Operational Tests of Brake Fluid in Passenger Cars

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Received: 23 June 2019, Accepted: 12 August 2019, Published online: 02 January 2020

Abstract
During the operation of vehicles, the properties of liquids and consumables deteriorate, which may affect the level of safety of technical systems and road traffic safety. The results of testing brake fluid aging as a function of boiling point and percentage of water content were presented on a selected group of passenger cars. The tested vehicles were varied in terms of age and kilometer mileage. The methodology for testing the quality of brake fluid based on glycol selected passenger cars remaining in service has been presented. In this study was shown a significant decrease in the brake fluids quality during the two years of operation in vehicles. The determination of boiling point was more efficient than the determination of water content. Despite the lack of full vehicle operational information, the obtained test results allow for exciting observations.

Keywords
automotive engineering, operational, vehicle safety system

1 Introduction
The automotive industry is dominated by four main development trends: improvement of vehicle dynamics, reduction of energy consumption and emissions, and improvement of transport safety (Zöldy, 2018). In the automotive industry, chemical products are widely used both in production processes as well as in the operation of vehicles. Car chemistry is a vital assortment department that ensures the supply of operating fluids, lubricants, and cosmetics necessary for the proper functioning of vehicles (Kuranc et al., 2018). In industry and the automotive industry (e.g. in lubrication means), synthetic hydrocarbons play the most important role, in particular, poly-alpha-olefins (PAO), carboxylic esters (complexes and polyesters), polyalkylene glycols (PAG) (Beran et al., 2003), and monoalkylene glycols (Depta, 2013). From safety in the vehicle, two types of operating fluids - engine coolant and brake fluid - are the most important. The above chemical preparations must meet a number of requirements for reasons of road safety (Droździel and Wrona, 2018; Gechev et al., 2017; Hudak and Madleňák, 2017; Jurecki et al., 2017; Levulyte et al., 2016; Poliak et al., 2018; Sipos, 2017), and contamination of the natural environment and human health (Limpert, 2015; Lizbetin et al., 2019 Rimkus et al., 2018).

Currently, there are several brake fluid classes available that meet the requirements of PN-C-40005: 2002, which is equivalent to the standard issued by the DOT (Department of Transportation of the United States), commonly used in the automotive industry to determine the brake fluid class. These are classes: DOT-3, DOT-4, DOT-5, and R-3. 95 % of cars in the world use a group of products based on glycol esters (Khamidullin et al., 2006). Table 1 presents the brake fluid elemental chemical composition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Share %</th>
</tr>
</thead>
<tbody>
<tr>
<td>alkylene glycol alkyl ethers, strongly hygroscopic substances that act as solvents</td>
<td>70-80</td>
</tr>
<tr>
<td>polyethylene or propylene polyglycols or borate esters of alkylene glycol alkyl ethers acting as a lubricant</td>
<td>20-30</td>
</tr>
<tr>
<td>inhibitors, i.e., anti-corrosion, anti-oxidation, stabilizing and anti-foaming additives</td>
<td>5-10</td>
</tr>
</tbody>
</table>

Table 1 The elemental chemical composition of the brake fluid (Poskrobko et al., 1994)
The braking system is a crucial element of safety necessary for the safe use of the vehicle (Jegadeeshwaran and Sugumaran, 2015). In the literature, there are many works in the field of testing of friction elements of braking systems (Indira et al., 2015; Pavlov et al., 2015; Sawase and Sano, 1999; Sergienko et al., 2013; Walczak et al., 2015), and work on testing of operating fluids: fuels and engine oils (Sejkorova, 2013; Sejkorova and Senkyr, 2017; Vališ et al., 2018). However, relatively few of them relate to brake fluids, hence deserving the attention of research (Bzura, 2007; Kuranc et al. 2018; Jakóbiec, 2006; Lee, 1999; Sejkorová et al., 2018).

As it results from the Polish National Council of Road Traffic Safety Report (National Road Safety Program, 2013), up to 22.5% of the causes of road traffic accidents among defects occurring in car safety systems are caused by a malfunction of the car braking system (National Road Safety Program, 2013). The requirements for car braking systems are set out in Regulation 13 of the United Nations Economic Commission for Europe (ECE) (UN ECE, Regulation 13, 2016). These requirements apply to braking performance, vehicle stability during braking and reliability of the braking system. The vehicle’s load (its center of gravity) is also crucial for vehicle stability. The position of the center of gravity affects the weight distribution between the individual wheels during cornering. The position of this point is unstable and depends on several factors (Skrúcaný et al., 2018). Skrúcaný et al. (2018) presented the methodology of measuring the center of gravity’s and the impact of its change depending on the occupancy of the car by passengers and baggage.

The exact requirements for brake fluids are presented in the PN-C-40005: 2002 standard (Polish Committee for Standardization, 2002) and the Western standards FMVSS No 116 (National Highway Traffic Safety Administration, 2011) and ISO 2005 (International Standards Office, 2005). The proper functioning of the braking system determines the properties of the brake fluid. Vehicle manufacturers recommend replacing the brake fluid every two years or after approx. 40,000 km. The fluid’s purity affects the proper functioning of such systems like ABS, ASR (anti-skid regulation), ESP (electronic stability program), and BA (brake assistant). Table 2 presents the required boiling point values for individual brake fluid classes.

<table>
<thead>
<tr>
<th>Brake fluid class</th>
<th>The boiling point of the new fluid [°C]</th>
<th>The boiling point of the fluid with 3.7% water content [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOT 3</td>
<td>Min. 205</td>
<td>Min. 140</td>
</tr>
<tr>
<td>DOT 4</td>
<td>Min. 230</td>
<td>Min. 155</td>
</tr>
<tr>
<td>DOT 5.1</td>
<td>Min. 260</td>
<td>Min. 180</td>
</tr>
<tr>
<td>DOT 5</td>
<td>Min. 260</td>
<td>Min. 180</td>
</tr>
</tbody>
</table>

During operation of the vehicle as a result of the cooperation of individual elements of the braking system, its wear takes place. The heat released due to friction negatively influences the functioning of the car braking system, especially the friction elements and brake fluid. It has been found that during the sequence of intensive braking, the brake disc can reach a temperature of even more than 530 °C, (Lee, 1999). Excessive heat accumulation in brake linings causes the phenomenon of fading, resulting in the loss of friction properties or the occurrence of the flow phenomenon. This problem can be solved by changing the design of friction elements, e.g., by using ventilated brake discs. Another threat is the accumulation of warm energy in the brake caliper elements that causes the brake fluid temperature to increase. During the braking phase, the fluid heats up, and steam bubbles may form in it (steam cork), as a result of which the fluid transfers the lower and lower pressure force to the brake cylinder piston. This phenomenon may consequently lead to a sudden loss of braking ability.

Brake fluids based on polyglycols, glycol ethers, methylglycium borate with additions of corrosion inhibitors have highly hygroscopic properties. Water absorption changes the chemical composition and worsens the fluid’s properties during operation. The increase of the water content in the liquid is associated with a decrease in the temperature of the formation of the steam cork and its boiling point. That is why it is so essential to control the quality of the brake fluid in the vehicle. The high-quality fluid helps to keep the system components in good condition and to avoid brake failure (e.g., "baking" and corrosion of the cylinders, damage to the seals of moving parts or the master cylinder). The use of new materials for the friction components of the braking system that increase the heat storage requires the use of a fluid with higher temperature parameters and more frequent control of its quality and level in the compensating tank.

The work aims to present and discuss the results of brake fluid operation tests realized on a selected group of passenger cars. The work includes testing the quality of car brake fluid based on the determination of the percentage of water content and the measurement of boiling point value in terms of the intensity of vehicle use expressed in kilometer mileage.
2 Research methodology
The brake fluid based on glycol quality tests were realized on a selected group of 32 passenger cars, at various ages and with different mileages. The research was carried out in two stages - year after year, in the same period (November-December), to obtain the total annual mileage of a given vehicle. The first stage of the research was carried out in 2017, the second in 2018. Changes in the usable properties of the fluid have been determined by the percentage of water content as well as the boiling point of the brake fluid. Subsequently, the results obtained for the measurement of the brake fluid parameters were analyzed as a function of the vehicle mileage. The tested vehicles were produced in the years 2000-2011, and the mileage values read from the odometer were in the range: 299-325 435 km.

The water content was tested using by electronic 4-diode tester (Fig. 1 (b)), and the temperature range is shown in Table 3. Boiling point measurements were made with the ATE-BFT 320 brake fluid tester (Fig. 1 (a)). In both cases, the measurement was made by immersing the measuring probe in the vehicle’s compensation tank according to the instruction manual of the measuring device. The BFT 320 ATE brake fluid tester used is very precise of determining the boiling point of all types of fluids based on glycol used in vehicles.

3 Research results
The first analysis carried out concerned about the assessment of the percentage of water content in the brake fluid. The comparison of the results of the percentage of water content in vehicles is shown in Fig. 2.

As can be seen in Fig. 2 in study 1, only for two vehicles, the result was a water content of 3 % and 4 %. In study 2, this number has doubled. It was shown that the tested vehicles in 82 % met the norm regarding the percentage of water content in the car brake fluid. After one year of operation, an approximate 10 % drop was found in vehicles with a 1 % water content in the car brake fluid. However, a slight increase in the percentage of water content in the car brake fluid of 2 % for vehicles in study 2 was obtained.

Furthermore, the vehicle population with the exact percentage of water content in the brake fluid has a downward trend in both test phases. In Study 2, the largest approx. 6 % increase in vehicles with a percentage of water content in the car brake fluid of 3 % was obtained.

Fig. 3 shows the change in the percentage of water content in the brake fluid depending on the course of the annual vehicle. Analyzing the data, it can be concluded

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Table 3

<table>
<thead>
<tr>
<th>The color of the signaling diode</th>
<th>Ranges of the boiling point</th>
<th>Brake fluid rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>Min. 205</td>
<td>fit</td>
</tr>
<tr>
<td>Yellow</td>
<td>Min. 230</td>
<td>fit - consider the exchange</td>
</tr>
<tr>
<td>Red</td>
<td>Min. 260</td>
<td>unfit</td>
</tr>
</tbody>
</table>

Fig. 1 a) The brake fluid tester BFT 320 during the measurement, b) 4-diode tester

Fig. 2 Comparison of the percentage of water content in the brake fluid

Fig. 3 An increase in the percentage of water content in the car brake fluid depending on the annual mileage
that only in 5 cases an increase in the percentage of water content in the car brake fluid was noted, i.e., its properties deteriorated by 1 %.

Fig. 4 presents the change in the boiling temperature of the brake fluid in the tested vehicles. In study 1, in the case of 2 vehicles, the boiling temperature of the car brake fluid was below 180 °C, and in these vehicles, the fluid qualifies for replacement with a new one. However, in the case of the second test, the boiling point below 180 °C was recorded for eight vehicles, and it was they who were qualified for fluid replacement. About the examination of the percentage of water content in the car brake fluid, the number of vehicles with fluid qualified for replacement after study 2, the boiling point of the fluid is twice as significant.

In Study 2, an approximate 20 % increase in the vehicle population with the boiling point of the car brake fluid in the range below 180 °C was obtained. In the next range of 180-200 °C, (the correct parameters of the fluid), also a significant increase in the vehicle population was recorded, almost 10 %. In subsequent intervals, the share of vehicles was reduced. In Study 2, no vehicle was found whose fluid boiling point would exceed 260 °C, which means that no fluid maintained high parameters in any vehicle and was aging during one year of operation.

Fig. 5 shows the change in the boiling temperature of the brake fluid depending on the annual vehicle mileage.

Researches of the boiling temperature of the car brake fluid showed changes in the temperature value in each of the tested vehicles. Therefore, the measurement of the boiling temperature of the car brake fluid is a more precise and reliable method than the percentage determination of the water content in the car brake fluid. The analysis shows that as the mileage increases, the change in the boiling temperature of car brake fluid is also increasing, which is also evidenced by the upward trend line. The average change in the boiling temperature of the brake fluid in the test is 15.97 °C. It can also be noted that the high concentration of results ranges from around 10 000 km up to 15 000 km mileage of vehicles. This testifies to the more frequent use of vehicles in this mileage range.

4 Conclusion
Active safety of the car is affected by the technical condition of all structural systems that make up its structure: powertrain, chassis, steering, braking system, electric system, suspension, etc. (Droździel et al., 2014). The so-called automotive active safety systems primarily include the steering, suspension, and braking system. Monitoring selected parameters of car brake fluid and replacement at the proper time not only ensures proper function of the all braking system but also contributes to the removal of brake system defects and thus increases the safety of road traffic (Sejkorová et al., 2018). Brake fluid tests carried out have demonstrated the usefulness of the methods used to determine the changes in fluid performance. It has been shown that boiling point measurement is a more accurate method to determine the quality of the car brake fluid than the water content determining method. This is evidenced by the fact that depending on the chemical composition of the fluid (brake fluid class), the same water content causes the boiling temperature to drop to a different degree.

It was shown that in the first study, 6 % of vehicles had a liquid with weak parameters and should be replaced. In study 2, the share of vehicles with poor brake fluid quality increased to around 25 %. It should be emphasized that in the second stage of the research vehicles involved in the first test showed a fluid with wrong parameters, which indicates that drivers ignore the problem (vehicle owners). Based on the conducted studies, it can be concluded that
75% of the tested vehicles used proper quality brake fluid. In turn, Kuranc et al. (2018) in his research, stated that only 55% of the tested population of vehicles has fluid with the right parameters. The obtained tests are much more optimistic than the data provided by brake fluid manufacturers who claim that only in 25% of vehicles is fluid with proper quality parameters. Brake fluid manufacturers also recommend a two-year cycle of replaced it on. The assessment of the quality of the brake fluid shows that during the two years of operation, the properties of the brake fluid deteriorate, but the replacement of the fluid may be premature.

Similarly to other investigators (Kuranc et al., 2018), it was confirmed that the higher annual mileage of the vehicle contributes to the deterioration of brake fluid parameters. In the light of the conducted tests, it is possible to recommend a higher frequency of brake fluid replacement in vehicles used in a more intensely determined by a more considerable average-year mileage. As shown in the tests, the average drop in the boiling temperature of the brake fluid was about 16 °C during the vehicle’s one-year lifetime. The average boiling point in study 1 was 212.22 °C, while in study 2, it dropped to 196.25 °C.

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