**Potential Applications of Ferrate (VI) Solution in the Steel Industry: A Sustainable Approach**

**Abstract**

The steel industry is one of the most water-intensive industrial sectors, requiring large volumes for cooling, gas scrubbing, and descaling. Water treatment and recycling are crucial for sustainability, and ferrate (VI) (FeO₄²⁻) has emerged as a promising green chemical for various applications, including oxidation, disinfection, coagulation, and the removal of heavy metals. This paper explores the potential uses of ferrate (VI) in the steel industry. The study concludes that ferrate (VI) can significantly improve water recycling, reduce chemical consumption, and support greener steel production.

**Keywords**: Ferrate (VI), steel industry, water treatment, heavy metal removal, cyanide removal, corrosion control, sustainability

**1. Introduction**

The steel industry consumes vast amounts of water, with an estimated 10-30 m³ of water required per ton of steel produced [1]. Efficient water treatment and recycling are essential to minimize environmental impact. Ferrate (VI), a powerful oxidant with multifunctional properties (oxidation, coagulation, disinfection), offers a sustainable alternative to conventional chemicals like chlorine and ferric salts.

Ferrate (VI) (FeO₄²⁻) is a highly oxidizing iron species in the +6 oxidation state, available as potassium ferrate (K₂FeO₄) or sodium ferrate (Na₂FeO₄). Its key properties include:

* High Oxidation Potential:
  + Acidic medium: E° = +2.20 V (stronger than ozone and chlorine)
  + Alkaline medium: E° = +0.72 V (still effective for most pollutants) [2].
* Multifunctionality:
  + Oxidation: Degrades organics (e.g., phenols, cyanides).
  + Coagulation: Decomposes to Fe(III), forming Fe(OH)₃ flocs that remove suspended solids.
  + Disinfection: Inactivates bacteria, viruses, and biofilms [3].
* Eco-Friendly Byproducts:
  + Unlike chlorine, ferrate does not produce toxic disinfection byproducts (DBPs).
  + Final product (Fe(III)) is non-toxic and can aid in phosphate removal.

Table 1: Comparison of Oxidants Used in Water Treatment

| **Oxidant** | **Oxidation Potential (V)** | **Byproducts** | **Environmental Impact** |
| --- | --- | --- | --- |
| Ferrate (VI) | 2.20 (acidic) | Fe(III), O₂ | Low toxicity |
| Ozone (O₃) | 2.07 | Bromate (if Br⁻ present) | Moderate |
| Chlorine (Cl₂) | 1.36 | THMs, HAAs | High (carcinogenic) |
| Hydrogen Peroxide | 1.78 | H₂O, O₂ | Low |

**2. Previous Studies on Industrial Applications of Ferrate (VI)**

Ferrate (VI) has been extensively studied for various industrial applications, particularly in water treatment and pollution control. In the steel industry, its multifunctional properties make it a promising alternative to conventional treatment methods. Research has demonstrated its effectiveness in cooling water systems, wastewater treatment from pickling and descaling processes, cyanide removal in coke oven gas scrubbing, and corrosion inhibition.

**Water Treatment in Steel Plants**

Cooling water systems in steel plants face significant challenges from scaling, biofouling, and microbial growth. Traditional biocides such as chlorine are effective but contribute to the formation of harmful disinfection byproducts (DBPs) and microbial resistance. Studies by Alshahri et al. [4] have shown that ferrate (VI) not only controls scaling caused by calcium carbonate and silica but also effectively mitigates biofouling. Its strong oxidative properties disrupt microbial cell membranes, reducing biofilm formation without promoting resistance. Compared to conventional treatments, ferrate (VI) offers a more sustainable solution by minimizing chemical usage and eliminating toxic byproducts.

Wastewater generated from pickling and descaling processes contains high concentrations of heavy metals, oils, and organic contaminants. Wei et al. [5] investigated the use of ferrate (VI) for treating spent steel pickling liquid and reported over 80% reduction in chemical oxygen demand (COD) alongside efficient removal of heavy metals such as chromium, nickel, and zinc. The mechanism involves oxidation of organic pollutants followed by coagulation with ferric hydroxide (Fe(OH)₃), which also enhances the removal of suspended solids. This dual functionality reduces the need for additional coagulants, simplifying treatment processes and lowering operational costs.

**Cyanide Removal in Coke Oven Gas**

Coke oven gas contains high levels of cyanide, which poses serious environmental and health risks. Traditional cyanide removal methods, such as chlorination, generate toxic intermediates like cyanogen chloride (CNCl). Ferrate (VI) provides a safer alternative by oxidizing cyanide (CN⁻) to cyanate (OCN⁻), a compound that is approximately 1,000 times less toxic. It is demonstrated that ferrate (VI) achieves over 99% cyanide removal at alkaline pH (9–11), which aligns with the typical conditions of coke oven gas scrubbers [6].

**Corrosion and Microbial Corrosion Inhibition**

Steel infrastructure in water-cooling systems is highly susceptible to corrosion and microbiologically influenced corrosion (MIC), particularly from sulfate-reducing bacteria (SRB). Ferrate (VI) not only forms a protective passive layer of iron oxides (Fe₂O₃/Fe₃O₄) on steel surfaces but also exhibits strong biocidal activity against SRB.

**Comparative Advantages Over Conventional Methods**

The growing body of research underscores the advantages of ferrate (VI) over traditional treatment chemicals. Unlike chlorine, ferrate (VI) does not produce regulated DBPs such as trihalomethanes (THMs) or haloacetic acids (HAAs). Its coagulation properties eliminate the need for additional flocculants, reducing sludge volume and disposal costs. Moreover, its rapid decomposition into non-toxic iron (III) species ensures minimal environmental impact. These benefits position ferrate (VI) as a key enabler for sustainable water management in the steel industry, aligning with global trends toward greener manufacturing practices.

**3. Potential Applications in the Steel Industry**

| **Application** | **Mechanism/Function** | **Advantages Over Conventional Methods** | **Challenges** |
| --- | --- | --- | --- |
| **1. Cooling Water Treatment** | - Oxidizes organics/biofilms. - Coagulates suspended solids (Fe(OH)₃). - Disinfects microbes. | - No toxic DBPs (vs. chlorine). - Single-step treatment (vs. coagulant + biocide). - Reduces scaling. | - Short half-life in water. - Requires pH control (optimal: 7–9). |
| **2. RO Pretreatment** | - Oxidizes oils/organics. - Removes silica/colloids via coagulation. - Prevents biofouling. | - Eliminates need for activated carbon. - Reduces antiscalant use. - Extends membrane lifespan. | - High dose may foul membranes. - Real-time monitoring needed. |
| **3. Cyanide Removal (Coke Oven Gas)** | - Oxidizes CN⁻ to OCN⁻. - Works at pH 9–12. | - No CNCl formation (vs. chlorination). - Faster reaction kinetics. | - Alkaline pH required. - Competes with ozone on cost. |
| **4. Heavy Metal Removal** | - Co-precipitates Zn/Cd/Fe as hydroxides. | - Single-step removal (vs. reduction + coagulation). - No secondary sludge. | - Efficiency drops at high salinity. - Fe(III) sludge disposal. |
| **5. Corrosion & Microbial Control** | - Forms passive Fe₂O₃ layer. - Kills SRB via oxidation. | - Non-toxic (vs. chromate inhibitors). - Dual action (corrosion + biofilm control). | - Requires continuous dosing. - Limited data in high-Cl⁻ waters. |
| **6. Gas Scrubbing (SO₂/NOx)** | - Oxidizes SO₂ to SO₄²⁻. - Converts NO to NO₃⁻. | - No scrubber clogging (vs. lime slurry). - Works at ambient temperature. | - Lower NOx efficiency vs. SCR. - Cost-prohibitive at scale. |

**4. Sustainability and Economic Benefits**

The adoption of ferrate (VI) in steel manufacturing offers significant sustainability and economic advantages over conventional water treatment methods. These benefits align with global efforts to reduce environmental impact while improving operational efficiency.

**Environmental Benefits**

Ferrate (VI) serves as a green alternative to traditional chemicals by eliminating toxic byproducts and reducing the carbon footprint of water treatment processes. Unlike chlorine-based disinfectants, ferrate (VI) does not produce regulated disinfection byproducts (DBPs) such as trihalomethanes (THMs) or haloacetic acids (HAAs), which are carcinogenic and strictly monitored under environmental regulations. The decomposition of ferrate (VI) yields non-toxic iron (III) oxides, which can be repurposed as coagulants or removed through standard filtration, minimizing hazardous waste generation. Additionally, its ability to treat multiple contaminants (organics, heavy metals, and pathogens) in a single step reduces the need for additional chemicals, lowering the overall chemical load discharged into the environment.

Water scarcity is a critical issue in steel production, where large volumes are required for cooling, descaling, and gas scrubbing. Ferrate (VI) enhances water recycling efficiency by enabling high-quality effluent suitable for reuse. Studies have demonstrated that ferrate-treated wastewater can achieve >90% removal of suspended solids, heavy metals, and organic pollutants, meeting stringent discharge standards. This capability supports closed-loop water systems, reducing freshwater intake and minimizing wastewater discharge.

**Economic Advantages**

While the upfront cost of ferrate (VI) is higher than conventional chemicals such as chlorine or ferric sulfate, its multifunctionality leads to long-term cost savings. By integrating oxidation, coagulation, and disinfection into a single treatment step, steel plants can reduce the number of chemicals needed, simplify dosing systems, and lower storage and handling costs. For example, a plant using ferrate (VI) for cooling water treatment can eliminate separate biocides and antiscalants, reducing chemical procurement expenses by 30–40%.

Operational savings are also realized through reduced sludge production. Traditional coagulation methods generate large volumes of chemical sludge, which requires costly dewatering and disposal. Ferrate (VI) produces denser, more compact iron (III) hydroxide sludge, decreasing disposal volumes by up to 50%.

Energy efficiency is another economic benefit. Ferrate (VI) operates effectively at ambient temperatures, unlike thermal-based treatments such as steam stripping for volatile organic compound (VOC) removal. Gas scrubbing systems using ferrate (VI) for SO₂ and NOx removal require less energy compared to conventional lime slurry scrubbing, which involves high pumping and mixing costs.

**Regulatory and Corporate Sustainability Goals**

The steel industry faces increasing pressure to meet stringent environmental regulations and corporate sustainability targets. Ferrate (VI) supports compliance with regulations such as the EU Industrial Emissions Directive (IED) and the U.S. Clean Water Act by providing a treatment solution that minimizes toxic discharges. Its non-toxic profile also aligns with green chemistry principles, enhancing corporate sustainability reporting and ESG (Environmental, Social, and Governance) ratings.

**Future Cost Projections**

The current high cost of ferrate (VI) is expected to decrease as advancements in production technology and scalability continue. Researchers are optimizing electrochemical synthesis methods to reduce energy inputs, while commercial suppliers are exploring bulk production to drive down prices. Ferr-Tech, a Dutch company, is at the forefront of producing ferrate (VI) solution under the trademark FerSol. The company has achieved significant milestones by enhancing the stability of the ferrate solution and lowering production costs. Projections suggest that ferrate (VI) could reach cost parity with conventional oxidants in the coming years, making it economically viable for widespread use.

**5. Conclusion**

Ferrate (VI) emerges as a transformative solution for the steel industry, offering a sustainable and efficient alternative to conventional water treatment methods. Its multifunctional capabilities—combining oxidation, coagulation, and disinfection—address critical challenges such as heavy metal removal, cyanide degradation, corrosion control, and gas scrubbing, while significantly reducing chemical consumption and toxic byproducts. The environmental benefits, including lower sludge production and enhanced water recyclability, align with global sustainability goals and regulatory requirements. Although current costs and stability issues pose challenges, ongoing advancements in production technology and large-scale implementation are expected to make ferrate (VI) economically viable in the near future. By adopting ferrate (VI), the steel industry can achieve greener operations, improved compliance, and long-term cost savings, paving the way for a more sustainable industrial future. Continued research and pilot projects will be essential to optimize its application and accelerate widespread adoption across the sector.

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