 260 °C
FMVSS No. 116 minimum wet boiling point requirement	≥ 155 °C	≥ 180 °C

stabilization behavior recorded by the thermocouple data logger, consistent with the criteria used in previous thermal characteristic studies on DOT 3 brake fluid [9]. Each boiling point measurement was repeated three times ($n = 3$) under identical laboratory conditions to evaluate experimental repeatability and reduce the influence of random measurement errors. The reported boiling point values represented the mean of the three measurements, while standard deviations were calculated to assess measurement variability and experimental consistency.

Bubble formation characteristics during fluid heating were observed and recorded using a high-speed video camera operating at a frame rate of 240 frames per second (fps). The recorded video data were subsequently converted into digital images and analyzed using image processing methods to obtain quantitative parameters related to bubble formation characteristics and bubble fraction. The method was selected because it provided objective, measurable, and reproducible results and has been widely applied in the analysis of two-phase flow phenomena in liquid fluids [22]. A schematic representation of the experimental setup and the general data acquisition process was shown in Figure 1.

The recorded video data were initially extracted into individual image frames corresponding to bubble development at selected temperature levels. These images were then analyzed using ImageJ software to quantify bubble formation in the observation region. Before measurement, all images were calibrated using a reference scale to convert pixel dimensions into physical units (mm^2). A consistent region of interest (ROI) was selected for all samples to ensure uniform observation conditions. The calibrated images were subsequently converted to grayscale and segmented using a fixed threshold value to distinguish vapor bubbles from the background.

After segmentation, several bubbles appeared as hollow objects due to lighting variations and thresholding effects. In these cases, the brush tool was applied simply to fill internal holes in the detected bubble boundaries without modifying the external contours, diameter, or projected area of bubbles. The brush tool was used to fill internal voids without modifying external bubble boundaries. However, a specific degree of

operator-dependent uncertainty existed and was considered a limitation of the present analysis. Future studies might use fully automated image-segmentation methods or inter-operator validation procedures to further reduce potential subjectivity in bubble area measurements. This procedure did not alter the actual bubble size and ensured that each bubble was recognized as a complete object during quantitative analysis. Identical calibration parameters, ROI dimensions, threshold settings, and measurement procedures were applied to all images that were analyzed to maintain consistency as well as minimize operator-dependent variability.

The segmented images were processed using the built-in measurement functions of ImageJ to determine the total bubble cross-sectional area and bubble fraction in the observation field. Bubble area measurements were obtained from representative image frames selected for each temperature and moisture content condition. A single calibrated frame was analyzed for each condition since the objective of the image-processing procedure was to quantify the instantaneous bubble formation characteristics observed during each heating experiment. Therefore, the reported bubble area values represented direct measurements rather than averaged values from repeated image analyses. Bubble area results were interpreted as comparative indicators of bubble formation under the investigated conditions rather than statistically validated population estimates.

The uncertainty associated with boiling point measurements primarily originated from thermocouple accuracy, measurement resolution,

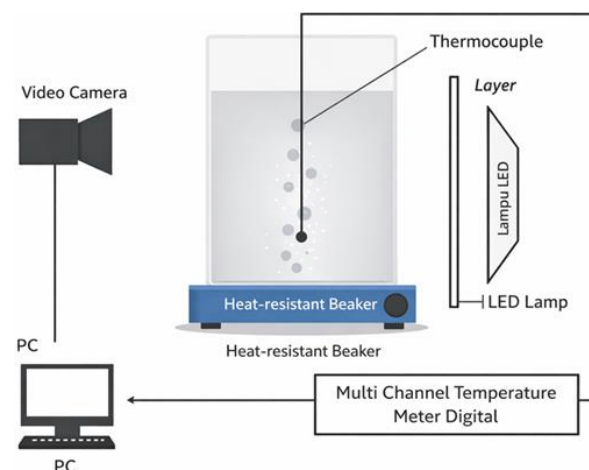


Figure 1. Schematic diagram of the experimental setup

and experimental repeatability. The thermocouple used in this study had a manufacturer-specified accuracy of ± 0.5 °C and a resolution of 0.1 °C. Boiling point measurements were repeated three times ($n = 3$) for each moisture content condition to improve reliability, and the reported values represented the mean $\pm$ standard deviation of the repeated measurements. Concerning image-based bubble area measurements, uncertainty originated from image calibration, pixel-to-length conversion, threshold segmentation, lighting conditions, and frame-selection procedures. Identical calibration parameters, region-of-interest dimensions, threshold values, and measurement settings were applied to all images to minimize variability. Since bubble area measurements were obtained from representative image frames extracted from a single heating experiment for each condition, statistical parameters such as standard deviation and confidence intervals could not be determined. Therefore, area results were interpreted as comparative quantitative indicators of bubble formation under the investigated laboratory conditions rather than statistically validated population estimates.

3. Results and Discussion

3.1. Boiling Point Characteristics of DOT 4 Brake Fluid

The experimental results for DOT 4 brake fluid indicated a pronounced decline in boiling point with increasing levels of water contamination. This behavior reflected a systematic reduction in boiling temperature corresponding to incremental additions of moisture. Table 2 showed the mean boiling point values obtained from three experimental repetitions ($n = 3$) for each moisture content condition. The relatively small standard deviations indicated good repeatability of the measurements.

The measured dry boiling point of the uncontaminated DOT 4 brake fluid (255.3 °C) exceeded the minimum manufacturer specification of 230 °C, indicating that brake fluid was initially in good condition before moisture contamination. Furthermore, the measured dry boiling point of DOT 4 brake fluid (255.3 °C) surpassed the minimum requirement specified in FMVSS No. 116 for DOT 4 brake fluid (230 °C). This result confirmed that the tested brake fluid

satisfied the internationally recognized performance standard before moisture contamination. As moisture content increased, boiling point progressively approached and eventually fell below the minimum wet boiling point requirement of 155 °C. This indicated a substantial degradation of thermal performance due to water absorption. A similar tendency had been widely reported in earlier investigations on DOT 3 brake fluid, including studies conducted by Hunter *et al.* [23], Kao *et al.* [24], and Wijayanta *et al.* [9]. These studies consistently showed that the presence of absorbed water led to a gradual degradation of boiling point due to the hygroscopic nature of glycol-based brake fluid [9], [23], [24]. This study focused on DOT 4 brake fluid, and the observed thermal response indicated a physical mechanism comparable to that previously reported for DOT 3 fluids. The similarity recommended that water-induced boiling point suppression remained a dominant phenomenon across different glycol-based brake fluid classifications, despite variations in additive composition and performance specifications. The comparative trend between DOT 3 and 4 boiling temperatures under varying moisture contents was shown in Figure 2.

Following the visualization of boiling point variation as a function of moisture content, the next step included developing a mathematical model to quantitatively represent this relationship. Linear regression analysis was selected as the modeling method because the experimental data showed a nearly linear downward trend with increasing water percentage. This method enabled the determination of a best-fit line that characterized the rate of boiling point reduction per unit increase in moisture content.

Based on regression analysis of the experimental data for DOT 4 brake fluid, the resulting regression line showed a negative slope,

Table 2. Repeatability of boiling point measurements for DOT 4 brake fluid

Moisture Content (%)	Boiling Point (°C) Mean $\pm$ SD
0	255.3 $\pm$ 3.1
1	235.0 $\pm$ 1.7
2	214.0 $\pm$ 1.5
3	188.0 $\pm$ 1.3
4	169.0 $\pm$ 1.2

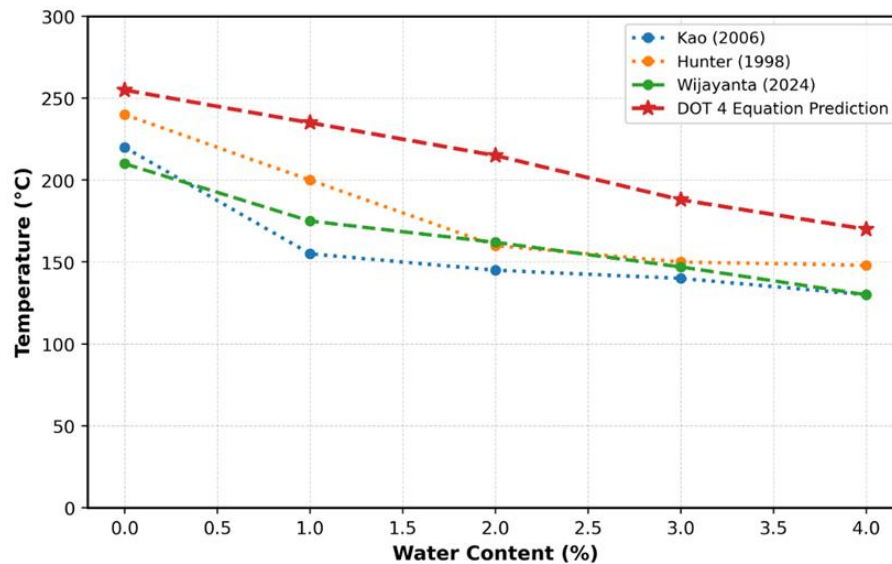


Figure 2. Comparison of boiling point temperature trends between DOT 3 and DOT 4 brake fluid

confirming that even a small increase in moisture content directly contributed to a measurable decrease in boiling temperature. The consistency between the observed data points and the fitted regression model indicated that the linear approximation was adequate for describing boiling point behavior in the tested water concentration range. The empirical relationship derived from the regression analysis for DOT 4 brake fluid was expressed as follows:

$$T = 256 - 21.9X \quad (1)$$

where, T is Boiling point of brake fluid (°C), and X is the moisture content in brake fluid (%)

Several goodness-of-fit indicators were analyzed to evaluate the reliability of the proposed regression model (Table 3). The relapse analysis produced a coefficient of determination (R^2) of 0.998 and an adjusted R^2 of 0.997, indicating that approximately 99.8% of the variation in boiling point temperature was explained by moisture content in brake fluid. This exceptionally high R^2 value showed an excellent agreement between the experimental measurements and the proposed linear regression equation. Analysis of variance (ANOVA) produced F-statistic of 1344.701 with a significance level of $p < 0.001$, confirming that the regression model was statistically significant. Furthermore, root mean square error (RMSE) was 1.32 °C, and the standard error of the estimate was 1.889 °C, indicating a relatively low prediction and fitting error in the investigated experimental dataset. The regression coefficients were also found to be

highly significant during the process. The intercept coefficient was 256.000 ± 1.463 , while the slope coefficient was -21.900 ± 0.597 ($p < 0.001$). The negative slope confirmed that increasing moisture content caused a substantial reduction in boiling point of DOT 4 brake fluid.

Residual inspection showed no apparent systematic trend, signifying that the linear model adequately represented the experimental data in the tested moisture content range. Therefore, the proposed empirical equation was considered a preliminary empirical model for estimating boiling point degradation in DOT 4 brake fluid due to moisture contamination.

3.2. Bubble Formation in DOT 4 Brake Fluid

Visualization of bubble formation in DOT 4 brake fluid under controlled heating conditions was shown in Table 1. The observations were conducted for brake fluid samples with moisture contents of 0%, 1%, 2%, 3%, and 4% across several

Table 3. Statistical validation of DOT 4 boiling point regression model

Parameter	Value
Regression Equation	$T = 256 - 21.9X$
R	0.999
R^2	0.998
Adjusted R^2	0.997
RMSE	1.32 °C
Standard Error of Estimate	1.889 °C
F-statistic	1344.701
Significance (p-value)	< 0.001
Intercept Coefficient	256.000 ± 1.463
Slope Coefficient	-21.900 ± 0.597

test temperatures. Each combination of temperature and water percentage showed distinct bubble characteristics, particularly in the projected bubble cross-sectional area generated during heating process. These variations allowed an obvious interpretation of fluid behavior as thermal energy increased. The visual patterns showed that brake fluid with lower or zero moisture content tended to remain relatively stable at lower temperatures, with minimal or no visible bubble formation. Consequently, samples containing higher moisture levels indicated earlier bubble nucleation and a more pronounced growth of bubble area at the same temperature conditions. The phenomenon showed that the presence of water significantly accelerated vapor generation in brake fluid matrix, leading to more extensive bubble development as heating progressed.

An increase in moisture content consistently led to a larger bubble cross-sectional area at identical temperature levels. This trend indicated that absorbed moisture reduced the effective boiling threshold of the fluid, promoting phase change from liquid to vapor at lower thermal inputs. As the temperature continued to rise, the expansion and coalescence of bubbles became more dominant, particularly in samples with 3% and 4% moisture content, which showed the most extensive bubble formation among all tested conditions.

Table 4 showed that brake fluid samples with 0% moisture content did not indicate any visible bubble formation at the initial test temperatures. Bubbles only started to appear when the temperature reached higher levels, implying that dry brake fluid was capable of maintaining adequate thermal stability during early heating stages.

Samples containing 1% to 4% water showed a significantly higher sensitivity to temperature increase. At identical temperature levels, particularly in the lower temperature range of the test, bubble formation had already occurred in samples with water contamination. This behavior indicated that the presence of water accelerated the onset of vapor formation in brake fluid.

Increasing moisture content led to a clearer tendency toward a higher number of bubbles and larger bubble sizes at each temperature level. As moisture concentration increased, brake fluid

quickly reached thermally unstable conditions, leading to a greater bubble cross-sectional area. These visual observations provided an initial qualitative understanding of how water contamination influenced the thermal behavior of brake fluid.

The visual information was further processed using image processing methods with ImageJ software to obtain quantitative data. This process converted the visual bubble formations into numerical values representing bubble cross-sectional area.

Based on ImageJ image-processing results, the visualization data were successfully transformed into quantitative measurements of bubble cross-sectional area. This method enabled a more objective evaluation of each combination of moisture content and temperature through direct area measurement. The obtained values were subsequently regrouped according to moisture content percentage, allowing clearer observation of trends in bubble area variation. A review of the processed image analysis results was shown in **Table 5**, serving as the basis for assessing the effect of increasing moisture content on bubble cross-sectional area during heating process. At each moisture content level, an increase in heating temperature showed a similar trend, namely the formation of progressively larger bubbles. This pattern was consistently observed across all moisture variations, where samples with higher moisture content responded more rapidly to temperature elevation. The combined effect of temperature variation and moisture content on the total bubble cross-sectional area was subsequently visualized in the graph shown in **Figure 3**, allowing the overall trend of bubble growth behavior to be visibly observed. The graph showed the relationship between temperature and bubble cross-sectional area for brake fluid with different moisture contents (0%, 1%, 2%, 3%, and 4%). Concerning all temperature levels, an increase in moisture content led to a larger bubble area. Brake fluid without moisture (0%) indicated negligible bubble formation even at higher temperatures, signifying stable thermal behavior. Consequently, brake fluid containing 3% and 4% moisture showed a substantial increase in bubble area as temperature increased, particularly above 220 °C. This trend confirmed that higher moisture content significantly accelerated vapor bubble

formation when brake fluid was subjected to elevated thermal conditions.

At the same temperature, brake fluid with higher moisture levels consistently produced a larger bubble cross-sectional area, indicating a

greater volume of vapor generation. This behavior showed that moisture content played a dominant role in reducing thermal stability and promoting vapor bubble formation during heating, indicating a greater tendency for vapor generation

Table 4. Visualization results of bubble formation during heating of DOT 4 brake fluid at various moisture contents

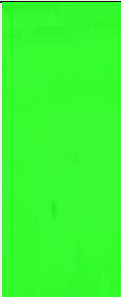
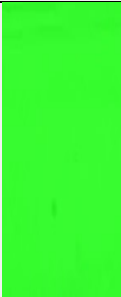
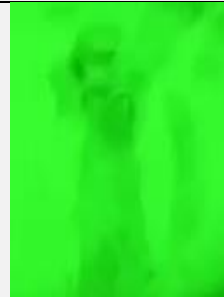
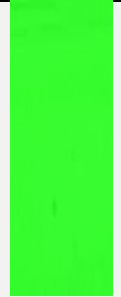
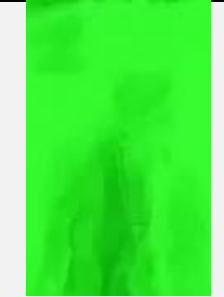
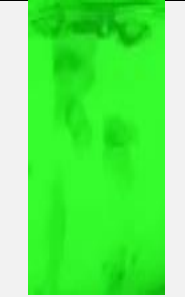
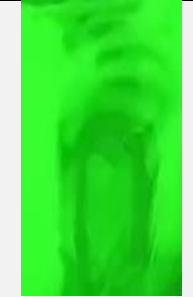
Temperature	Moisture Content in Brake Fluid				
	0%	1%	2%	3%	4%
210 °C					
220 °C					
230 °C					
240 °C					

Table 5. Results of bubble cross-sectional area measurement using ImageJ for DOT 4 brake fluid

Moisture content (%)	Bubble Cross-Sectional Area (mm ²)			
	210 (°C)	220 (°C)	230 (°C)	240 (°C)
0	0.00	0.00	0.00	12.31
1	12.38	27.45	109.50	168.00
2	63.25	95.85	199.85	214.44
3	79.97	185.01	220.01	240.00
4	150.00	220.25	250.22	300.00

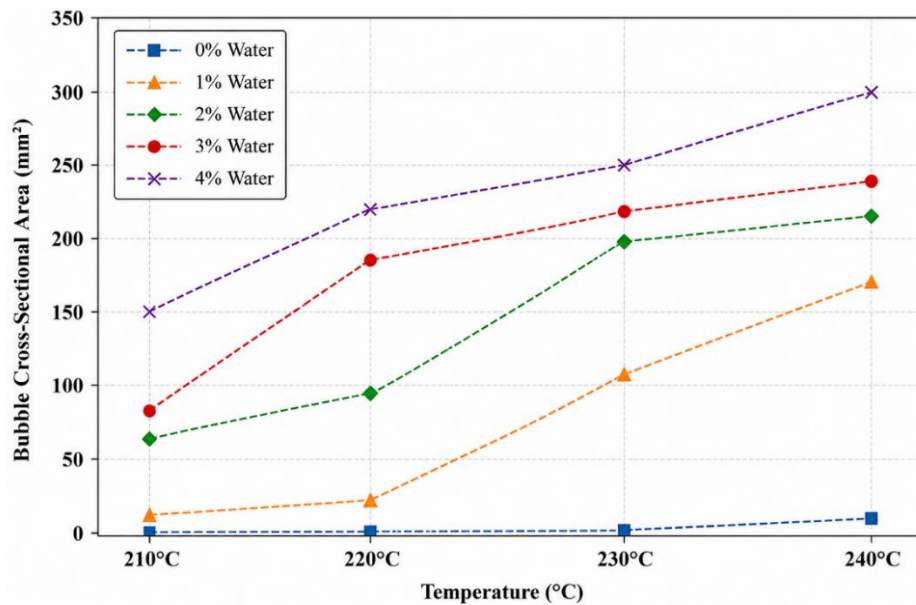


Figure 3. Comparison of bubble cross-sectional area of DOT 4 brake fluid under different moisture content variations

in moisture-contaminated brake fluid. Based on the observed relationship between temperature, moisture content, and bubble formation characteristics, an empirical model was developed to quantitatively described bubble fraction behavior. Nonlinear regression analysis was applied using moisture content and temperature as independent variables, while bubble fraction was treated as the dependent variable. The resulting empirical relationship during the process was expressed as follows:

$$F = 2.3 \times 10^{-14} \cdot X^{0.781} \cdot T^{6.145} \quad (2)$$

where, F is bubble fraction (%); X is moisture content in brake fluid (%); T is Temperature (°C).

The contribution of this study was observed in providing experimentally derived datasets connecting moisture contamination, boiling point degradation, and bubble formation characteristics in DOT 4 and 5.1 brake fluid under controlled laboratory conditions. Empirical relationships were developed to review the observed trends in the investigated moisture content range. These models were interpreted as preliminary predictive tools applicable only to the experimental conditions considered in the analysis. This model was developed using regression analysis combined with logarithmic transformation, allowing the relationship between bubble fraction, moisture content in brake fluid, and temperature variation to be described in a quantitative as well as systematic style.

The modeling results showed that temperature exerted the most significant influence on the increase in bubble fraction. This effect was reflected by the exponent of the temperature variable (T), which reached a value of 6.145, signifying that even a relatively small temperature rise activated a substantial growth in bubble formation. Moisture content also contributed to vapor generation, but the influence was comparatively lower, as indicated by the exponent of 0.781 for variable X. The observed tendency of bubble formation under the investigated laboratory conditions was approximated using the developed empirical relationship.

3.3. Boiling Point Characteristics of DOT 5.1 Brake Fluid

Boiling point measurements obtained in this study showed a visible decreasing trend as moisture content in DOT 5.1 brake fluid increased. This behavior indicated a systematic reduction in boiling temperature associated with incremental moisture absorption. Table 6 showed boiling point measurements obtained from three experimental repetitions ($n = 3$) under each moisture content condition. The relatively low standard deviation values indicated good measurement consistency and experimental repeatability.

The measured dry boiling point of the uncontaminated DOT 5.1 brake fluid (270.3 °C) exceeded the minimum manufacturer specification of 260 °C, confirming that the fluid

Table 6. Repeatability of boiling point measurements for DOT 5.1 brake fluid

Moisture Content (%)	Boiling Point (°C) Mean $\pm$ SD
0	270.3 $\pm$ 1.5
1	234.3 $\pm$ 2.1
2	210.0 $\pm$ 1.8
3	193.7 $\pm$ 1.5
4	182.3 $\pm$ 2.5

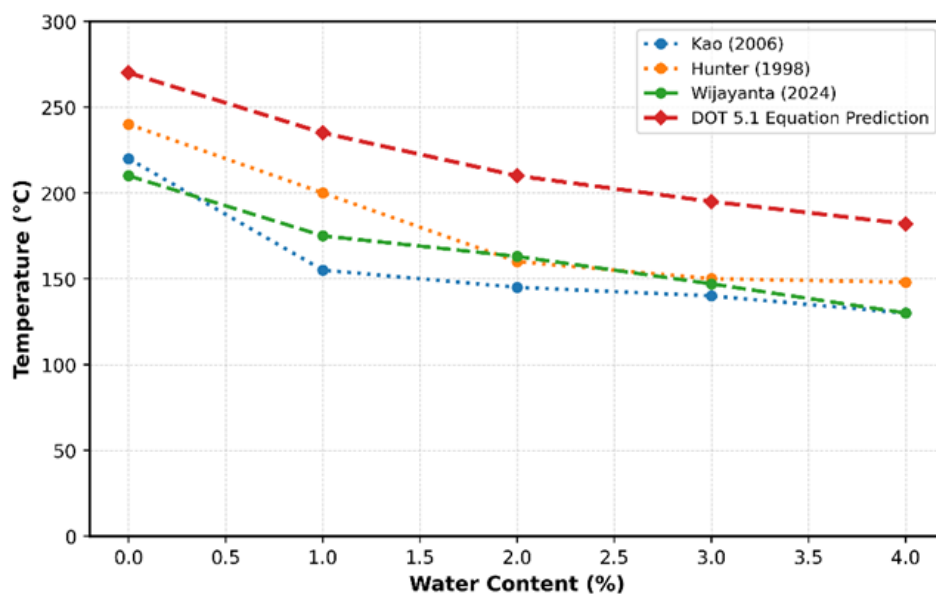
complied with the expected performance requirements before water was intentionally introduced. Similarly, the measured dry boiling point of DOT 5.1 brake fluid (270.3 °C) exceeded the minimum FMVSS No. 116 requirement for DOT 5.1 brake fluid (260 °C). The process confirmed compliance with the international standard under dry conditions. However, progressive moisture contamination caused a substantial reduction in boiling point, showing the sensitivity of glycol-based brake fluid to water absorption and signifying the importance of periodic brake fluid maintenance. The results showed that boiling point measurements were highly reproducible across repeated tests. The standard deviation values ranged from 1.5 °C to 2.5 °C, indicating relatively low experimental variability. Therefore, the observed reduction in boiling point with increasing moisture content was considered a consistent and repeatable phenomenon. A similar tendency had been extensively reported in previous studies on DOT 3 brake fluid, including investigations by Hunter

et al. [23], Kao *et al.* [24], and Wijayanta *et al.* [9]. The outcome consistently showed that absorbed water significantly lowered boiling point due to hygroscopic nature of glycol-based brake fluid.

This study specifically examined DOT 5.1 brake fluid, and the observed thermal response followed the same fundamental physical mechanism reported for DOT 3 fluid. The presence of water promoted earlier vapor formation, reducing thermal stability under elevated temperatures. However, DOT 5.1 showed a relatively higher boiling point across all moisture content levels, reflecting the improved formulation and higher performance specification compared to DOT 3.

The comparison between boiling point trends reported in previous DOT 3 studies and the predicted boiling behavior of DOT 5.1 based on the empirical model developed in this study was shown in Figure 4. The results confirmed that water-induced boiling point suppression remained a dominant phenomenon across glycol-based brake fluid classifications, including DOT 5.1, despite differences in additive composition and baseline performance.

Figure 4 showed the comparative trends of boiling point reduction in DOT 3 and 5.1 brake fluid as a function of moisture content. The experimental data indicated that increasing water fraction in brake fluid consistently lowered boiling point, reflecting the progressive loss of thermal stability with moisture contamination.

**Figure 4.** Comparison of boiling point temperature trends between DOT 3 and 5.1 brake fluid

Among the fluids analyzed, DOT 5.1 showed higher initial boiling temperatures compared to DOT 3, and it remained highly sensitive to even minor moisture content. DOT 5.1 derived from this study provided a visible quantitative representation of this effect, indicating the linear relationship between moisture content and boiling point reduction. The empirical relationship provided a preliminary estimation of boiling point behavior in the investigated moisture content range. Based on the regression analysis of the measured data, the empirical equation describing boiling point behavior of DOT 5.1 brake fluid was expressed as follows:

$$T = -21.6X + 261.2 \quad (3)$$

where, T is boiling point of brake fluid (°C); X is moisture content in brake fluid (%)

A goodness-of-fit analysis was performed using the experimental boiling point data to assess the validity and predictive capability of the proposed regression model (Table 7). During the process, the regression analysis produced R^2 of 0.953 and adjusted R^2 of 0.937, indicating that approximately 95.3% of the variation in boiling point temperature was explained by moisture content of brake fluid. The result showed a strong correlation between water contamination and boiling point degradation in DOT 5.1 brake fluid. RMSE value was 7.59 °C, while the standard error of the estimate was 8.764 °C, signifying an acceptable prediction accuracy for the investigated moisture content range. ANOVA produced F-statistic of 60.750 with a significance level of $p = 0.004$. The result confirmed that the regression relationship was statistically significant at the 95% confidence level. The standard error of the estimate was 8.764 °C, indicating an acceptable prediction error for the investigated moisture content range.

Based on the description above, the regression coefficients were statistically significant. The intercept coefficient was 261.200 ± 6.788 , and the slope coefficient was -21.600 ± 2.771 ($p = 0.004$). The negative slope confirmed that increasing moisture content caused a substantial reduction in boiling point of DOT 5.1 brake fluid. The high coefficient of determination, combined with the statistically significant regression coefficients, indicated that the proposed empirical equation provided a preliminary empirical representation

due to moisture absorption. A slightly higher prediction error was observed compared with DOT 4 model, and the developed regression equation remained suitable for estimating boiling point reduction in the investigated moisture content range. This might be useful for describing the observed trend in the investigated experimental range.

3.4. Bubble Formation in DOT 5.1 Brake Fluid

Visualization of bubble formation in DOT 5.1 brake fluid with moisture content variations of 0%, 1%, 2%, 3%, and 4% under several test temperature conditions was shown in Table 8. Each combination of moisture content and temperature indicated visible differences in bubble cross-sectional area formed during heating process, allowing changes in fluid behavior to be observed more clearly.

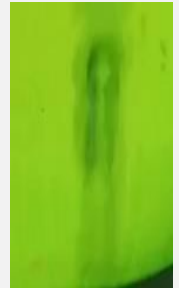
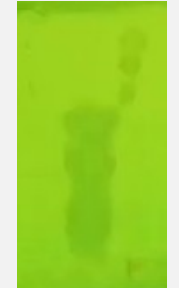
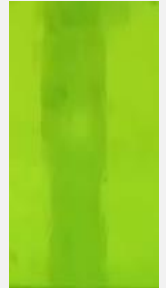
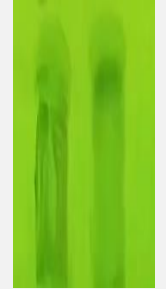
Visual patterns showed that an increase in moisture content accelerated the onset of bubble formation and enlarged bubble area at the same temperature level. These observations indicated that water contamination played a significant role in promoting vapor generation in DOT 5.1 brake fluid under thermal loading. The results in Table 4 showed that, for DOT 5.1 brake fluid without water contamination (0%), heating in the temperature range of approximately 240 °C to 260 °C did not produce any visible bubble formation. This behavior confirmed that dry brake fluid was able to maintain thermal stability under elevated temperature conditions.

Brake fluid contained water at levels of 1%, 2%, 3%, and 4% and the initial appearance of bubbles was observed at temperatures around 240 °C. This phenomenon became increasingly pronounced as moisture content increased, with larger bubble

Table 7. Statistical validation of DOT 5.1 boiling point regression model

Parameter	Value
Regression Equation	$T = -21.6X + 261.2$
R	0.976
R^2	0.953
Adjusted R^2	0.937
RMSE	7.59 °C
Standard Error of Estimate	8.764 °C
F-statistic	60.750
Significance (p-value)	0.004
Intercept Coefficient	261.200 ± 6.788
Slope Coefficient	-21.600 ± 2.771

Table 8. Visualization results of bubble formation during heating of DOT 4 brake fluid at various moisture contents

Temperature	Moisture Content in Brake Fluid				
	0%	1%	2%	3%	4%
240 °C					
250 °C					
260 °C					
270 °C					

sizes clearly visible at higher moisture concentrations. The observations showed that water contamination significantly accelerated vapor formation in DOT 5.1 brake fluid during heating.

The image data were further analyzed using image processing methods with ImageJ software after all bubble formation visualizations were successfully recorded. This procedure was performed to obtain quantitative values of bubble cross-sectional area for each moisture content variation. The reviewed results of ImageJ measurements were shown in [Table 9](#).

Bubble cross-sectional area values were determined for each tested moisture content

variation based on the data processing results obtained using ImageJ software, as shown in [Table 5](#). These values were subsequently analyzed and visualized in the form of graphical plots to indicate the variation in bubble cross-sectional area under different moisture content conditions, as shown in [Figure 5](#).

The graph presented the variation of bubble cross-sectional area with temperature for DOT 5.1 brake fluid at different moisture contents, including 0%, 1%, 2%, 3%, and 4%. Similar to the behavior observed in DOT 4, an increase in temperature led to a progressive enlargement of bubble area for all moisture levels. However, DOT 5.1 showed a more pronounced growth in bubble

formation at elevated temperatures, particularly for moisture contents of 3% and 4%, indicating higher sensitivity to thermal loading.

Brake fluid without moisture (0%) showed minimal bubble formation at lower temperatures, signifying stable thermal characteristics. Consequently, brake fluid containing moisture indicated a clear temperature-dependent increase in bubble area. As the temperature increased from 240 °C to 270 °C, fluids with higher moisture content consistently produced larger bubble areas, reflecting an accelerated vapor generation process. This trend signified that increasing moisture content promoted vapor bubble formation in DOT 5.1 brake fluid under the investigated laboratory conditions, serving as an indicator of increased vapor generation tendency. Based on the relationship between temperature, moisture content, and bubble formation characteristics observed in DOT 5.1 brake fluid, an empirical model was developed using nonlinear regression analysis. Moisture content and temperature were treated as independent variables, while bubble fraction served as the dependent variable. The resulting empirical

equation during the analysis was expressed as follows:

$$F = 8.3 \times 10^{-18} \cdot X^{0.517} \cdot T^{7.433} \quad (4)$$

where, F is bubble fraction (%); X is moisture content in brake fluid (%); T is temperature (°C)

Quantitative empirical relationships connecting moisture content, temperature, and bubble formation characteristics in DOT 5.1 brake fluid under controlled laboratory conditions have been hardly reported, according to some investigations. The mathematical model was constructed through nonlinear regression using a logarithmic method, allowing a quantitative description of the relationship between bubble fraction, moisture content, and temperature. The results showed that bubble fraction was predominantly influenced by temperature, as reflected by the exponent of 7.433 for variable T. Moisture content also contributed to the increase in bubble fraction, although the effect was less pronounced, as shown by the exponent of 0.517 for variable X. The model enabled estimation of bubble formation tendencies under the investigated laboratory conditions. Consequently,

Table 9. Measured bubble cross-sectional area obtained using ImageJ

Moisture content (%)	Bubble Cross-Sectional Area (mm ²)			
	240 (°C)	250 (°C)	260 (°C)	270 (°C)
0	0.00	0.00	0.00	26.33
1	32.22	55.09	80.14	84.42
2	44.30	66.66	86.78	93.87
3	67.23	80.41	96.62	103.49
4	82.02	125.31	132.23	172.38

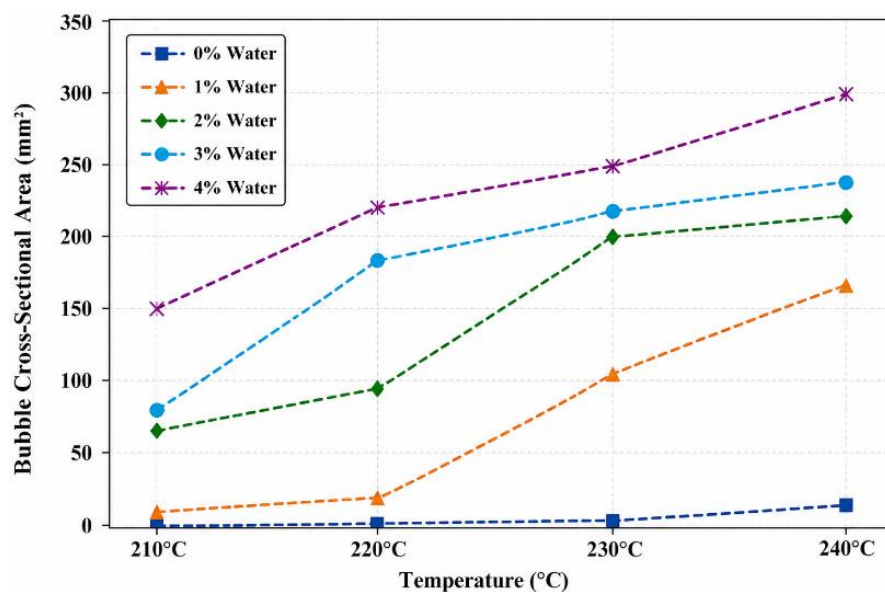


Figure 5. Comparison of bubble cross-sectional area in DOT 5.1 brake fluid at different moisture contents

the model served as a reference for evaluating vapor formation tendencies in DOT 5.1 brake fluid, providing a valuable understanding of high-temperature braking system safety analysis. Moisture contents reported in this study corresponded to nominal contamination levels established through volumetric addition of distilled water. Homogeneous mixing was promoted using a magnetic stirrer, and the actual moisture concentration was not independently verified through Karl Fischer titration or equivalent measurement methods. Therefore, the obtained relationships were interpreted in controlled laboratory-prepared contamination levels.

3.5. Limitation

This study was conducted using laboratory-prepared brake fluid samples under atmospheric-pressure conditions. Moisture contamination levels were established by volumetric addition of distilled water followed by magnetic stirring to achieve homogeneous mixtures. However, the actual moisture content was not independently verified using Karl Fischer titration or other standardized moisture analysis methods, as the reported moisture contents were interpreted as nominal values. During the analysis, the experiments were performed in static containers and did not reproduce hydraulic pressure, brake-line geometry, or dynamic operating conditions encountered in actual automotive braking systems.

Several limitations were considered when interpreting the results of this study. First, moisture contamination levels were prepared using volumetric addition of distilled water and verified using a commercial brake fluid tester. However, the actual moisture content was not quantified using standardized laboratory methods including Karl Fischer titration, and the reported moisture levels were interpreted as nominal contamination levels. Second, the experiments were conducted in static laboratory containers under atmospheric-pressure conditions. The test environment did not reproduce hydraulic pressure, brake line geometry, fluid circulation, transient heat loading, or other operational conditions encountered in actual automotive braking systems. Third, bubble area measurements were obtained through

representative frames extracted from a single heating experiment for each condition. As a result, statistical parameters such as standard deviation and confidence intervals could not be determined.

Future studies should use repeated experiments and multiple-frame analyses to provide more comprehensive statistical validation. The experiments were conducted using static brake fluid samples under atmospheric-pressure laboratory conditions. No hydraulic pressure, brake-line geometry, fluid circulation, or vehicle-level braking operation was reproduced during testing. Consequently, the observed boiling point degradation and bubble formation characteristics should be interpreted as indicators of vapor generation behavior rather than direct measurements of vapor lock occurrence in actual braking systems. Future investigations related to pressurized hydraulic systems and vehicle level validation are required before the proposed empirical relationships can be applied to real-world braking conditions. Bubble area measurements were derived from representative image frames obtained from a single heating experiment for each test condition. Subsequently, statistical analyses such as standard deviation, confidence intervals, and significance testing could not be performed for bubble area dataset. The reported values should be interpreted as comparative measurements intended to show relative differences in bubble formation behavior among the investigated conditions. Future studies should incorporate repeated experiments and multiple-frame analyses to establish statistical repeatability and uncertainty bounds.

In conclusion, this study investigated the influence of moisture content on boiling point characteristics and bubble formation behavior of DOT 4 and 5.1 brake fluid under controlled laboratory heating conditions. The experimental results showed that increasing moisture content consistently reduced boiling point of both brake fluid types. Concerning DOT 4 brake fluid, boiling point decreased from 255.3 °C at 0% moisture content to 169.0 °C at 4% moisture content. Similarly, boiling point decreased from 270.3 °C to 182.3 °C over the same moisture content range for DOT 5.1 brake fluid. These results confirmed that water contamination significantly degraded the thermal performance of glycol-based brake fluid.

The visual observations and image processing analysis further indicated that higher moisture content promoted earlier vapor bubble formation and increased bubble cross-sectional area at identical temperature levels. Concerning both brake fluid types, bubble formation became more pronounced as temperature increased, with the largest bubble areas consistently observed in samples containing 4% moisture. The quantitative ImageJ analysis confirmed a visible relationship between moisture content, temperature, and bubble growth characteristics during heating. Regression analysis successfully produced empirical relationships describing the effect of moisture content on boiling point reduction in both DOT 4 and 5.1 brake fluid. In addition, empirical models were developed to represent the observed relationship between moisture content, temperature, and bubble formation characteristics in the investigated experimental range. These models provided a preliminary quantitative description of the laboratory-observed trends and served as useful references for future investigations of brake fluid thermal behavior. In general, the results showed a clear relationship between moisture contamination, boiling point degradation, and increased vapor formation under controlled laboratory conditions. The results contributed experimental data, boiling point measurements, and image-based quantitative analysis concerning the thermal and bubble formation characteristics of DOT 4 and 5.1 brake fluid with varying moisture levels. Since the experiments were conducted using static fluid samples under atmospheric-pressure laboratory conditions, the results were interpreted in the scope of the present experimental setup. Future studies incorporating hydraulic pressure, fluid circulation, transient thermal loading, and full-scale braking-system configurations are required to evaluate the applicability of these outcomes to actual vehicle operating conditions as well as braking-system performance.

4. Conclusion

This study investigated the effect of hydroxy gas addition on diesel engines running on 30% and 40% biodiesel concentrations. It significantly affected combustion efficiency, fuel consumption, and overall engine performance. The addition of hydroxy gas improves combustion rate and

efficiency and significantly reduces energy consumption compared to biodiesel without hydroxy, especially at low to medium torque levels. Hydroxy gas reduces BSFC across all torque ranges, bringing fuel consumption closer to pure diesel engines.

The enrichment of hydroxy results in improved thermal efficiency and continuously increases, particularly at higher torque, over diesel fuel at 30 N.m for B30. While high biodiesel blends tend to reduce efficiency due to their higher viscosity, low-calorie value, and surface tension, hydroxy effectively mitigates these issues. Although biodiesel's thermal efficiency remains slightly lower than pure diesel, adding hydroxy narrows the gap. Compared to pure diesel, the average decrease in thermal efficiency was only 1.31% for B30H and 2.91% for B40H. Due to its high flame speed and heating value, hydroxy gas reduces ignition delay and accelerates ignition and fuel vaporization, resulting in higher engine performance.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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All data are available from the authors.

Competing interests

The authors declare no competing interest.

Generative AI statement

The author(s) declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Additional information

This study was conducted as part of an experimental study in the field of vehicle safety and braking systems. All data used were obtained from laboratory tests conducted directly by the authors. Supporting data generated and analyzed during the study are available from the sponsoring authors upon reasonable request. The authors declare no conflicts of interest that could influence the results and interpretation of this study.

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