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Study on the Corrosion Inhibition Performance of Gemini Surfactants on Steel in Hydrochloric Acid Solution

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ABSTRACT

This study systematically reviews the research progress on the corrosion inhibition performance of Gemini surfactants on steel in hydrochloric acid solutions. By analyzing benzimidazole derivatives, composite corrosion inhibitors, and the synthesis and performance optimization of Gemini surfactants, their potential in reducing metal corrosion rates, enhancing interfacial stability, and optimizing process conditions is summarized. The findings reveal that Gemini surfactants, due to their unique double-chain structure and spontaneous micellization characteristics, exhibit higher corrosion inhibition efficiency and interfacial activity compared to traditional single-chain surfactants. However, current research still faces challenges such as insufficient mechanistic understanding of corrosion inhibition, lack of systematic theoretical frameworks, and fragmented optimization strategies. Future studies should integrate multidisciplinary approaches to deepen mechanistic investigations and bridge the gap between corrosion inhibitor design and practical industrial applications.

KEYWORDS

Gemini surfactants; hydrochloric acid solution; corrosion inhibition performance; steel corrosion; interfacial stability

1 Introduction

The corrosion of metallic materials in hydrochloric acid solutions severely restricts the service life and safety of industrial equipment, making the development of efficient corrosion inhibitors a core focus in corrosion protection. In recent years, benzimidazole derivatives, composite inhibitors, and Gemini surfactants have emerged as research hotspots due to their excellent corrosion inhibition and interfacial activity. Existing studies indicate that Gemini surfactants significantly reduce critical micelle concentrations and enhance adsorption on metal surfaces through their dual hydrophobic chains and flexible spacer groups, thereby effectively inhibiting corrosion (Wang Xinxin, 2022; Zhu Ruihua, 2017). Nevertheless, current research has notable limitations: (1) insufficient systematic analysis of corrosion inhibition mechanisms, with most studies focusing on performance characterization rather than molecular interactions; (2) weak correlation between interfacial stability and corrosion inhibition, particularly under high-temperature or complex media conditions; and (3) optimization strategies often targeting single factors rather than interdisciplinary integration. Addressing these issues, this review synthesizes recent advances and proposes future directions, emphasizing multiscale mechanistic studies, AI-driven optimization of inhibitor design, and industrial-scale applications of green corrosion inhibitors.

2 Research Status

2.1 Research on Benzimidazole Derivatives and Surfactant Synthesis

Focusing on benzimidazole derivatives synthesis to address carbon steel corrosion in hydrochloric acid solutions. Yuan Shan (2015) synthesized novel benzimidazole derivatives (BDC6T and BDC8T) and evaluated their surface activity and corrosion inhibition in hydrochloric acid. The results showed that their inhibition efficiency increased significantly with concentration and remained stable below 30° C, offering a new approach to reducing metal corrosion and acid consumption[1]. Zhao Bin (2015) developed three composite inhibitors using salicylaldehyde, significantly improving the corrosion inhibition of zinc in hydrochloric acid and mitigating energy waste caused by scaling in galvanized equipment[2].

Focusing on Gemini surfactant synthesis for performance optimization. Wang Xinxin (2022) prepared Gemini quaternary ammonium surfactants (2C_nGeQS) via amidation and quaternization. These surfactants exhibited higher surface activity and spontaneous micellization/adsorption compared to single-chain analogs, enhancing corrosion inhibition[3]. Zhu Ruihua (2017) synthesized carboxylate-type Gemini surfactants (TDDS-n series) with varying hydrophobic tail lengths. These surfactants demonstrated superior micellization thermodynamics, surface activity, and emulsification capabilities, broadening their application potential[4].

Focusing on ion exchange and micellization for waste treatment and interfacial activity. Ouyang Jie (2019) regenerated hydrochloric acid by removing iron ions from pickling waste using ion exchange resins, reducing costs and enabling resource recovery[5]. Zhang Shanshan (2016) studied quaternary ammonium Gemini surfactants, revealing that their critical micelle concentrations and interfacial properties depend on chain length and spacer groups, providing theoretical support for applications in food, medicine, and materials[6].

2.2 Interfacial Stability and Corrosion Inhibition Performance

Focusing on corrosion and hydrolysis behavior in acidic environments. Yue Yingying (2013) investigated the localized corrosion of ferritic stainless steel in hydrochloric acid. Adding oxidizers altered corrosion characteristics, improving uniform corrosion resistance and informing acid-picking process development[7]. Wang Guowei (2012) optimized hydrolysis conditions for 3-butenenitrile, determining key parameters (concentration, temperature, HCl concentration) to enhance 3-butenoic acid synthesis efficiency[8].

Focusing on Gemini surfactants for interfacial emulsification. Wen Zhen (2022) modified Gemini surfactant structures (spacers and chain lengths), enhancing interfacial emulsification and reducing critical micelle concentrations. This eliminated the need for co-surfactants in microemulsions, advancing oil-displacement agent development[9]. Wang Hui (2021) synthesized Gemini ionic liquid surfactants via microwave-assisted methods, optimizing process conditions to improve interfacial tension and emulsification performance[10].

Focusing on corrosion behavior and novel eco-friendly processes. Wu Xiaoyan (2014) optimized redox potential and ion concentrations in sulfuric-hydrochloric acid mixtures, controlling corrosion/passivation behavior of stainless steel. This led to an environmentally friendly acid-picking process with improved surface quality [11]. Fan Ruibin (2014) demonstrated that tris-triazine dithiol compounds effectively inhibit aluminum alloy corrosion in hydrochloric acid by reducing corrosion current density, offering a green inhibitor alternative[12].

2.3 Metal Corrosion and Corrosion Inhibition Optimization

Focusing on alloy corrosion resistance and inhibitor interactions. Meng Kang (2019) enhanced TA31 alloy corrosion resistance in hydrochloric acid via cold deformation and heat treatment, expanding its industrial applicability [13]. Zheng Sisi (2016) studied the electrochemical behavior of copper in acidic solutions, showing that domperidone inhibitors effectively passivated copper surfaces, mitigating chloride- and hydrogen-induced corrosion [14].

Focusing on green inhibitors and high-temperature performance. Wang Jing (2022) synthesized nitrogen-doped carbon nanoparticles (N-CNPs), significantly improving corrosion inhibition for carbon steel in hydrochloric acid via enhanced adsorption [15]. Yang Xue (2019) identified natural plant extracts (e.g., soybean extracts) as effective inhibitors for A3 steel, forming protective coordination bonds with iron ions [16]. Li Wentao (2021) synthesized diphenylethanone imidazoline quaternary salts, achieving high inhibition efficiency for Q235 steel in HCl through optimized adsorption mechanisms [17]. Hu Huihui (2021) enhanced high-temperature inhibition efficiency of aniline Schiff base inhibitors by halogen substitution, benefiting deep-well oilfield applications [18].

3 Critical Review

Significant progress has been made in the synthesis of benzimidazole derivatives and surfactants, the interfacial stability and corrosion inhibition properties of materials, and the optimization of metal corrosion and corrosion inhibition properties. At the synthetic level, the corrosion inhibition performance of new benzimidazole derivatives and composite corrosion inhibitors provides a new way for metal corrosion protection. In terms of material interfacial stability, the preparation of Gemini surfactants and the improvement of their interfacial properties provide a theoretical basis for the development of oil displacement agents. In terms of optimization of metal corrosion and corrosion inhibition, the research on the corrosion inhibition performance of new corrosion inhibitors in acidic media and high temperature conditions provides a new idea for corrosion protection, but there are still problems to be solved:

3.1 Existing Issues

3.1.1 Lack of Systematic Theoretical Frameworks

There are significant deficiencies in the construction of theoretical frameworks in current research, and most of the studies lack systematization and fail to form a unified theoretical system. Researchers are often confined to a single perspective and fail to fully consider the cross-integration of different disciplines, resulting in a lack of depth and breadth in theoretical analysis. In addition, in the process of constructing the theoretical framework, the integration and refinement of existing research results are insufficient, and a forward-looking theoretical model cannot be formed, which restricts the further development of research.

3.1.2 Limitations in Empirical Methods

Although empirical research methods have been widely used in current research, there are many limitations. On the one hand, there are biases in sample selection and data analysis methods, which may lead to less reliable research results. On the other hand, study designs are often too simplistic to fully reflect the real situation of the research subjects. In addition, the application of empirical research methods lacks innovation and fails to make full use of emerging technologies, such as big data analysis and artificial intelligence, which limits the diversity and effectiveness of research methods.

3.1.3 Low Knowledge Conversion Efficiency

The inefficiency of knowledge transfer is another major shortcoming in the current research field. The conversion rate of research results in practical application is low, and its social and economic benefits cannot be fully utilized. On the one hand, there is a disconnect between the research results and the actual needs, which leads to many obstacles in the transformation process. On the other hand, there is a lack of effective incentive mechanism in the process of knowledge transformation, which leads to the low enthusiasm of researchers for the transformation work. In addition, the lack of communication and collaboration in the process of knowledge transformation also affects the improvement of transformation efficiency.

3.2 Research Gaps

3.2.1 Insufficient Mechanistic Studies

Although significant progress has been made in the application of benzimidazole derivatives and surfactants in the field of corrosion inhibition in recent years, the systematic research on the corrosion inhibition mechanism is still insufficient. Current research tends to focus on the observation and evaluation of the effect of corrosion inhibition, and there is relatively little in-depth exploration of its mechanism of action. For example, although some new benzimidazole derivatives have been shown to have excellent corrosion inhibition effects in hydrochloric acid solution, their corrosion inhibition mechanism has not been systematically eluciated. In addition, there is a lack of detailed analysis of the specific mechanism of action of Gemini surfactants in the corrosion inhibition process, which limits the further optimization of corrosion inhibitor design and the development of new corrosion inhibitors.

3.2.2 Inadequate Interfacial Stability Analysis

Interfacial stability is a critical factor in maintaining the structural integrity and functionality of a material during corrosion. However, the current research on the interfacial stability of materials is still insufficient. For example, when discussing corrosion and hydrolysis behavior, although some studies point out the influence of oxidant and process condition optimization on material stability, the in-depth analysis of its interfacial structure change and stability mechanism still needs to be strengthened. In particular, although the research on the interfacial emulsification properties of Gemini surfactants has found that they have excellent interfacial properties, the in-depth analysis of their mechanism is insufficient, and it is difficult to guide their application in the field of oil displacement agents.

3.2.3 Fragmented Optimization Strategies

Although some achievements have been made in the research on the optimization of metal corrosion and corrosion inhibition, the improvement and integration of optimization strategies are still in the initial stage. Most of the existing studies focus on the influence of a single factor on corrosion inhibition performance, but lack the systematic research and integration of different optimization strategies. For example, in the study of alloy corrosion resistance and corrosion inhibitors, although it has been found that cold deformation and heat treatment can improve the corrosion resistance of alloys, how to combine these optimization strategies with corrosion inhibitors to form a more effective corrosion protection system needs to be further studied. In addition, the synthesis and screening strategies of new corrosion inhibitors need to be further optimized to achieve high efficiency and economy in practical applications for the corrosion inhibition performance of new corrosion inhibitors under acidic media and high temperature conditions.

4 Conclusion

Research on Gemini surfactants in hydrochloric acid has demonstrated their potential for steel corrosion inhibition. Their dual-chain structure and spontaneous adsorption significantly reduce corrosion current density. However, gaps in theoretical frameworks, mechanistic understanding, and optimization strategies impede industrial adoption. Future work should combine experimental and computational methods to elucidate dynamic interfacial mechanisms, integrate multidisciplinary approaches for complex environments, and promote sustainable practices such as green inhibitor production and waste recycling.

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