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# Investigation of Tribological Characteristics of Cu-Fe-Ni-Al-Mn Heat Exchanger Alloys for Automotive Applications in Different Antifreeze Ratios

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**Abstract**

This study investigates the effects of antifreeze and water mixtures on the wear resistance of copper alloys, a topic that has not been sufficiently explored in the literature, particularly regarding the environmental impact. While previous research has emphasized the importance of material properties and surface modifications in improving wear resistance, the role of environmental factors, such as the mixture of antifreeze and water, has been less discussed. In this study, experiments were conducted using a 4D-DTM25 wear tester with antifreeze ratios of 25%, 50%, and 100%, under a constant load of 10N and a sliding distance of 100 meters. The results show that increasing the antifreeze concentration significantly improves the wear resistance of copper alloys. Notably, the use of 100% antifreeze resulted in a remarkable change in the morphology of the wear marks, shifting from abrasive to adhesive characteristics. This transition highlights the potential of anti-freeze mixtures to improve sliding conditions and reduce wear. Additionally, surface roughness measurements and Scanning Electron Microscope (SEM) images further supported the experimental results, providing a detailed understanding of wear patterns and surface characteristics. These findings offer valuable insights into the behavior of copper alloys under varying environmental conditions, contributing to the optimization of copper alloys, particularly in automotive and industrial applications where wear resistance is critical. This research suggests that antifreeze-water mixtures could serve as an effective solution for enhancing wear resistance and performance in real-world conditions.

*Keywords*: : Antifreeze; Automotive; Copper Alloy; Heat Exchanger; Roughness Wear.

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## 1. Introduction

The automotive industry recognizes that the performance of alloys used in engine cooling systems is of critical importance in terms of engine efficiency and life. The components in these systems must be resistant to wear while operating under high temperatures and pressures. Therefore, the properties of the materials used in this area are of great importance not only in terms of functionality but also in terms of economic life and maintenance costs [1-5]. In this context, the role of the operating environment, particularly the effect of antifreeze and water mixtures, emerges as a key factor influencing wear behavior. Examining the interactions between these mixtures and material surfaces is considered an important step toward innovative solutions in the sector [6-8]. The use of copper alloys in automotive cooling systems is among the essential elements that increase the effectiveness of such systems. Copper is known for its excellent electrical conductivity, thermal conductivity, and corrosion resistance properties. However, copper alloys must also exhibit high wear resistance under the high temperature and pressure conditions encountered during engine operation. The composition of the copper alloy (80.1% Cu, 4.22% Fe, 5.12% Ni, 9.57% Al, and 0.95% Mn) offers significant advantages in terms of corrosion and wear resistance, making it a widely preferred option in automotive applications compared to other alloys commonly used in this sector [6, 9-11]. In particular, the iron (Fe) ratio in the copper alloy enhances the mechanical properties of the alloy, while the nickel (Ni) ratio improves corrosion and wear resistance. Simultaneously, the aluminum (Al) content plays a crucial role in providing a balance between lightness and durability. These properties, combined with their performance in antifreeze-water environments, create an effective material that meets the stringent requirements of cooling systems and enhances engine efficiency [6, 12].

A study highlighting the significance of vibration-induced wear in power plant components concluded that antifreeze-water mixtures can significantly affect wear behavior, especially in systems operating under high temperatures and pressures[13-15]. The role of these mixtures is particularly critical as they directly interact with the material surface, modifying its wear resistance and contributing to material degradation. Faes et al. emphasized the effect of the chemical structure of the alloy on wear and corrosion in their study on corrosion and corrosion prevention methods in heat exchangers [6]. Similarly, Skela et al. demonstrated that wear resistance varies depending on the microstructure of the material. Their study specifically highlighted that optimizing the material's microstructure is essential for enhancing its wear performance in varying environmental conditions. In this context, the effects of the microstructure of hot work tool steel on wear behavior were investigated, with a strong emphasis on understanding how changes in the microstructure influence wear resistance [8, 10]. This underscores the importance of designing copper alloys with tailored microstructures for specific environmental interactions, including antifreeze-water mixtures. The findings of Addepalli et al. further support this notion, demonstrating that such mixtures can optimize material interactions and mitigate degradation in heat exchanger elements [16]. Additionally, Günen et al. [1] investigated high-temperature wear behavior, revealing the potential of surface modifications in enhancing wear resistance under challenging environmental conditions.

This collection of papers explores various aspects of wear in materials, particularly relevant to automotive applications. Wear data exhibit variability, necessitating multiple tests for reliable results [17]. In automotive parts, wear impacts efficiency and service life, with factors like loads, speeds, and temperatures influencing wear patterns [18]. Specific wear mechanisms, such as soot-induced wear in engine components, have been investigated, revealing a corrosive-abrasive mechanism in boundary lubrication conditions [19]. Advanced aluminum nanocomposites show promise in improving wear resistance, with Al-4 wt.%TiC nanocomposites demonstrating a 25% improvement over base alloys [20]. Machine learning techniques, particularly gradient boosting regression, have proven effective in predicting erosion wear rates, achieving an R2 value of 0.97 [20]. These findings contribute to understanding and mitigating wear in automotive and industrial applications.

This research aims to evaluate the changes in wear resistance of copper alloy (80.1% Cu, 4.22% Fe, 5.12% Ni, 9.57% Al, and 0.95% Mn) under different environmental conditions using water and antifreeze mixtures (dry, 25%, 50%, and 100% antifreeze). While previous studies have focused on the influence of material properties and surface modifications on wear resistance, the effect of environmental factors, such as the antifreeze concentration, has not been sufficiently addressed. In this study, wear tests were conducted to assess how different antifreeze-water mixtures influence wear resistance. The surface morphology, obtained during the wear tests, will be analyzed alongside SEM images and roughness measurements to determine which antifreeze concentration provides the best wear resistance. This research aims to bridge the gap in the literature by highlighting the importance of environmental factors in improving wear performance of copper alloys.

## 2. Materials and Methods

A wear test is a key method for determining the material's resistance to surface damage under different conditions. In this study, a wear test was conducted instead of the abrasive wear test originally mentioned. The test was carried out using the 4D-DTM25 erosion tester, a high-precision system designed to evaluate the performance of materials under conditions, where solid particles or liquids contribute to wear. This system is specifically tailored for evaluating the behavior of materials when exposed to erosion processes, offering insight into the material’s durability under such conditions. A schematic drawing of the system simulating the erosion wear stage is illustrated in Fig.1.

For this experiment, a copper alloy was selected, obtained from the upper retaining plate of a scrap car radiator (heat exchanger). The alloy sample was analyzed using XRF (X-ray fluorescence spectroscopy), revealing a chemical composition of 80.1% Cu, 4.22% Fe, 5.12% Ni, 9.57% Al, and 0.95% Mn. This alloy was chosen because copper maintains its high thermal conductivity while the addition of elements such as nickel and aluminum enhances its corrosion resistance and mechanical strength. These properties are especially crucial for ensuring reliable performance under conditions, where the material is subjected to high-velocity particles or fluids.

During the test process, a 10N load was applied to the sample, and a total distance of 100 meters was covered. This distance is essential for evaluating the effects on the material’s surface, simulating the long-term impact of forces. The test speed was set to 100 rpm to determine the material’s resistance to wear. The wear rate was calculated as approximately 33 mm/s during the test process.

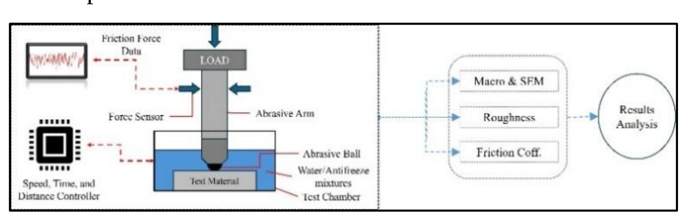


Figure 1. Schematic graph of experimental process.

The friction coefficient (COF) was measured by recording the lateral load applied during the wear test, considering the experimental load. This allowed for a more accurate assessment of how the surfaces interacted during the erosion process, providing crucial data on the material's performance under conditions.

The experiments involved different antifreeze ratios: 100% water (D), 25% antifreeze + 75% water (025A), 50% antifreeze + 50% water (05A), and 100% antifreeze (1A). These mixtures were used to study their effect on wear performance under conditions. The antifreeze coolant used in these tests was SHELL Coolant Essential 4, selected for its known performance characteristics. Although the exact chemical composition of SHELL Coolant Essential 4 is proprietary and unavailable, it can be reasonably assumed, based on similar industrial coolants, that it contains a mixture of ethylene glycol or propylene glycol, corrosion inhibitors, and pH stabilizers. These components are typically found in automotive coolants and likely contribute to the lubricant properties observed in the wear tests.

To measure wear resistance, 1.4140 high-quality (hardness-45HRC), 6 mm diameter balls were used during the tests. These balls simulate the impact of particles on the material surface, playing a critical role in understanding the wear behavior. Surface traces were examined using SEM (Scanning Electron Microscope) imaging at a magnification of 250X using the Quanta 450 SEM device. This analysis provided detailed insights into the material's surface morphology after the wear process.

Finally, surface roughness measurements were carried out using the Insize ISR-C300 mobile surface roughness device, which effectively measures the surface profile after erosion, offering further understanding of the material's response to wear. The design and execution of these experiments were meticulously planned to ensure the reliability and repeatability of the results. Each stage of the process was carefully monitored, and the data obtained were systematically analyzed to draw accurate conclusions regarding the material's performance under conditions.

## 3. Results and Discussion

The experimental results reveal that the wear rates show a significant variation depending on the antifreeze ratio. The data obtained during the 100% water experiments provided the opportunity to examine the morphology of the wear marks in particular. At the beginning of the experiments, in the wear tests carried out under 100% water conditions, serious abrasive wear marks were observed on the material surface. These wear marks created significant changes in the surface structure of the material and negatively affected the wear resistance. These findings reveal the effect of wear, especially on the microstructure of the material surface. However, as the antifreeze ratio increased, it was determined that the wear mark morphology changed and gained a more adhesive structure and approximately disappeared with the use of 100% antifreeze. This condition left only adhesive traces on the surface. Adhesive wear properties were evaluated as an indicator of the potential of antifreezes to improve the sliding condition. Antifreezes serve to reduce wear by increasing the sliding condition under friction conditions [21, 22]. This is a particularly important finding for the automotive industry, as it contributes greatly to increasing the efficiency of cooling systems. The macro and micro images obtained as a result of the wear tests are given in Figure 2.

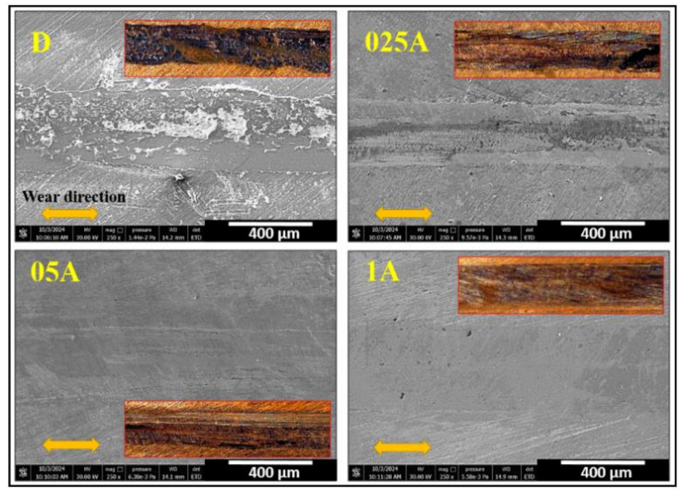


Figure 2. SEM and macro images of the traces obtained as a result of the wear test.

The surface roughness measurements showed that the surface roughness is optimized by the increase of antifreeze ratio. The maximum and minimum depth amounts of surface roughness were presented in Figure 3, and the effect of each antifreeze mixture on wear was clearly shown. From Figure 3, the roughness values obtained with different mixture ratios can be compared, which revealed that 100% antifreeze has the best performance. The surface depth morphology values obtained during the surface roughness measurement are given in Figure 3.

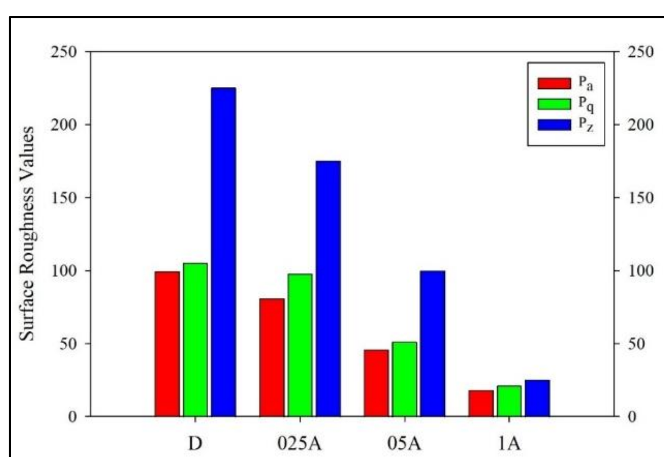


Figure 3. Trace depth morphology surface roughness values

The data in the table compares the COF, weight loss and wear rates of different samples (Table 1). Specimen D had the highest

COF (0.045) and wear rate (0.125 mg/m), while specimen 1A showed the best performance with the lowest COF (0.015) and wear rate (0.030 mg/m). This reveals that the choice of material significantly affects the wear behavior.

Table 1. Wear weight loss

| Sample | COF | Weight Loss (mg) | Sliding Distance (m) | Wear Rate (mg/m) |
|---|---|---|---|---|
| D | 0.045 | 12.5 | 100 | 0.125 |
| 0.25A | 0.030 | 8 | 100 | 0.080 |
| 0.5A | 0.020 | 5.5 | 100 | 0.055 |
| 1A | 0.015 | 3 | 100 | 0.030 |

The studies examine the tribological behavior of various materials, focusing on COF and wear rate. Godse et al [23] found that COF increases with normal load for different steel types, while wear rate is influenced by chemical composition. Alajmi & Shalwan [24] investigated graphite/epoxy composites, noting that graphite improved tribological properties but had mixed effects on mechanical properties. Idriss et al [25] observed that TiC-coated low alloy steel exhibited significantly lower wear rates and higher hardness compared to untreated steel. Jagadeesh et al [26] studied basalt-reinforced polymer composites, concluding that 30 wt% basalt addition substantially reduced both COF and specific wear rate. Across these studies, material composition, surface properties, and testing conditions (e.g., load, speed, distance) were found to significantly impact COF and wear behavior, highlighting the importance of optimizing these factors for specific applications.

In addition, another important finding of the experiments is the change in the COF. The COF obtained (4 measurements/second) were presented in tables at different stages of the experiment, and thus, the results obtained under different conditions were compared. The change in COF over time clearly reveals the effect of antifreeze ratios on the material. In 100% water, the average COF value was calculated as 0.045. However, as can be seen in the graphs, the COF remained below 0.02 at the highest level in corrosive wear processes applied with antifreeze, and the average values were realised at 0.01 levels. In particular, it was observed that the use of 100% antifreeze significantly reduced the COF, which in turn increased the wear resistance [27, 28]. The graphs of the COF are given in Figure 4.

The overall evaluation of the experimental results allows us to better understand the effects of antifreeze and water mixtures on the material. These findings provide important clues for the design and improvement of engine cooling systems, especially in the automotive industry. This data provides information that will contribute to the development of more efficient and durable materials in the fields of material engineering and automotive engineering. Thus, both cost reduction and performance increase can be achieved.

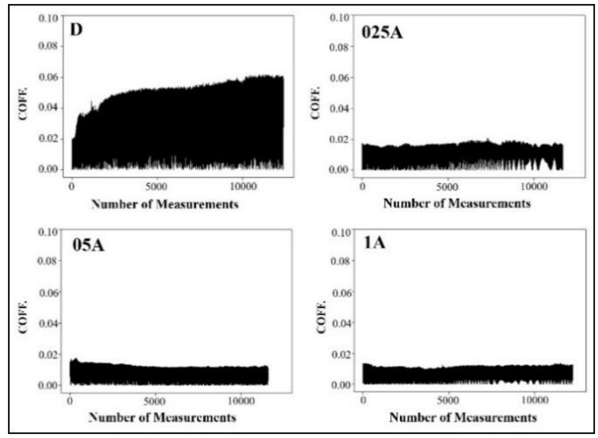


Figure 4. Friction coefficient graphs

Recent studies have explored the potential of advanced coolants and materials for improving automotive cooling systems and evaporative cooling technologies. Bargal et al. [29] conducted a comprehensive study on automotive radiators using different water/ethylene glycol mixtures, identifying optimal conditions for maximizing engine cooling efficiency. Shah et al. [30] investigated the use of SiO2-water nanocoolants in aluminum tube radiators, demonstrating significant improvements in heat transfer rates. Abbas et al. [31] reviewed the potential of nanofluids in automotive cooling systems, highlighting their superior thermal properties but noting challenges with long-term stability. To address this, hybrid nanofluids combining high thermal conductivity and stability have been proposed. Li et al. [32] examined water-based evaporative cooling technologies, focusing on material design and engineering for direct evaporative cooling, cyclic sorption-driven liquid water evaporative cooling, and atmospheric water harvesting-based evaporative cooling. These advancements offer promising solutions for enhancing cooling efficiency and sustainability in various applications.

This collection of studies examines friction and wear characteristics under various conditions. Water lubrication generally reduces COF and wear rates compared to dry sliding for materials like PEEK and its composites [33]. The addition of graphene ink to water further improves lubrication, significantly reducing friction and wear on graphene coatings [34]. COF are influenced by factors such as normal load, sliding velocity, and material composition [35]. For steel combinations, COF typically decrease with increasing normal load but increase with sliding velocity [8, 35]. The water content in lubricant mixtures plays a crucial role, with low water content (below 30%) in phytic acid ionic liquid mixtures resulting in low COF (below 0.06) and minimal wear due to the formation of adsorption films [36]. These findings highlight the importance of lubricant composition and environmental conditions in tribological performance.

## 4. Conclusions

In this study, the relationship between the wear tests and the antifreeze ratios of the copper alloy (80.1% Cu, 4.22% Fe, 5.12% Ni, 9.57% Al, and 0.95% Mn) used in heat exchangers was explored by examining the morphological structure of the wear marks. A significant focus was placed on the impact of antifreeze ratios on wear resistance and material performance.

First, we developed a corrosive wear test process using water-antifreeze mixtures to simulate erosive wear most effectively. This approach yielded significant results, demonstrating the strong potential of antifreeze ratios in improving wear resistance. As the antifreeze ratio increased in the water mixture, the wear rate per unit mass decreased, highlighting the importance of antifreeze concentration in enhancing material durability.

Additionally, the study supported these findings with SEM images, weight loss measurements, depth morphology assessments, and COF evaluations. The integration of these different testing methods provided a comprehensive understanding of wear behavior. It was observed that increasing the antifreeze ratio, especially in the case of 100% antifreeze, significantly optimized wear track morphology. This change in the wear tracks is considered an indicator of antifreezes' capacity to enhance sliding interactions and mechanical behavior on the material, leading to increased efficiency and reliability of engine components for long-term use.

Finally, the study also highlighted how the ratio of water to antifreeze in the lubricants altered the tribological balance in the wear processes. This research contributes to the literature on automotive cooling systems, particularly regarding the water-antifreeze processes used in such systems, offering insights into their impact on material performance in practical applications.

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## Conflict of Interest Statement

The authors declare no conflict of interest study.

## CRediT Author Statement

**Yaşar Yetişken:** Conceptualization, Funding acquisition,
**Yavuz Sun**: Project administration, Visualization,
**Bunyamin Cicek**: Data curation, Formal analysis,
**Harun Çuğ**: Investigation, Resources,
**Rajab Elkilani**: Methodology, Writing-original draft.

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