Reusable Extractant and Direct Catalytic Mediation of Water/Oil/Chlorodifluoromethane Nano-Emulsion in Natural Gas Condensate for Efficient Conversion of Chloride Impurities Into the Dicopper Chloride Trihydroxide Nanoparticles

Zohre Banan Khorshid and Mohammad Mahdi Doroodmand*

Department of Chemistry, College of Sciences, Shiraz University, Shiraz, Iran

This research introduces an oil-in-water (O/W) nano-emulsion (oil-water-CHClF₂) as the reusable extractant phase using liquid–liquid extraction methodology for the removal efficiency of Cl⁻ and Hg(0) [between 90% and ~100%, deepening on the nature of the natural gas condensate (NGC)] at a brief separation time (<3.0 min). The achieved safety of the NGC using this nano-emulsion results in efficient reduction in the corrosion rate during testing iron-based fragments (vs. the untreated ones as controls) and increase in the NGC economic value. Another advantage of the synthesized nano-emulsion is its capability and catalytic mediating behavior to efficiently separate and synthesize highly pure dicopper chloride trihydroxide nanoparticles. The synthesized nanoparticles were characterized by different analytical methods such as Fourier transform infrared spectrometry, X-ray diffraction, X-ray photoelectron spectrometry, and direct visualization by some electron microscopies. Direct synthesis, fast synthetic time (<3.0 min), high purity (>99%), and scalability are the main advantages of this synthetic method. This nanoparticle is not only safe but also is efficiently applicable in different industries, especially as an eco-friendly agricultural pesticide for different plants and trees such as pistachio. Consequently, this method is accepted as direct, simple, low-cost, and scalable conversion of some upstream industries with the downstream ones. All these possibilities are attributed to the intermediate transport properties of the introduced O/W nano-emulsion. At this condition, this reagent plays role as a recycled motor for the NGC purification and conversion of these impurities into the safe and usable products. To the best of knowledge, this research is considered as the first report that shows application of this O/W medium for both chloride and mercury removal from the NGC and its direct use as top element in the synthesis of eco-friendly nanoparticles. This system is applicable in some parts of the fuel and oil centers of the “Middle East.”

Keywords: natural gas condensate, mercury and chloride impurities, nano-emulsion, dicopper chloride trihydroxide, catalytic mediator, agricultural pesticide
INTRODUCTION

Natural gas condensates (NGCs) often involve serious impurities such as chloride ion (Cl$^-$), hydrogen sulfide (H$_2$S), mercaptans (R-SH), mercury element (Hg(0)), and inorganic salts. These impurities are often attributed to the neighborhood of the NGCs to the geological contexts (Sabbaghi et al., 2012). However, in the NGCs, some pollutions, especially Cl$^−$ and Hg(0), are so high that they can even be detected via direct visualizing their intensive colorimetric turbidity in some parts of the fuel and oil centers, especially in the "Middle East" (Pierce et al., 2007; Sabbaghi et al., 2012; Hou et al., 2013; Wu et al., 2013; Lavela et al., 2015; Sun et al., 2019).

In fact, the Cl$^-$, as one of the most aggressive ionic species, can seriously cause inadequate flammability and pitting corrosion (Ergun and Turan, 1991); this issue would consequently produce failure of the oil/gas production lines and the transportation equipment (Jiang et al., 2013). The importance of this problem is more serious when some different metal-chloride complexes are formed that play significant role as catalytic poisoning (Argyle and Bartholomew, 2015). Besides, elemental mercury (Hg(0)), even at its trace levels (Bingham, 1990), has also corrosive property that extremely damages some piping equipment, especially the aluminum heat exchangers (Wilhelm, 2009). Moreover, Hg(0) extremely provides health problems for the industrial workers (Wilhelm and Bloom, 2000). All these problems reveal strong demand for purification (removal) of the NGC from these serious impurities.

Although different methodologies have been proposed for the Cl$^-$ removal from various real samples (Pierce et al., 2007; Sabbaghi et al., 2012; Hou et al., 2013; Wu et al., 2013; Lavela et al., 2015; Sun et al., 2019), but (to the best of knowledge) these methods have not been suitable, especially because of altered problems such as sophisticated matrix and irreversible fouling effect(s) of the NGC. On the other hand, other systems such as sorbent-based mercuric filters (Yan, 1987; Yang et al., 2007; Abai et al., 2015; Liu et al., 2020) have frequently high cost, small efficiency, and often need high temperature. Hence, current study introduces a nano-emulsion as extractant phase (extraction solvent) for efficient and simultaneous removal of the Cl$^-$ and Hg(0) using liquid–liquid extraction (LLE) methodology. In addition, the nano-emulsion’s catalytic mediation results in the conversion of the extracted Cl$^-$ to the dicopper chloride trihydroxide (Cu$_2$(OH)$_3$Cl$_{0.5}$) nanoparticles (Jackson and Fulton, 1996; Scott, 2000; Lubej et al., 2004; Luo et al., 2005; Lu et al., 2010) with eco-friendly agricultural pesticide applications.

Briefly, dicopper chloride trihydroxide is considered as an appropriate compound that is useful as an effective pesticide for various plants and trees, especially pistachio (Brühl et al., 2021). The general synthetic process of this compound is often based on the reaction between copper salts and chloride compounds at the basic condition (Jackson and Fulton, 1996; Lubej et al., 2004). However, the efficiency of the formation of this compound is seriously limited due to some different side reactions. The attribution of these reactions leads to the formation of some impurities such as Cu(OH)$_2$ and CuCl$_2$, besides some various coordination compounds such as CuCl$_3^-$ and CuCl$_2^{2-}$ (Scott, 2000; Hussain et al., 2019; FAO/WHO, 2021). These producers are often generated on the basis of different mechanisms such as coprecipitation and crystal-based complex formation.

Besides the abovementioned problems, the lack control on other factors like size distribution and the morphology is also other problems, owing to the harness of the relative supper saturation and the absence of any suitable template and capping agents (Luo et al., 2005; Lu et al., 2010; Chen and Zhong, 2022; Pathania et al., 2022). Fortunately, the introduced oil-in-water (O/W) emulsion plays significant roles as almost all of the abovementioned reagents for reaching to pure, size-controllable, and high-efficient pesticide. Therefore, the novelty of this study is brief: Not only is the Cl$^-$ and Hg(0) removal from the NGC but also is accessing an important and applicable compound. To the best of knowledge, no applicable methodology has been introduced for solving the current problem, especially at the industrial scale.

EXPERIMENTAL

Materials

The necessity reagents related to the nano-emulsion syntheses have been from Merck Company; their information and the NGC sample data were given in Supplementary Material S2.1. How to prepare this nano-emulsion as an O/W medium was presented in detail in Supplementary Material S2.2. Stable homogeneity (Chen and Zhong, 2022; Pathania et al., 2022) of the synthesized O/W nano-emulsion was confirmed for a long time (up to 24 h), which could be re-homogenized simply via vigorously shaking for a few seconds (maximum 10 s).

Nano-Emulsion Preparation (Standard Extracting Medium)

The HCFC-22 (R$_{22}$)-treated oil was prepared using descriptions methodology in the previous study (Mohammadi et al., 2016; Banan Khorshid et al., 2021). Briefly, the stock nano-emulsion medium with oil concentration of 20.80 g L$^{-1}$, as the extracting medium, was simply prepared by weighting 1,040.0 mg of this oil sample. Then, it was mixed with the triply distilled water (20.0 ml) during stirring using a magnet stirrer for a few minutes (3.0 min) at 400 ± 2 rpm using a hotplate stirrer (RT$_{2}$, Denville Scientific Inc., American Cleanstat, LLC, Phenix Research Products Inc., Candler, NC, USA). In this synthetic process, the stability of the R$_{22}$-treated oil for a long time. The results exhibited no significant desorption of the R$_{22}$ from the oil matrix. This practically revealed no toxicity of the R$_{22}$-treated oil using this procedure.

The R$_{22}$ was then purged with flow rate of 5.00 ± 0.01 ml min$^{-1}$ for 10.0 min using a mass flow controller (MFC, Bronkhorst high-tech. B.V., England). After that, it was transferred into a 50.0-ml glass volumetric flask (Thermo Scientific™ Nalgene™ Class B Polypropylene Copolymer Volumetric Flasks with Closure) and diluted to the mark using the triply distilled water. Then, it was vigorously
shaken for about 1 min to form the homogenous nano-emulsion. The synthesized nano-emulsion was visualized using a fluorescence optical microscope (Olympus IX70, UK). Daily dilution of the stock nano-emulsion was achieved via sampling a fixed volume of the stock solution using an “Eppendorf” pipette (Eppendorf Research Plus Pipettes; Sigma-Aldrich) and transferring into a glass volumetric flask. Afterward, it was stirred for 1 min and sonicated in a sonication bath (Ultrasonic cleaner, 400 W, 9.5 L, 40 kHz, C250X, MEGA Lab, UK) for 30.0 s at room temperature. Finally, it was diluted to the mark using the triply distilled water. As is expected, direct imaging the nano-emulsion, multiple circular phases revealed the existence of plenty of efficient interfaces for direct interaction with the NGC sample during simultaneous Cl\(^{-}\) and the Hg(0) removal purpose.

It also should be noted that the concentration of the nano-emulsion was expressed in grams per liter. This was because of 1) better dealing with the \(\text{R}_{22}\) gas, 2) dependency of the concentration to the temperature, and 3) the lack of knowledge about the precise gram formula weights of each oil and the NGC. Consequently, it was impossible to introduce the composite of the synthesized nano-emulsion based on mole fraction. Therefore, in this experiment, it was decided to focus on some general terms such as flow rate, volume, and purging time for the reproducible synthesis of the nano-emulsions. Nevertheless, about other reagents such as Ag\(^{+}\) and Cu\(^{2+}\) solutions, the concentrations were reported based on moles per liter to have better comparison and interpretation during the optimization process.

**Liquid–Liquid Extraction**

Complete detail of the LLE method is given in Supplementary Material S2.3.

**Analysis Process**

Experimental detail about the semi-quantitative test for the Cl\(^{-}\) detection via silver chloride (AgCl) particles formation has been reported in Supplementary Material S2.4. In addition, the corrosion test was evaluated via following the weight loss and direct visualization of the corrosion of some iron fragments during contacting with the treated and untreated NGCs, under similar conditions, by scanning electron microscopy (SEM) as shown in Supplementary Material S2.5. Besides, quantitative tests for the Hg(0) determination based on standard addition and external calibration methods using ion-exchange chromatography (IEC) and cold vapor–atomic absorption spectrometry (CV-AAS) were shown in Supplementary Material S2.6.

**Formation of Dicopper Chloride Trihydroxide Nanoparticles**

Along the accomplishing the extraction step, Cu\(_2\)(OH)\(_4\)Cl\(_4\) nanoparticles were generated based on the catalytic mediation of the nano-emulsion using the Cu\(^{2+}\) solution as both the de-emulsifier and the responsible reagent according to the recommended procedure (see Supplementary Material S2.7). In particular, the term “Catalytic Mediation” is a famous phrase that can be looked up in different reported articles (D’Acunzo and Galli, 2003; D’Alfonso et al., 2014). In this research, the synthesized nano-emulsion was therefore applied to the system to finalize the precipitation process and removal of insoluble particles with maximum removal efficiency.

**RESULTS AND DISCUSSION**

**Evidence About the Morphology of the Synthetized Nano-Emulsion**

In the synthesized nano-emulsions, often, these compounds are evaluated indirectly via following their chemical stability. In this nano-emulsion, because of its Brownian motion, besides its thermal stability, often, it is impossible to directly observe them even by cryo–transmission electron microscopy (TEM) imaging. Hence, in the synthesized nano-emulsion, the characterization was limited only to the evaluation of its mechanical stability for a long time, for instance, 24 h, which could be re-homogenized simply via vigorously shaking for a few seconds (maximum 10 s). This characterization was considered as appropriate and acceptable methodology for selection of the term “Nano-Emulsion” about this system (Chen and Zhong, 2022; Pathania et al., 2022).

**Chloride and Mercury Removal From the NGC**

The Cl\(^{-}\) and Hg(0) impurities removal process from sophisticated organic phases such as NGC and their determining methodology have regarded with different problems (see Supplementary Material S3.1). These challenges therefore encouraged us to focus on the LLE as a simple method. This process was also along with adopting direct observing (visualization) probe for semi-quantitative tracing the optimization steps during introduction of the synthetic nano-emulsion. Formation of inorganic particles therefore revealed the presence of the Cl\(^{-}\) as corrosive impurity into the NGC samples. During the optimization process (see Supplementary Materials S3.2 and S3.3), maximum insoluble inorganic particles (colloids) were observed, when using the Ag\(^{+}\) solution, compared to other cationic species (Table 1, see also Supporting Information, Supplementary Figure S1), with optimum concentration as large as 0.2350 mol L\(^{-1}\) (see Supporting Information, Supplementary Material S3.3).

On the basis of the results (Table 1), only the nano-emulsion, containing the Cu\(^{2+}\), had good effect on the Cl\(^{-}\) removal from the NGC matrix. Whereas, in other cations problems, such as 1) nano size of the generated particles, 2) necessity to introduce excess amounts of cation, 3) long extraction time, 4) hard conditions (such as necessity of the suspension to a shaker for long time, 5) high cost, and/or 6) template effects of the nano-emulsion, extremely limited the extraction process. To select the Cu\(^{2+}\) solution, its nitrate salt was considered as the best reagent because of its pitting corrosion inhibition property (Ergun and Turan, 1991). On the basis of the analysis, this process therefore led to efficiently removal of both Cl\(^{-}\) and Hg(0) from the NGC matrix. As conclusion, for the efficient extraction and effective
mass transfer of the Cl\(^-\) from the NGC samples to the aqueous phase through using the nano-emulsion, Cu\(^{2+}\) played role as both extracting and de-emulsifying agents.

**Optimization Process**

Detailed study about the optimization of effective factors by on one-factor-at-a-time method such as Cu\(^{2+}\) concentration, oil volume, and effect(s) of acidity/basicity condition (pH value) was reported quantitatively in Table 2 and evaluated by photographic imaging (see Supplementary Materials S3.4–S3.6 and Supplementary Figures S3 and S4).

On the basis of the results (Table 2), concatenation of Cu\(^{2+}\) was strongly dependent on the oil concentration. In another word, optimum concentration of oil simply led to decrease the amount of Cu\(^{2+}\) that was needed for playing role as both complex forming and de-emulsifying agent. This condition not only did not provide major change(s) in the matrix of the NGC sample during the extraction process but also majorly reduced the probable side effect of residual Cu\(^{2+}\) medium, possibly present inside the NGC after applying the extraction process. Therefore, it was needed to have full confidence about the optimum Cu\(^{2+}\) concentration in the presence of a fixed amount of oil solution using another independent analysis such as direct visualization of the AgCl particles formations (Hong et al., 2006) inside the NGC after introducing different amounts of Cu\(^{2+}\).

For this purpose, six nano-emulsion samples were prepared with the same oil concentration (oil, 10,400.0 \(\mu\)g ml\(^{-1}\); which was optimized in the previous section) in the presence of different Cu\(^{2+}\) concentrations (lower concentrations): 1.3 \(\times\) 10\(^{-3}\), 9.9 \(\times\) 10\(^{-3}\), 6.6 \(\times\) 10\(^{-3}\), 3.3 \(\times\) 10\(^{-3}\), 2.0 \(\times\) 10\(^{-3}\), and 1.0 \(\times\) 10\(^{-3}\) mol L\(^{-1}\) (apparent concentration). After performing the extraction process between 5.0 ml of NGC and the same volume (apparent concentration), after extraction, the concentration of Hg(0) from the NGC phase to the aqueous one was followed during applying the de-emulsification process. At this condition, change in the oxidation number of the mercuric species from zero to the Hg\(^{2+}\) and/or Hg\(^{2+}\) using oxidants like (for instance H\(_2\)O\(_2\)) could seriously limit the toxicity and danger of mercury inside the receiving aqueous solution.

**Effect of Temperature on the Extraction Process**

Clearly, besides the thermodynamic equilibrium constant, the kinetics of the reactions strongly depends on the temperature of the reactions. However, in a flammable and volatile sample such as NGC, high temperature was not so safe for the laboratory experiments. Therefore, for more safety and for more simplicity, it was recommended to operate the removal process at room temperature. Providentially, the chloride removal efficiency in this study was so high that small fluctuation in the temperature seemed to have no significant effect(s) on the chloride removal efficiency of the NGC samples.

**Figures of Merit**

The CV-AAS method was utilized to determine the concentration of Hg(0) the same as 231 ± 15 ng ml\(^{-1}\) \((n = 3)\) in the raw NGC. This result pointed to the serious effect(s) of Hg(0) in the condensate. Hence, after treating the NGC with the nano-emulsion at the optimum condition, extraction (mass transfer) of the Hg(0) from the NGC phase to the aqueous one was followed during applying the de-emulsification process. At this condition, change in the oxidation number of the mercuric species from zero to the Hg\(^{2+}\) and/or Hg\(^{2+}\) using oxidants like (for instance H\(_2\)O\(_2\)) could seriously limit the toxicity and danger of mercury inside the receiving aqueous solution.

The IEC analysis also revealed the Hg\(^{2+}\) concentration in the aqueous phase to be 228 ± 6 ng ml\(^{-1}\) \((n = 3)\). The result was in good agreement with the Hg\(^{2+}\) concentration, estimated using

---

**Table 1** Effect of nano-emulsion (oil, 5,200.0 \(\mu\)g ml\(^{-1}\)) containing different cations on chloride removal from the NGC sample at 25°C.

| Extracting medium | Chloride concentration (µg ml\(^{-1}\)) in NGC ± SD | Extraction efficiency (%) |
|-------------------|---------------------------------|--------------------------|
| Before extraction | 315.0 ± 4.0                     | --                       |
| Ag\(^{+}\)         | 23.0 ± 2.0                      | 92.7                     |
| Cu\(^{2+}\)        | 21.0 ± 1.0                      | 93.3                     |
| Fe\(^{3+}\)        | 235.0 ± 4.0                     | 25.1                     |
| Fe\(^{2+}\)        | 220.0 ± 2.0                     | 30.1                     |
| Mn\(^{2+}\)        | 205.0 ± 3.0                     | 34.9                     |
| Cu\(^{2+}\)        | 230.0 ± 3.0                     | 27.0                     |

*SD, standard deviation.

*\(n = \text{number of replicate analyses.}\)

**Table 2** Effect of Cu\(^{2+}\) concentration in nano-emulsion (oil, 5,200.0 \(\mu\)g ml\(^{-1}\)) on chloride extraction efficiency.

| Cu\(^{2+}\) concentration (mol L\(^{-1}\)) (apparent concentration) | Chloride concentration (µg ml\(^{-1}\)) in NGC (after extraction) ± SD | Extraction efficiency (%) |
|-------------------------------------------------------------------|-------------------------------------------------|--------------------------|
| 3.0 \(\times\) 10\(^{-3}\)                                       | 219 ± 1                                         | 30.5                     |
| 6.6 \(\times\) 10\(^{-3}\)                                       | 211 ± 2                                         | 33.0                     |
| 1.3 \(\times\) 10\(^{-3}\)                                       | 112 ± 3                                         | 64.0                     |
| 1.7 \(\times\) 10\(^{-3}\)                                       | 52 ± 4                                          | 83.5                     |
| 2.0 \(\times\) 10\(^{-2}\)                                       | 32 ± 3                                          | 89.8                     |
| 2.3 \(\times\) 10\(^{-2}\)                                       | 29 ± 4                                          | 90.8                     |
| 2.6 \(\times\) 10\(^{-2}\)                                       | 27 ± 2                                          | 91.4                     |

*Chloride concentration before extraction was 315 ± 4 \((n = 3)\).

*SD, standard deviation.

*\(n = \text{number of replicate.}\)
the CV-AAS (218 ± 7 ng ml\(^{-1}\), \(n = 3\)). However, for more confidence, the CV-AAS analytical process on the treated NGC revealed the residual Hg concentration to be below 10.0 ng ml\(^{-1}\).

For the uncertainty of the Hg content in the NGC, this value is related to the reproducibility of the mercuric element. For the efficiency, we deal with repeatability (for single NGC sample). In addition, for this analysis, we handle the CV-AAS, as a reliable method with detection limit less than ~2 ng ml\(^{-1}\) and precision (reproducibility, RSD %) below around 4.0%. In addition, the statistical test such as (t-test) points to the presence or absence of any the Hg levels. Hence, the selected method for mercury removal showed removal efficiency between 90% and around 100% (deepening on the nature of the NGC). This pointed to its
effective capability for removal of toxic reagents such as Hg(0) from the NGC samples along with their transfer and protected into a viscous fluid like oil medium.

Nevertheless, to confirm this claim, the IEC analyses also pointed to small concentration of the Cl− inside the treated NGC (below 20.0 ng ml−1), compared to the raw ones (315 ± 4 μg ml−1) that again exhibited >90% Cl− removal efficiency (see ion-exchange chromatogram and image analyses, Supplementary Figure S2). On the basis of the maximum time interval of the Cl− and Hg(0) removal from the NGC, the extraction time was estimated below 3.0 min. However, this value was dependent to the volume ratio of the gas condensate and the nano-emulsion phase. Consequently, the recommended method in this study again showed effective capability to remove both Cl− and Hg(0) at standard temperature and pressure (i.e., 0°C and 1.0 atm. pressure).

Reusability of theSynthesized Nano-Emulsion
The reusability of the synthesized nano-emulsion was also evaluated. The experiments showed that the synthesized nano-emulsion at the optimum Cu2+ and oil concentrations could be reused for at least four sequential analyses during extracting the Cl− ions from the NGC, sequentially. After that the efficiency of extraction would practically decrease, as it could not be reused for long time, owing to partial increase in the Cu2+ concentration in the treated NGC. However, this can be almost compensated via R22 purging based on the recommended procedure. Subsequently, the Cl− and Hg(0) removal process can be managed in a returned removal cycle, without any major need(s) to adopt extra nano-emulsion as the extracting phase (see Supporting Information, Supplementary Material S2.3).

Selectivity of the Extraction Process
The selectivity of this method was evaluated during extraction and separation of different kinds of anions such as Cl−, Br−, and S2− and trace quantity of RS−, presented in the NGC matrix according to chronograms shown in Figure 2.

On the basis of the IECs, not only the capability of the method was investigated for chloride removal purposes but also the effective role of de-emulsifying agents such as Cu2+ and Ag+ has been studied. On the basis of the results, the synthesized nano-emulsion had enough capability for removal of anionic species such as Cl− and S2−. For the Br− and RS− ions, probably large sizes and trace quantity of these anions limited their removal by using this LLE technique.

Non-corrosive Property of the NGC
Corrosion test was performed to investigate the Cl− and Hg(0) removal efficiency of the treated NGC. For this purpose, weight loss analysis and direct visualization by field-emission SEM (FE-SEM) of some iron fragments, under similar conditions. This process was achieved via situation inside both treated (Figure 3, row A) and pristine (raw) NGC (Figure 3, row B). The results were compared to the untreated one as the blanking control (Figure 3, row C).

As shown (Figure 3), no significant change was observed on the surface structure of the treated Fe fragments versus the untreated and control ones. In addition, no major weight loss was observed in the Fe fragments, contacted to the treated NGC, opposed to the control ones, which were introduced to the pristine NGC under similar conditions.

According to the weight loss analysis, the non-corrosion efficiency was also defined as the mass gradient (weight loss) of the Fe fragment before and after contact with the NGC at a fixed time interval vs. the mass of the fresh fragment, × 100. In this experiment, this value was estimated to be >90%. Therefore, the performed extraction methodology on the pristine NGC was successful for simultaneous removing of both Cl− and Hg(0) and major promotion of the non-corrosion efficiency.

Proposed Mechanisms
Because of the sophisticated matrix of the condensate, it was not easy to report certain mechanism for the Hg(0) and the Cl− removal process in this method. Nevertheless, a probable mechanism has been proposed according to some experimental and theoretical evidence. This hypothetical proposal was almost based on focusing on the formation constants of copper and chloride ions (Zhang et al., 2014). However, on the basis of the results evaluated in the previous sections, it seemed that the synthesized nano-emulsion played role as an intermediate for effective interaction between Cu2+ in aqueous phase and Cl− in the NGC phase. This behavior could be related to the interaction among water, sweet oil, and R22. To interpret the intermediate species, the effects of formation of different copper species such as Cu2+, CuCl+, CuCl2, CuCl3−, and CuCl4− were evaluated. These estimations were based on different analytical calculations such as cation-exchange chromatography (IEC, Figure 4).

In Figure 4, we adopted the IEC system that utilized suppressor. This module played role as multiple (at least four) ports: 1) memory effect elimination, 2) pH controlling system, 3) ionic strength controlling, and 4) a transient value for the transport of the samples toward the EC detector. These features were automatically arranged via controlling the mass transfer of different liquid media such as buffer solution and solvent. In this system, for the retention time of 20.0 min, the sensitivity of the system for the Cl− removal (at large scale) was adjusted via setting the mass transfer broadening of the analyte using the suppressor. This was achieved to rapidly control the mass transfer of the analyte at the interface (dead volume) between the column and the EC detector. This caused to more reliably analyze the responsible species as maximum as possible. That is why, in Figure 4, as clearly seen, the onset peak at 20 min was tilted backward toward the Y axis. This process was consequently general in the chromatographic systems. On the basis of this result, the synthesized nano-emulsion was considered as suitable intermediate medium for effective interaction between the Cu2+ (in the nano-emulsion phase) and the Cl− (in the condensate phase). This probably caused the formation of the CuCl− as the intermediate species.

For this purpose, the molar concentrations of the species were estimated at different chloride concentrations based on the mole fractions and their thermodynamic constants at the aqueous solution at room temperature. This process was provided
FIGURE 2 | Ion-exchange chromatograms showing selectivity as well as effects of Cu$^{2+}$ and Ag$^{+}$ on Cl$^{-}$ and S$^{2-}$ removal.

FIGURE 3 | Row FE-SEM images of iron fragments, placed inside row (A) pristine NGC and row (B) treated condensate. Row (C) FE-SEM images of fresh iron fragments as blanking control.
using a program the written Visual Basic 6. This program was based on the related mass/charge balance equations (Zhang et al., 2014) (see Embedded Visual Basic 6, VB6 program, Zip Files). Equations of formation copper(II) chloride complexes and their formation constants are shown in Eqs. 1–4 (Zhang et al., 2014). In addition, other prediction and some different theoretical calculations for the estimated mole fractions of each probably generated species majorly promoted this proposed mechanism.

\[
\begin{align*}
Cu^{2+} + Cl^- &\rightleftharpoons CuCl^+ \quad k_f = 1.86 \\
CuCl^+ + Cl^- &\rightleftharpoons CuCl_2 \quad k_f = 2.34 \times 10^{-1} \\
CuCl_2 + Cl^- &\rightleftharpoons CuCl_3^- \quad k_f = 3.63 \times 10^{-7} \\
CuCl_3^- + Cl^- &\rightleftharpoons CuCl_4^{2-} \quad k_f = 1.26 \times 10^{-9}
\end{align*}
\] (1–4)

On the basis of the results, molar ratio of species such as CuCl_2, CuCl_3^-, and CuCl_4^{2-} was very low (order of below 10^{-12} mol L^{-1}). Whereas molar concentrations of species such as CuCl^+ and CuCl^- had been estimated at the order of about 10^{-4} mol L^{-1}. This result was probably in good agreement with the probable formation of CuCl^+, estimated by the IEC as shown in Figure 4.

However, this result also pointed to the effective role of the Cu^{2+} for interaction with the Cl^- in the raw NGC. Whereas, in the Hg(0) removal process, the lack of adopting any oxidant(s) for oxidation of Hg(0) to Hg(II) in this method effectively revealed the probability of the presence of electrochemical interaction(s) and complex formation between Hg and Cl^- as cathodic and anodic half reactions, respectively (see Supporting Information, Supplementary Equations S1–S6). These were in agreement with other reports (Milazzo et al., 1978; Yan, 1987).

Nevertheless, precisely talking about the mechanism of extraction needs confidence knowledge about other factors such as role of R_{22}, behavior of -NH_2 functional group in oil and/or formation of other intermediates like ion-pairing. These were considered as a good topic for future studies in this field. The proposed mechanism for the effect of the -NH_2 functional group is shown in Eq. 5. In addition, the proposed mechanism for the effect of ion-pairing formation is shown in Eq. 6, where M^{n+} is ion pair of Cl^- in the NGC.

\[
\begin{align*}
Cu^{2+} + Cl^- + NH_2 &\rightleftharpoons Cu_2(OH)_3Cl \quad (5) \\
Cu^{2+} + Cl^- + M^{n+} &\rightleftharpoons CuX(M)_nCl_2
\end{align*}
\]

**Formation of Dicopper Chloride Trihydroxide Nanoparticles**

Another part of this study was related to the formation of the Cu_2(OH)_3Cl nanoparticles by the precipitation process after addition of NH_3 solution (25%) for controlling the acidity value to ~7.5. The formation of these nanoparticles was achieved after applying the extraction process on the NGC samples according to the recommended procedure. On the basis of Eq. 4.7 (Tanimizu et al., 2007), removed chloride ion in the presence of Cu^{2+} and OH^- led to synthesize Cu_2(OH)_3Cl particles based on the following reaction (Eq. 7):

\[
2Cu^{2+} + Cl^- + 3OH^- \rightleftharpoons Cu_2(OH)_3Cl(s) \quad (7)
\]

Effective factors such as Cu^{2+} concentration and the acidity were considered as the most important factor during the synthesis of Cu_2(OH)_3Cl nanoparticles.

**Effect of Acidity**

At pH values higher than ~7.5, Cu_2(OH)_3Cl was unstable and could be converted to Cu(OH)_2 (Eq. 8) (Frost et al., 2002; Boita et al., 2014). Therefore, pH controlling was very important factor in the workup step. Figure 5 shows the precipitate in different pH values.

Consequently, a pH value as large as ~7.5 (that was adjusted by commercial NH_3 solution, purity 25.0%, W/W) was selected. On the basis of the images, the promotion of pH from ~7.5 to ~9.0 led to have dark color precipitation due to the formation of Cu(OH)_2 according to Eq. 8:

\[
Cu_2(OH)_3Cl(s) + OH^- \rightleftharpoons 2Cu(OH)_2(s) + Cl^- \quad (8)
\]

**Effect of Different Bases on the Sedimentation Process**

The effects of different bases such as NaOH and NH_3 were studied. Sedimentation was occurred in both cases, but NH_3 was adopted for pH controlling in the workup step for facilitation of the procedure. This was due to the effectiveness of NH_3 for buffering the solution. However, the buffer capacity of NH_3 was low at pH ~7.5, but some side effects like formation of by-product precipitation of other buffer compounds such as phosphate limited the use of other buffer species.

**Effect of Cu^{2+} as de-emulsifying Reagent on the Formation of Dicopper Chloride Trihydroxide Nanoparticles**

To form the precipitation, after extraction step by nano-emulsion, the extractant medium (nano-emulsion) was separated and Cu(NO_3)_2 salt was added to it to increase the Cu^{2+} concentration up to about 1.7 × 10^{-2} mol L^{-1}. Then, it was centrifuged for 5 min at 3,000 rpm to demulsify the nano-emulsion and to remove oil from solution. Figure 6A shows the nano-emulsion (oil, 6.6 mmol L^{-1} Cu^{2+} and 10,400.0 μg ml^{-1})
before extraction. Whereas, Figure 6B shows the nano-emulsion after extraction (before demulsifying step). Figure 6C exhibits the solution after applying the de-emulsification process on the NGC samples (i.e., after removing oil from internal wall of sample tube). This was therefore ready for addition of NH₃ and formation the sedimentation.

The addition of NH₃ should be occurred after applying the de-emulsification during introducing Cu²⁺. At this condition, Cu₂(OH)₃Cl nanoparticles were observed in the aqueous phase. On the basis of the direct observation (Figure 6), at least 1.7 × 10⁻² mol L⁻¹ concentration of Cu²⁺ was needed for this purpose during centrifuging for 5 min at 3,000 rpm. This result was in good agreement with Cu²⁺ concentration that was needed for the Cu₂(OH)₃Cl formation. It should be noted that increasing Cu²⁺ concentration decreased time and rate of centrifuging step but formed Cu(OH)₂ and Cu₂(OH)₃Cl precipitate. Therefore, these condition was selected as optimum procedure during formation of Cu₂(OH)₃Cl nanoparticles.

Stability of Dicopper Chloride Trihydroxide Nanoparticles: Effect of Drying Step
Solid-state product was unstable in humidity condition after ~24 h. This was because this product had probably been converted to Cu(OH)₂. Therefore, it was recommended to air dry the synthesized sediments by a fan for ~6 h.

Characterization of Dicopper Chloride Trihydroxide
In this study, the formation of Cu₂(OH)₃Cl was confirmed by the following analytical techniques. Because of the presence of competition between the formation of Cu₂(OH)₃Cl and Cu(OH)₂, sometimes, characters of Cu₂(OH)₃Cl were needed to be compared to the Cu(OH)₂. On the basis of the literature, there are several reactions in which Cu₂(OH)₃Cl and Cu(OH)₂ can compete with each other. Some of the reactions are shown in Eqs 9–12 (Frost et al., 2002; Boita et al., 2014): 

\[
\begin{align*}
\text{Cu}_2(\text{OH})_3\text{Cl} + 3\text{NaOH} & \rightleftharpoons 2\text{Cu(OH)}_2 + \text{NaCl} \quad (9) \\
\text{Cu}_2(\text{OH})_3\text{Cl} + 3\text{HCl} & \rightleftharpoons 2\text{CuCl}_2 + 3\text{H}_2\text{O} \quad (10) \\
2\text{CuCl}_2 + 3\text{NaOH} & \rightleftharpoons \text{Cu}_2(\text{OH})_3\text{Cl} + 3\text{NaCl} \quad (11) \\
\text{CuCl}_2 + 3\text{CuO} + 3\text{H}_2\text{O} & \rightleftharpoons 2\text{Cu}_2(\text{OH})_3\text{Cl} \quad (12)
\end{align*}
\]

According these equations, the structures of Cu(OH)₂ and Cu₂(OH)₃Cl should be comprised in detail.

Comparison Between the Structures of Dicopper Chloride Trihydroxide and Copper Hydroxide
For precise evaluation of the difference between Cu₂(OH)₃Cl and Cu(OH)₂, the structures of these two compounds were compared to each other (Frost et al., 2002; Boita et al., 2014). On the basis of these references, the Cu₂(OH)₃Cl compound consisted of functional groups such as Cu-O, O-H, and Cu-Cl. Cu²⁺ had been coordinated with -OH and -Cl. In addition, the O-H bonds...
have been bridged through the hydrogen bonding; whereas, for the Cu(OH)$_2$, there were some functional groups such as Cu-O and O-H bonds. Consequently, compared to the Cu$_2$(OH)$_3$Cl, the difference between the functional groups was only related to the presence of Cu-Cl functional group in the Cu$_2$(OH)$_3$Cl compound. Far Fourier transform infrared (FT-IR) spectra of Cu$_2$(OH)$_3$Cl and Cu(OH)$_2$ are shown in Figure 7.

No significant difference was observed during compassion between the Far FT-IR spectra of Cu$_2$(OH)$_3$Cl and Cu(OH)$_2$. However, small difference was exhibited between the Cu-Cl functional groups at frequencies of 245–250 cm$^{-1}$. The presence of several shoulders at this frequency range pointed to the presence of different Cu-Cl bonds in the synthesized nanoparticles vs. other copper species such as Cu(OH)$_2$. However, for characterization of the sample with more detail, middle FT-IR spectrometry was utilized (Figure 8).

On the basis of the middle FT-IR spectra, the observation of strong peaks at frequencies of 473 and ~825 cm$^{-1}$ was related to the Cu-O functional group of Cu(OH)$_2$; whereas the observation of significant shift to higher frequencies was probably related to the presence of hydrogen bond in the Cu$_2$(OH)$_3$Cl compound. Compared to the Cu(OH)$_2$, the presence of two split absorption bonds at frequency of around 3,420 cm$^{-1}$ clearly pointed to the presence of hydrogen bonds in Cu$_2$(OH)$_3$Cl.
Raman spectroscopy was also considered as another applicable tool for characterization of Cu$_2$(OH)$_3$Cl, as shown in Figure 9 (Thermo Nicolet FT-Raman, 670). The presence of significant peak at frequency of around 250 cm$^{-1}$ was attributed to the Cu-Cl functional group, which was in good agreement with that estimated in literature (Frost et al., 2002; Boita et al., 2014). Compared to Cu(OH)$_2$, major shift was observed on the Raman spectra at frequencies between 450 and 500 cm$^{-1}$. This result again differentiated the formation of Cu$_2$(OH)$_3$Cl from Cu(OH)$_2$.

The X-ray powder diffraction (XRD; Bruker’s X-ray Diffraction D8-Discover instrument) pattern of the synthesized Cu$_2$(OH)$_3$Cl was shown in Figure 10. On the basis of the XRD pattern, the peaks situated at 2$\theta$ = 15°, 27°, 32°, 34°, 60°, and 64° were, respectively, related to special lattices of the Cu$_2$(OH)$_3$Cl structure, which were in accordance with other reports (Boita et al., 2014).

The size of Cu$_2$(OH)$_3$Cl structure was also evaluated; for this purpose, the peak width (W$_{1/2}$) positioned at 2$\theta$ = 27° was selected.

FIGURE 8 | Middle FT-IR spectra of Cu$_2$(OH)$_3$Cl and Cu(OH)$_2$.

FIGURE 9 | Raman spectra of Cu$_2$(OH)$_3$Cl and Cu(OH)$_2$.
and the crystalline size of the Cu₂(OH)₃Cl. This was estimated using Debye–Scherrer equation (Frost et al., 2002). On the basis of this equation, the average size of Cu₂(OH)₃Cl was calculated to be ~150 nm, which is in good agreement with the high-resolution TEM (HR-TEM, Zeiss EM10) and FE-SEM images shown in Figure 11.

The formation of Cu₂(OH)₃Cl was also confirmed using X-ray photoelectron spectroscopy (XPS) analysis (Figure 12). In accordance with the XPS spectrum, the strong peaks, positioned at 952 and 933 eV, were related to the Cu 2P½ and Cu 2P½, respectively, which agreed with those reported in the literature (Boita et al., 2014).

The X-ray fluorescence (XRF) was considered as another important and effective analytical spectroscopy that can be used to estimate the elemental percentages of Cu₂(OH)₃Cl. On the basis of the XRF analysis (XRF, Rigaku ZSX Primus II model, rhodium X-ray tube; 4.0-kW maximum power), the weight percentages of the elements presented in the analyzed structure are shown in Table 3. These results pointed to the accuracy of the structure of the analyzed sample during the Cl⁻ removal process.

In addition, CHN-S-Cl elemental analysis was performed to know the molar ratio of elements. The results showed 3.61:2.89:1.03 ratios of H:O:Cl. Therefore, it was hypothesized that precipitation formula was Cu₂(OH)₃Cl, not Cu(OH)₂(H₂O)₄ that was predicated with 5.21:3.12 ratios for H:O.

All these characterizations therefore revealed the catalytic property, as well as the nano-template effect of the synthesized nano-emulsion for selective synthesis of the Cu₂(OH)₃Cl nanoparticles with narrow diameter distribution and high purity at room temperature condition.
Evaluation of the Introduced Method

As explained before, the selectivity of this method was strongly evidenced on the basis of abovementioned documents that revealed high purity of the synthetic product. In addition, the acceptable removal efficiency and the lack of significant memory effect inside the nano-emulsion during its several reusability (at least four times) pointed to the sensitivity of this method. Simple and direct reaction process was also considered as other advantages of this process. Although, the main basis of the synthesized nano-emulsion was the commercial oil; nevertheless, the usability of this extractant strongly reveals the cost-effectiveness of this compound. However, the total price of this compound is not comparable with the economic value of the NGC, especially when resulting in synthesizing a suitable pesticide. Fast reaction time and non-significant toxicity (almost due to the viscous nature of the synthesized nano-emulsion) also made it suitable for such industrial applications.

Fortunately, this synthetic process was not comparable with the previous reports; as (to the best of knowledge) those methods were often suffered from problems such as 1) high cost, 2) small efficiency, 3) long synthetic time, and/or 4) hard conditions such as high temperature and pressure (Frost et al., 2002; Boita et al., 2014).

CONCLUSION

This report introduces an O/W nano-emulsion as the reusable extractant phase using LLE methodology for the removal efficiency of Cl\(^{-}\) and Hg(0). The removal efficiency was estimated between 90% and ~100%, deepening on the nature of the NGC at a brief separation time (<3.0 min). Consequently, serious impurities in condensate were removed by the scalable introduced methodology. In this method, the synthesized nano-emulsion as the extractant phase in the LLE methodology has significant advantages, especially 1) elemental mercury and chloride ion removal and 2) selective synthesis of the Cu\(_2\)(OH)\(_3\)Cl nanoparticles as useful product, specifically as an eco-friendly agricultural pesticide. The achieved safety of the NGC using this nano-emulsion results in efficient reduction in the corrosion rate during testing iron-based fragments (vs. the untreated ones as controls) and increasing of the NGC economic value. All these possibilities are attributed to the intermediate transport properties of the introduced O/W nano-emulsion. At this condition, this reagent plays role as a recycled motor for the NGC purification and conversion of these impurities into the safe and usable products. The introduced method is therefore accepted as direct, simple, low-cost, and scalable conversion of some upstream industries with the downstream ones. To the best of knowledge, this study is considered as the first report for dealing with the chloride and mercury impurities inside the gas condensate.
DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

This study was admitted and approved by the ethics committee of the Shiraz University Consul.

AUTHOR CONTRIBUTIONS

MD directed the research group, supported the necessary methods, and edited the manuscript; ZBK consulted the project, analyzed the data, and edited the manuscript. She also performed all the chemical experiments, analyzed the data, and wrote the manuscript.

REFERENCES

Abai, M., Atkins, M. P., Hassan, A., Holbrey, J. D., Kuah, Y., Nockemann, P., et al. (2015). An Ionic Liquid Process for Mercury Removal from Natural Gas. *Dalton Trans.* 44, 8617–8624. doi:10.1039/C4DT03273J

Argyle, M., and Bartholomew, C. (2015). Heterogeneous Catalyst Deactivation and Regeneration: A Review. *Catalysts* 5, 145–269. doi:10.3390/catal5010145

Banab Khorshid, M., Mahdi Dorooodmand, M., and Abdollahi, S. (2021). UV-vis. Spectrophotometric Method for Oil and Grease Determination in Water, Soil and Different Mediates Based on Emulsion. *Microchemical J.* 160, 105620. doi:10.1016/j.micchem.2020.105620

Bingham, M. D. (1990). Field Detection and Implications of Mercury in Natural Gas. *SPE Prod. Eng.* 5, 120–124. doi:10.2118/19357-pa

Boita, J., do Carmo Martins Alves, M., and Morais, T. (2021). Direct Pesticide Exposure of Insects in Nature Conservation Areas in Germany. *Scientific Rep.* 11, 24414–24415.

Chen, H., and Zhong, Q. (2022). Physical and Antimicrobial Properties of Self-Emulsified Nanoemulsions Containing Three Synergistic Essential Oils. *Int. J. Food Microbiol.* 365, 109557. doi:10.1016/j.ifomicro.2022.109557

D’Alfonso, C., Lanzalunga, O., Lapi, A., and Vadala, R. (2014). Comparing the Catalytic Efficiency of Ring Substituted 1-hydroxybenzotriazoles as Laccase Mediators. *Tetrahedron* 70, 3049–3055. doi:10.1016/j.tet.2014.02.068

D’Acunzo, F., and Galli, C. (2003). First Evidence of Catalytic Mediation by Phenolic Compounds in the Laccase-Induced Oxidation of Lignin Models. *Europ. J. Biochem.* 270, 3634–3640. doi:10.1046/j.1432-1323.2003.03752.x

Ergun, M., and Turan, A. Y., Pitting Potential and Protection Potential of Carbon Steel for Chloride Ion and the Effectiveness of Different Inhibiting Anions, *Corrosion Sci.* 32 (1991) 1137–1142. doi:10.1016/0010-938X(91)90098-A

FAO/WHO (2021). FAO/WHO Meeting on Pesticide Residues by the 2021 Meeting, 6–17 September; 4 and 7 October 2021.

Hussain, A., AlAjmi, M. F., Rehman, M. T., Amir, S., Husain, F. M., Alsalme, A., et al. (2019). Copper(II) Complexes as Potential Anticancer and Nonsteroidal Anti-inflammatory Agents: In Vitro and In Vivo Studies. *Sci. Rep.* 9, 5237–5254. doi:10.1038/s41598-019-41063-x

Jackson, K., and Fulton, J. L. (1996). Microemulsions in Supercritical Hydrochlorofluorocarbons. *Langmuir* 12, 5289–5295. doi:10.1021/la960210j

Jiang, X., Nešić, S., Kinsella, B., Brown, B., and Young, D. (2013). Electrochemical Investigation of the Role of Cl− on Localized Carbon Dioxide Corrosion Behavior of Mild Steel. *Corrosion* 69, 15–24. doi:10.5006/0620

Lavela, P., Macías, C., Ovín Ania, M. C., Rasines, G., Tirado, J. L., and Zafra, M. C. (2015). Mesoporous Carbon Black-Aerogel Composites with Optimized Properties for the Electro-Assisted Removal of Sodium Chloride from Brackish Water. *J. Electroanal. Chem.* 50, 42–50. doi:10.1016/j.jelechem.2015.01.016

Luo, L., Wang, R. L., Zhang, Z. J., Steward, F. A., Luo, X., and Liu, B. (2010). Effect of Dietary Supplementation with Copper Sulfate or Tribasic Copper Chloride on the Growth Performance, Liver Copper Concentrations of Broilers Fed in Floor Pens, and Stabilities of Vitamin E and Phytase in Feeds. *Bioc. Trace Elem. Res.* 138, 181–189. doi:10.1007/s12011-010-8623-3

Lubej, A., Koloini, T., and Pohar, C. (2004). Industrial Precipitation of Cupric Hydroxyl-Salts. *Acta Chim. Slov.* 51, 751–768.

Luo, X. G., Ji, F., Lin, Y. X., Steward, F. A., Lu, L., Liu, B., et al. (2005). Effects of Dietary Supplementation with Copper Sulfate or Tribasic Copper Chloride on Broiler Performance, Relative Copper Bioavailability, and Oxidation Stability of Vitamin E in Feed. *Poult. Sci.* 84, 888–893. doi:10.1093/ps/84.6.888

Milazzo, G., Caroli, S., and Braun, R. D. (1978). Tables of Standard Electrode Potentials. *J. Electrochem. Soc.* 125, 261C. doi:10.1149/1.2131790

Mohammadi, A., Dorooodmand, M. M., and Sadegh, M. M. R. (2016). Selective Speciation of Cu(III) and Cu(VI) by Micro-emulsion Using UV-Vis. Spectrophotometry. *J. Textile Sci. Eng.* 6, 1–6. doi:10.4172/2165-8064.1000243

Pathania, R., Najda, A., Chawla, P., Kaushik, R., and Khan, M. A. (2022). Low-energy Assisted Sodium Alginate Stabilized Phyllanthus Niruri Extract Nanoemulsiion: Characterization, In Vitro Antioxidant and Antimicrobial Application. *Biotecnol. Rep.* 33, e00711. doi:10.1016/j.btre.2022.e00711

Pierce, R. A., Campbell-Kelly, R. P., Visser, A. E., and Laurinat, J. E. (2007). Removal of Chloride from Acidic Solutions Using NO2. *Ind. Eng. Chem. Res.* 46, 2572–2576. doi:10.1021/ie061167p

Sabbaghi, S., Maleki, R., Shariat- Niassar, M., Zerafat, M. M., and Nematollahi, M. M. (2012). Modeling of Chloride Ion Separation by Nanoemulsion Using Machine Learning Techniques. *Int. J. Nanosci. Nanotechnol.* 8, 185–190.

FUNDING

This study was financially supported by Shiraz University (grant no. 164116-131).

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of this work by the Shiraz University Research Council.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at https://www.frontiersin.org/articles/10.3389/fchem.2022.823357/full#supplementary-material
Scott, D. A. (2000). A Review of Copper Chlorides and Related Salts in Bronze Corrosion and as Painting Pigments. *Stud. Conservation* 45, 39–53. doi:10.1179/sic.2000.45.1.39

Sun, W.-Q., Xu, X.-D., Zhang, Y., and Wu, J.-Z. (2019). Chlorine Corrosion of Blast Furnace Gas Pipelines: Analysis from thermal Perspective. *J. Min Metall. B Metall.* 55, 197–208. doi:10.2298/JMMB181016028S

Tanimizu, M., Takahashi, Y., and Nomura, M. (2007). Spectroscopic Study on the Anion Exchange Behavior of Cu Chloro-Complexes in HCl Solutions and its Implication to Cu Isotopic Fractionation. *Geochem. J.* 41, 291–295. doi:10.2343/geochemj.41.291

Wilhelm, S. M., Risk Analysis for Operation of Aluminum Heat Exchangers Contaminated by Mercury, *Proc. Saf. prog.* 28 (2009) 259–266. doi:10.1002/prs.10322

Wilhelm, S. M., and Bloom, N. (2000). Mercury in Petroleum. *Fuel Process. Techn.* 63, 1–27. doi:10.1016/S0378-3820(99)00068-5

Wu, X., Liu, Z., and Liu, X. (2013). Chloride Ion Removal from Zinc Sulfate Aqueous Solution by Electrochemical Method. *Hydrometallurgy* 134-135, 62–65. doi:10.1016/j.hydromet.2013.01.017

Yan, T. Y. (1987). Removal of Mercury from Natural Gas and Liquid Hydrocarbons Utilizing Downstream Guard Chamber. *Yang, H., Xu, Z., Fan, M., Bland, A. E., and Judkins, R. R. (2007). Adsorbents for Capturing Mercury in Coal-Fired Boiler Flue Gas. J. Hazard. Mater.* 146, 1–11. doi:10.1016/j.jhazmat.2007.04.113

Zhang, N., Zhou, Q., Yin, X., and Zeng, D. (2014). Trace Amounts of Aqueous Copper(II) Chloride Complexes in Hypersaline Solutions: Spectrophotometric and Thermodynamic Studies. *J. Solution Chem.* 43, 326–339. doi:10.1007/s10953-014-9129-8

**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Publisher’s Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Banan Khorshid and Doroodmand. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.