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STUDY OF IR, TGA/DTA, AND ELECTROCHEMICAL PROPERTIES OF A NEW GENERATION ANTIFRIZE CORROSION INHIBITOR

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Abstract

Corrosion is currently a global problem of a worldwide scale. Combating it with corrosion inhibitors (CIs) is highly effective. At present, two million tons of CIs are produced annually across the globe. Corrosion inhibitors are used almost ubiquitously to protect metals. The internal combustion engines of automobiles are also protected from corrosion by CIs added to antifreeze. However, antifreezes are considered very toxic to the environment and human health. This presents a major problem in our era, as the number of cars increases daily and used antifreeze is discharged into the environment. The production of antifreezes that are non-toxic to the environment and human health is one of the most pressing challenges of our time. Naturally, this, in turn, creates the need to discover CIs that are harmless to the environment and human health. We have tested the inhibiting properties of a synthesized CI in our antifreeze, which is based on propylene glycol. To address these issues, the inhibitory properties of potassium adipate (the potassium salt of adipic acid) were studied using electrochemical methods. This was investigated for its use as a non-toxic corrosion inhibitor in a propylene glycol-based antifreeze, which itself is harmless to the environment and human health.

Keywords: *Corrosion inhibitor, antifreeze, propylene glycol, TGA, DTA, IR spectrum; IQ Tracer-100 by SHIMADZU CORP, thermal analyzer SHIMADZU DTG-60*

Introduction

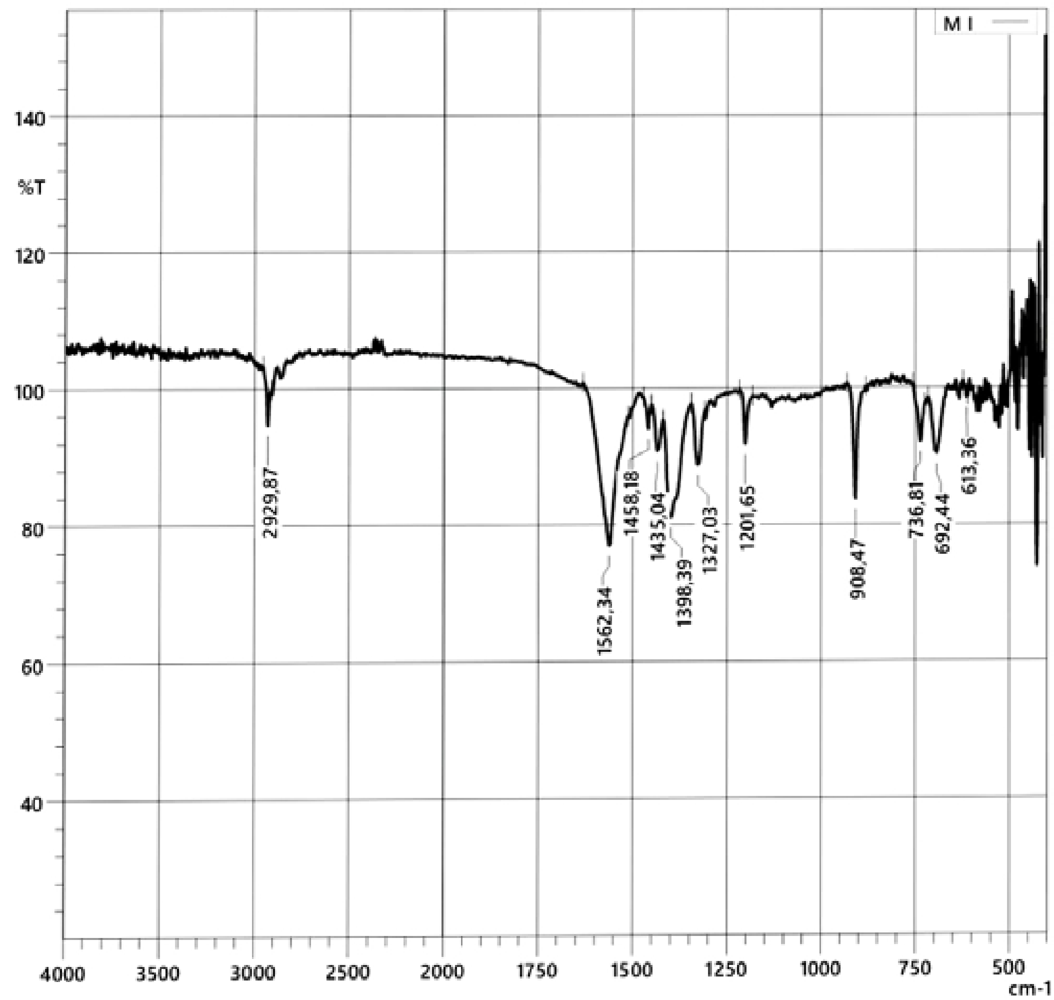
Corrosion is the degradation of metals due to environmental exposure. All nations incur significant economic losses as a result of corrosion (Revie, R. W., & Uhlig, H.H., 2025; Harsimran, S., Santosh, K., & Rakesh, K., 2021; Srikanth, P. S., 2026). While corrosion cannot be stopped completely, it can be slowed down. Substances that slow down corrosion are called inhibitors. The use of corrosion inhibitors (CIs) is one of the most common methods of corrosion control (Oliveira, K. W. D., Faccioli, Y. E. D. S., De Araújo, G. P., Converti, A., Da Silva, R. D. C. F. S., & Sarubbo, L. A., 2026; Al-Amiery, A. A., Isahak, W. N. R. W., & Al-Azzawi, W. K., 2023). One area where CIs are applied is in antifreezes, which are coolants for the cooling systems of automotive internal combustion engines. Initially, phosphates and silicates were used as corrosion inhibitors in antifreezes (Al-Amiery, A.A., Yousif, E., Isahak, W.N.R.W., & Al-Azzawi, W.K., 2023; Coelho, L.B., Lukaczynska-Anderson, M., Clerick, S., Buytaert, G., Lievens, S., & Terryn, H.A., 2022; Ma, I. W., Ammar, S., Kumar, S.S., Ramesh, K., & Ramesh, S., 2022; Alamiery, A., 2025). However, these substances have a toxic effect on the environment. Consequently, there is now a growing interest in carboxylates and "green" plant-based inhibitors, which are harmless to the environment and human health (Huang, L., Chen, W.Q., Wang, S.S., Zhao, Q., Li, H.J., & Wu, Y.C., 2022; Holla, B.R., Mahesh, R., Manjunath, H.R., & Anjanapura, V.R., 2024). The production cost of "green" corrosion inhibitors derived from plants is very high. Therefore, inhibitors based on environmentally safe carboxylates remain the optimal choice. The antifreezes currently in use are manufactured from ethylene glycol (Hans, J.M.J., 2025; Bhattarai, B.C., Parajuli, A., & Stiansen-Snoerud, K.B., 2025). However, ethylene glycol is extremely toxic to both the environment and human health. The use of propylene glycol instead of ethylene glycol solves this problem, as propylene glycol is non-toxic and even used in the food industry. Its price is also not prohibitively high.

Thus, a corrosion inhibitor was synthesized based on such a carboxylate, which is harmless to the environment and human health, and its inhibitory properties were studied.

Materials and methods

Potassium hydroxide (KOH) and adipic acid (HOOC-$(CH_2)_4$-COOH) were used for the synthesis of the corrosion inhibitor.

Figure 1. *IR spectrum of the synthesized corrosion inhibitor*



A 10 g sample of potassium hydroxide was weighed and placed into a 250 ml laboratory beaker. The beaker was placed on a magnetic stirrer, and a 5 cm magnetic stir bar was placed inside it. Then, 50 g of distilled water was added, and the stirrer was turned on to the second speed setting. The KOH dissolved quickly in the distilled water. Next, a 13.035 g sample of adipic acid was added. To ensure the reaction went to completion, the solution was stirred on the magnetic stirrer at room temperature for 30 minutes. A pH meter was used to confirm the completion of the reaction: pH=7. That is, in an acidic medium, pH < 7, and in an alkaline medium, pH > 7. A pH meter was used to confirm the completion of the reaction: pH=7.

$$HOOC\text{-}(CH_2)_4\text{-}COOH + 2KOH \rightarrow$$
$$\rightarrow KOOC\text{-}(CH_2)_4\text{-}COOK + 2H_2O$$

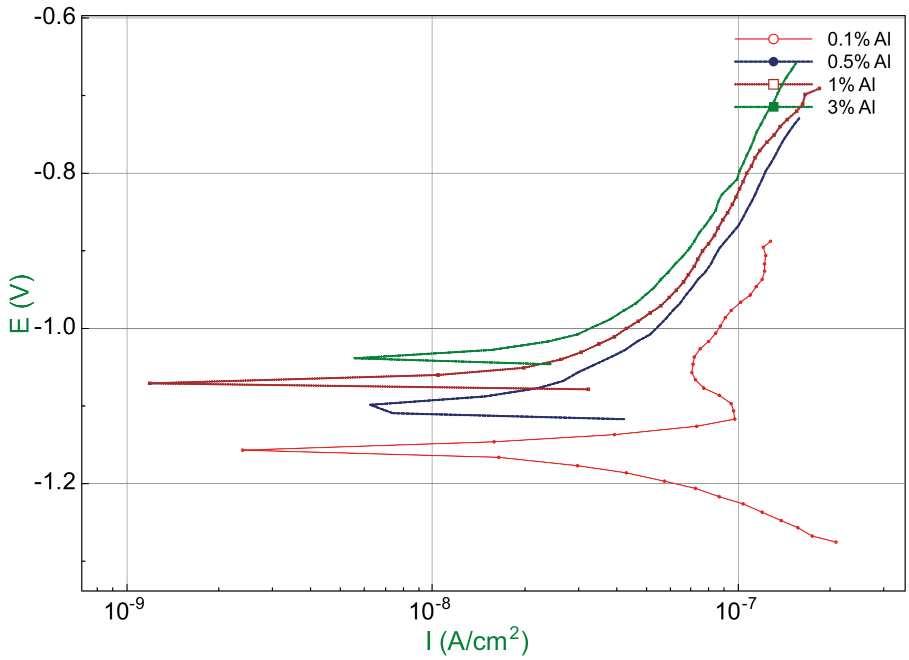
The resulting potassium adipate was then dried in a drying oven for 48 hours. To confirm that a potassium salt of adipine acid was indeed formed in the reaction, the IR spectrum of the dried substance was taken. Using the IR spectrum, it can be determined that the potassium salt of adipine acid has formed completely and that no excess adipine acid remains in the solution.

Infrared spectroscopy was performed using an IQ Tracer-100 spectrometer (SHIMADZU CORP., Japan, 2017). This equipment has a high sensitivity (signal-to-noise ratio of 60,000:1), which allows for the precise analysis of various wavenumbers in the samples despite the low intensity of the spectral lines. The measurement range covers the interval from 4000 to 450 cm^{-1}.

Analysis of the IR spectrum of the synthesized corrosion inhibitor shows that the absorption band at 3650–3500 cm^{-1}, corresponding to the stretching vibrations of the O-H group (not involved in hydrogen bonding), is not observed. This indicates that the adipic acid and potassium hydroxide have completely reacted. Furthermore, the vibration in the 2929 cm^{-1} absorption region indicates the presence of a CH_2 group in the potassium adipate.

The inhibitory properties of the potassium salt of synthesized adipic acid (KI) were studied using a CS-350 potentiostat. For this purpose, four metal samples were prepared for the experiment: steel-3, aluminum, copper, and POS-60 solder. These metals were selected because they are used to manufacture cooling systems for automotive internal combustion engines. The metal samples were first insulated, leaving an exposed surface area of 1 cm^2. The metal surface was thoroughly cleaned with sandpaper and degreased in ethyl alcohol. The samples were then dried at room temperature without a prolonged waiting period.

Figure 2. *Tafel polarization curves for aluminum in antifreeze with a corrosion inhibitor additive*

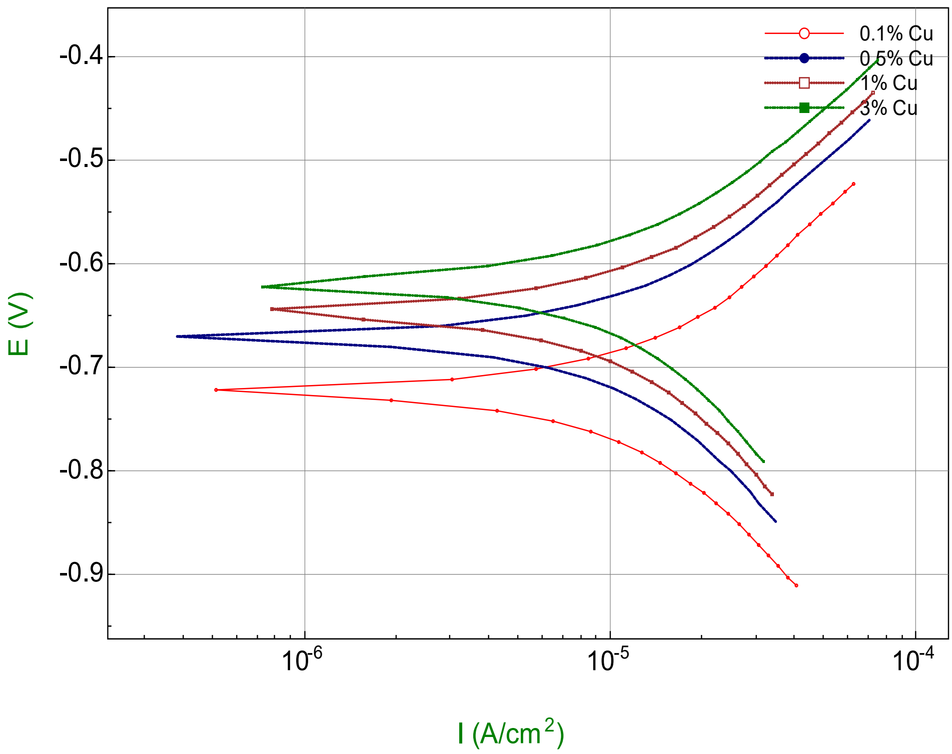


The antifreeze composition was prepared using a propylene glycol base, which, in accordance with modern requirements, is harmless to the environment and human health. To do this, a mixture consisting of 60 grams of propylene glycol and 40 grams of distilled water was prepared, which corresponds to a freezing point of −45 to −60 °C (Hans, J.M.J., 2025). The antifreeze was then precisely measured and poured into a special potentiostat cell, after which KI of the required concentration was added.

A metal sample was connected to the working electrode (WE) of the potentiostat, an Ag/AgCl electrode was used as the reference electrode (RE), and a platinum electrode was connected to the auxiliary electrode (CE). The experiment was conducted with the following parameters: Initial potential: 250 mV below the open-circuit potential (OCP); Final potential: 250 mV above OCP; Quiet time: 1800 s; Scan rate: 1 mV/s. A corrosion test was then conducted, and the inhibitory effect of KI on the four different metals at various concentrations was investigated. The test results are presented in Table 1. The Tafel and LPR analysis plots are provided below.

According to the results in Table 1, the effectiveness of the corrosion inhibitor was evaluated for Steel-3, aluminum, copper, and Solder-60 at various concentrations using the Tafel polarization method.

Figure 3. *Tafel polarization curves in antifreeze with a copper corrosion inhibitor additive*



An analysis of the resulting electrochemical parameters (ba, bc, E0, i0, and corrosion rate) showed that the corrosion protection efficiency reaches its highest value at an inhibitor concentration of 1%. At this concentration, the corrosion current density (i0) is reduced to a minimum, which indicates a significant deceleration of both the anodic and cathodic reactions. Furthermore, the sharp decrease in the corrosion rate (mm/year) points to the formation of a protective adsorption layer on the metal surface. The relative positive shift of the corrosion potential (E0) suggests that the inhibitor has anode-suppressing properties. The analysis indicates that optimal adsorption of the inhibitor molecules on the metal surface and maximum formation of the protective layer occur at a concentration of 1%. Therefore, this concentration can be considered optimal for corrosion protection. The requirements specified in GOST 9.202–2025 are listed in Table 2. Consequently, the corrosion inhibitor we have identified meets the requirements of this GOST standard.

Figure 4. *Tafel polarization curves for Steel-3 in antifreeze with the addition of a corrosion inhibitor*

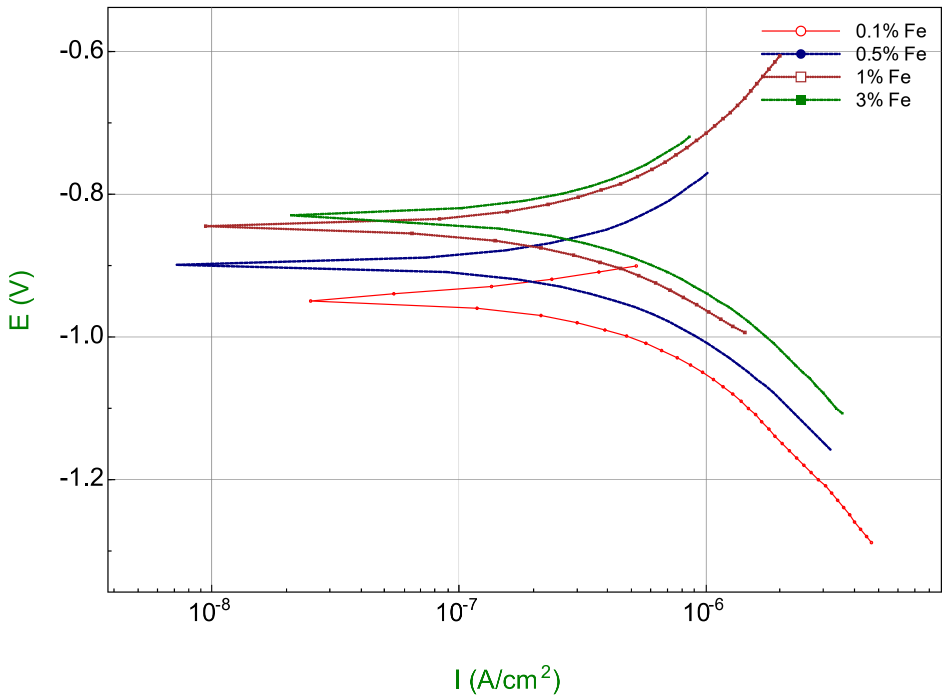
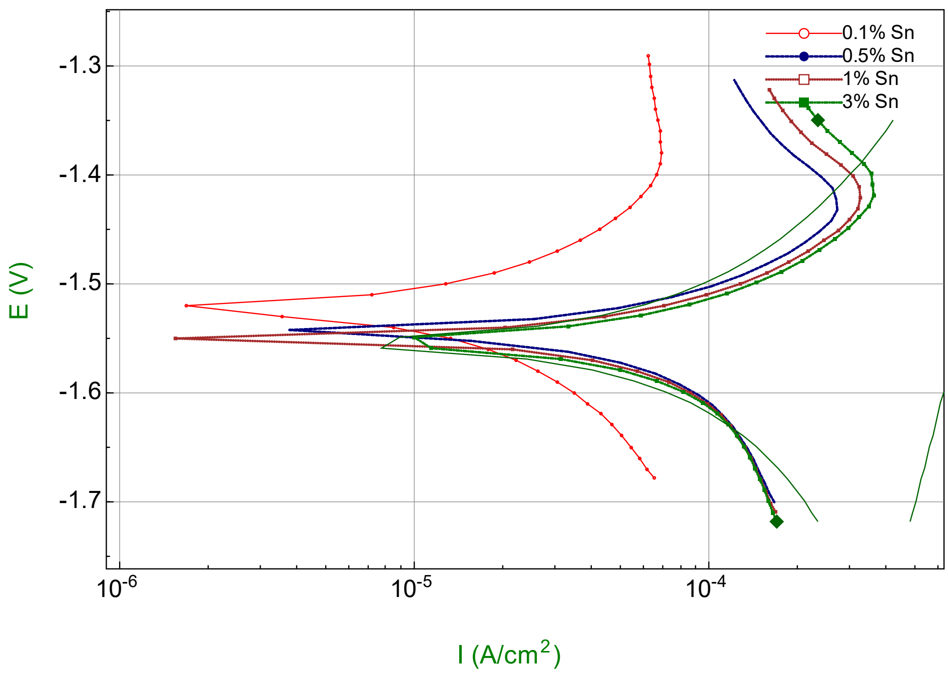


Figure 5. *Tafel polarization curves for antifreeze with the addition of solder-60 corrosion inhibitor*



Results analysis

The thermal properties of the corrosion inhibitor were investigated using a SHIMADZU DTG-60 thermal analyzer, an instrument designed for simultaneous thermogravimetric (TGA) and differential thermal analysis (DTA). During the study of the corrosion inhibitor's thermal characteristics, TGA and DTA were performed concurrently over a temperature range of 29.28–601.68 °C (Fig. 6).

Table 1. *Corrosion test results obtained using a CS-350 apparatus*

Me	IK%	ba (mV/dec)	bc (mV/dec)	i_0 (Amps/cm²)	E_0 (Volts)	Corrosion rate(mm/a)
Al	0.1	1147.5	350.74	1.4393E-07	–1.156	0.0015678
Al	0.5	190.31	82.655	1.1667E-08	–1.1089	0.000127
Al	1	154.45	85	8.0768E-09	8.0768E-09	0.000088
Al	3	183.19	75.735	1.1546E-08	–1.0473	0.0001257
Cu	0.1	841.2	346.6	6.9476E-05	–0.72479	0.081635
Cu	0.5	644.95	328.8	5.0078E-05	–0.67288	0.058842
Cu	1	657.34	373.4	5.5042E-05	–0.64804	0.034675
Cu	3	573.11	477.4	4.5194E-05	–0.61949	0.053103
Fe	0.1	470.64	486.25	9.2606E-07	–0.94724	0.011298
Fe	0.5	548.54	418.1	8.365E-07	–0.89887	0.010206
Fe	1	432.7	351.93	6.245E-07	–0.84685	0.0076192
Fe	3	773.68	475.4	1.0579E-06	–0.83215	0.012907
Sn	0.1	348.38	254.3	1.256E-07	–0.89852	0.047
Sn	0.5	232.54	245.32	5.325E-07	–0.88258	0.045
Sn	1	573.73	541.2	2.253E-06	–0.87225	0.037
Sn	3	448.4	325.1	4.546E-07	–0.89758	0.064

Table 2. *Requirements for the corrosion resistance of metals in accordance with GOST 9.202–2025*

Corrosion rate, mm/year	State
< 0.01	Excellent protection
0.01–0.05	Good / Safe
0.05–0.1	Satisfactory
0.1–0.5	Increased corrosion
< 0.5	dangerous

All samples of the carboxylate inhibitor were thermally analyzed in dynamic mode under an inert argon (Ar) atmosphere. Argon was supplied continuously at a flow rate of 80 ml/min. The samples were heated at a rate of 10 °C/min in an aluminum crucible on a corundum (Al_2O_3) substrate.

Furthermore, the DTA results were used to identify and confirm the endothermic and exothermic effects of the corrosion inhibitor, which allowed for an assessment of its thermal behavior and stability upon heating.

TGA results showed that the carboxylate-based corrosion inhibitor possesses high thermal stability up to 200 °C. In the temperature range of 246–511 °C, a 30.18% mass loss was observed, which is associated with the thermal decomposition of the main organic skeleton. On the DTA curve at 518.56 °C, a strong exothermic effect was recorded, confirming the occurrence of oxidation and molecular destruction processes at this stage. The results obtained indicate that the inhibitor is fully stable in low-temperature antifreeze systems and resistant to high temperatures.

Figure 6. *DTA and TGA analyses of the corrosion inhibitor*

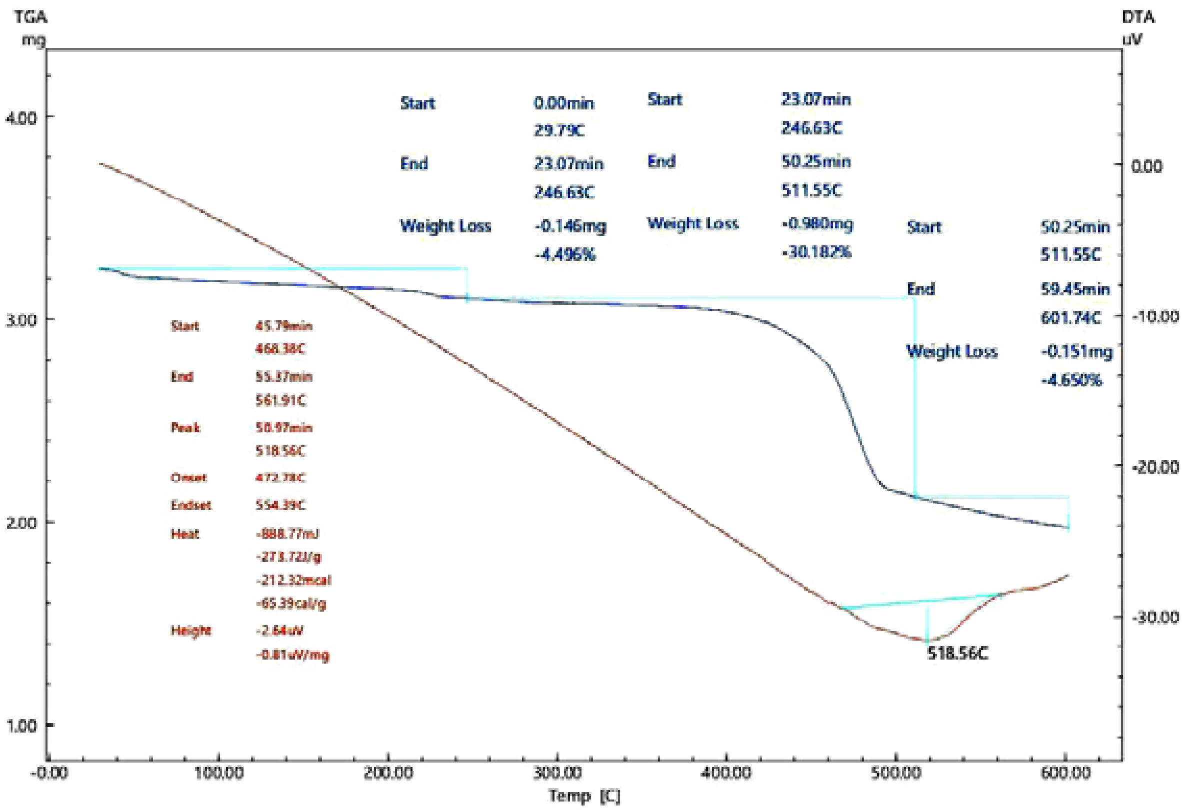


Table 3. *DTA and TGA results*

Temperature (°C)	TGA	DTA	Notes
30–246	Mass loss 4,5%	Weak signal	Moisture release
246–511	A great loss 30%	The peak is high	Basic decomposition
511–601	Additional losses 4,6%	Weak peak	Final oxidation

Conclusion

Based on the study of scientific literature on corrosion inhibitors, the goal was set to investigate the inhibitory properties of adipine acid potassium salt under laboratory conditions. The potassium salt of adipine acid was synthesized in the laboratory. IR, DTA, and TGA spectra were obtained for the synthesized substance. A new generation of antifreeze has been developed that is harmless to the environment and human health. The inhibitory properties of adipine acid potassium salt in an antifreeze medium were studied using a potentiostat. In conclusion, it can be noted that the studied potassium salt of adipine acid can be used as a corrosion inhibitor in new-generation antifreezes.

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