Journal of Analytical Sciences, Methods and Instrumentation, 2026, 16(1), 1-20
https://www.scirp.org/journal/jasmi
ISSN Online: 2164-2753
ISSN Print: 2164-2745

# An Investigation on the Effect of Viscosity on Mass Transfer Coefficient Using Cyanex 272 Solvent Extractant during Cobalt-Nickel Extraction and Separation

**Stanford Mudono, Hilda Vimbai Kaitano, Farai Musendo, Eli Mtetwa**

Department of Chemical Engineering, Faculty of Technology, National University of Science & Technology, Bulawayo, Zimbabwe
Email: stanford.mudono@nust.ac.zw

**How to cite this paper:** Mudono, S., Kaitano, H.V., Musendo, F. and Mtetwa, E. (2026) An Investigation on the Effect of Viscosity on Mass Transfer Coefficient Using Cyanex 272 Solvent Extractant during Cobalt-Nickel Extraction and Separation. *Journal of Analytical Sciences, Methods and Instrumentation*, **16**, 1-20.
https://doi.org/10.4236/jasmi.2026.161001

**Received:** March 4, 2024
**Accepted:** March 23, 2026
**Published:** March 26, 2026

## Abstract

The separation of cobalt from nickel in aqueous solutions remains a major challenge in hydrometallurgy due to their chemical similarities. Solvent extraction (SX) using organophosphorus acids, particularly Cyanex 272, offers a promising approach for achieving selective separation with high yields and purity. This study investigates the effect of organic phase viscosity on mass transfer coefficients during SX of cobalt (Co) and nickel (Ni), with the objective of identifying operating conditions that maximize diffusivity and extraction efficiency. Viscosity experiments were conducted using Cyanex 272 in kerosene as diluent and iso-octanol as modifier, with a saponification ratio of 70% at 25˚C in an agitated water bath, thermostatically controlled and mass transfer coefficient experiments were carried out in a Drop Swarms apparatus of 0.10 m diameter and 0.60 m height, equipped with a multi-channel precise syringe pump and a computerized video imaging system to help monitor and capture the movement of drops in the extraction column. Results show that viscosity decreases significantly with the addition of diluents and modifiers, leading to higher mass transfer coefficients and improved solute diffusion. At 15% v/v Cyanex 272, viscosity was reduced to below 10 cP, ensuring optimal diffusivity. Mass transfer experiments confirmed preferential extraction of cobalt over nickel, explained by coordination chemistry: cobalt forms tetrahedral, hydrophobic complexes that retain less water, while nickel forms octahedral, hydrophilic complexes that retain more water molecules. The novelty of this research lies in its systematic linkage between viscosity control and mass transfer efficiency, providing a clear operating window for SX optimization. By demonstrating how diluents and modifiers can be strategically employed to reduce viscosity and enhance cobalt selectivity, the study offers practical guidance for industrial hydrometallurgical operations. These findings underscore the importance of Cyanex 272 as a cost-effective and efficient extractant for cobalt-nickel separation, with direct implications for improving recovery yields and process sustainability. This research provides both fundamental insight into solvent extraction mechanisms and practical guidance for hydrometallurgical operations, contributing to more efficient and sustainable production of battery-grade cobalt and nickel.

## Keywords

Cyanex 272 Extractant, Cobalt, Nickel, Mass Transfer Coefficient, Metal Loading, Reverse Micelle, Viscosity

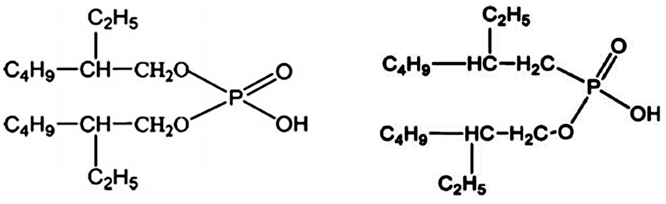
## 1. Introduction

The global demand for cobalt and nickel has risen sharply in recent years, driven primarily by their critical role as cathode materials in lithiumion batteries, alongside established applications in aerospace superalloys, gas turbine engines, automotive components, electronics, catalysts, pigments, magnets, and electroplating [1]-[3]. Their widespread industrial use underscores the urgent need for efficient separation and purification technologies. However, separating cobalt from nickel remains a persistent challenge in hydrometallurgy due to their cooccurrence in ores and concentrates and their similar physicochemical properties arising from adjacent positions in the Periodic Table properties [1] [4]-[6]. Traditional methods such as precipitation, oxidation, and crystallization often fail to achieve economical and effective separation of the cobalt-nickel pair, particularly from sulphate and chloride solutions. Solvent extraction (SX) has therefore emerged as one of the most promising techniques for selective separation from pregnant leach solutions. Among extractants, organophosphorus acids have attracted significant attention because of their ability to preferentially extract cobalt over nickel, while carboxylic acids tend to favour nickel [1] [7]. Comparative studies have shown (**Table 1**) that the separation factor between cobalt and nickel increases in the order: D2EHPA < PC88A < Cyanex 272, with Cyanex 272 demonstrating superior selectivity and efficiency [1] [7] [8]. This research focuses on the effect of viscosity on mass transfer coefficients during SX using Cyanex 272. By examining how diluents and modifiers influence viscosity and diffusivity, the study aims to establish optimal operating conditions for maximizing cobalt extraction while minimizing nickel co-extraction. The novelty lies in linking viscosity control directly to mass transfer efficiency, providing practical insights for scaling SX processes in industrial hydrometallurgical operations. Ultimately, the work addresses a critical bottleneck in cobalt-nickel separation, offering pathways to higher recovery yields, reduced purification costs, and improved sustainability in battery material supply chains.

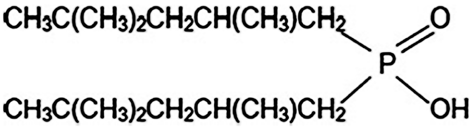
**Table 1.** Separation factors of different extractants [9].

| Extractant | Co/Ni separation factor |
|---|---|
| D2EPHA | 14 |
| PC-88A | 280 |
| CYANEX 272 | 7000 |

The process of solvent extraction techniques, involving these organophosphorous based extractants provides a higher degree of extraction and separation, and yields demanded by industry nowadays to recover and separate cobalt and nickel from aqueous solutions [10] [11]. Because of the high nickel to cobalt ratio encountered in the liquors produced in the sulphate-based high nickel leach processes or those produced in the acid pressure leaching of nickel laterites, very high separation factors (>1000) and the dialkyl phosphinic acid Cyanex 272 has become the reagent of choice for such duties since it has a separation factor of around 7000 [9] [11] [12]. The structures of the organophosphorous acid extractants are shown in **Figure 1**.



(a) Phosphoric D2EHPA (b) Phosphonic PC-88A



(c) Phosphinic Cyanex 272

**Figure 1.** Structures of the organophosphorous acid extractants.

Previous experimental studies employing the Lewis cell have extensively examined how parameters such as temperature, pH, organic phase loading, drop diameter, extraction kinetics, equilibrium constants, solvent modifiers, drop velocity, contact time, surface-active impurities, agitation of the continuous phase, coalescence, and drop distortions influence mass transfer rates, with several predictive equations developed to describe these phenomena [9] [11]. Most of these investigations were conducted in relatively non-viscous systems and consistently confirmed the high selectivity of cobalt over nickel, which remains a major advantage in solvent extraction. A review of the literature over the past two decades shows that research has largely focused on the fundamental aspects of extraction and its application to cobalt-nickel separation from sulphate and chloride media, predominantly using phosphorus-based extractants. However, comparatively little attention has been devoted to the role of viscosity in governing mass transfer coefficients during Co-Ni separation. Since mass transfer between immiscible liquids is a complex yet critical mechanism underpinning separation and purification processes in industry, understanding the impact of viscosity is essential. In this study, the effect of Cyanex 272 extractant viscosity on mass transfer coefficients during cobalt-nickel extraction from prepared sulphate solutions was investigated.

In aqueous solution, both cobalt(II) and nickel(II) ions primarily exist as hexaaqua complexes, $[Co(H_2O)_6]^{2+}$ and $[Ni(H_2O)_6]^{2+}$, respectively. However, their coordination chemistry differs in ways that strongly influence solvent extraction behavior. Cobalt (II) has a relatively larger ionic radius and lower hydration energy, which makes its bound water molecules easier to displace during ligand substitution. When Cyanex 272 is introduced, cobalt tends to form tetrahedral complexes that are more hydrophobic, expelling water molecules and favoring transfer into the organic phase. Nickel (II), on the other hand, has a smaller ionic radius and stronger hydration energy, meaning its water molecules are more tightly bound and harder to replace. As a result, nickel prefers to form octahedral complexes that retain water molecules, making them more hydrophilic and less soluble in the organic phase. This difference in geometry and hydration explains why cobalt is preferentially extracted: tetrahedral cobalt complexes diffuse more readily into the organic phase, while octahedral nickel complexes remain in the aqueous phase. When viscosity is reduced through the addition of diluents and modifiers, diffusivity is enhanced, further amplifying cobalt's selective transfer [1] [13]. Thus, the interplay between hydration energy, coordination geometry, and viscosity control provides the mechanistic basis for efficient cobalt-nickel separation using Cyanex 272. These experiments provide important insights into how increasing viscosity with metal loading reduces diffusivity and mass transfer rates, thereby offering a more comprehensive understanding of the separation mechanism and supporting the development of predictive models for hydrometallurgical applications.

## 2. Solvent Extraction (SX) Mechanism

Solvent extraction (SX) is one of the most useful techniques that are used for the selective removal and recovery of metal ions from aqueous solution and it is largely applied in the purification process in chemical and metallurgical industries [12]. SX makes use of an organic compound capable of extracting the metal ion of interest, or a complex of it, from the aqueous phase into an immiscible organic solution. Cyanex 272 is a dialkyl phosphinic acid extractant that has proven to be the potential reagent of choice for the separation of cobalt from nickel to produce high purity cobalt salts and cobalt metal in both sulphate and chloride media. The metal or solute of interest is transferred from the aqueous phase to the organic phase after the phases are put in contact via agitation. The active component is a phosphinic acid and metals are extracted through a cation exchange mechanism. Although Cyanex 272 extractant is selective for cobalt in the presence of nickel, a variety of other cations can also be extracted depending on the solution pH [12].

Cyanex 272 extractant is totally miscible with common aromatic and aliphatic diluents, and is extremely stable to both heat and hydrolysis.

The principle of cobalt-nickel separation in solvent extraction is rooted in their distinct coordination chemistry in aqueous solution. Cobalt (II), with its $3d^7$ electronic configuration, exhibits greater flexibility in coordination, forming both octahedral complexes such as $[Co(H_2O)_6]^{2+}$ and tetrahedral complexes with weaker ligands. This dual morphology allows cobalt to interact more strongly with organophosphorus extractants like Cyanex 272, which preferentially stabilize cobalt complexes at the organic-aqueous interface. In contrast, Nickel(II), with a $3d^8$ configuration, predominantly forms stable octahedral complexes such as $[Ni(H_2O)_6]^{2+}$, and only under specific ligand conditions does it adopt square planar or tetrahedral geometries. This rigidity in coordination limits nickel's affinity for Cyanex 272, keeping it largely in the aqueous phase. The extraction mechanism therefore exploits cobalt's structural adaptability versus nickel's geometric stability: cobalt complexes are more readily solvated into the organic phase, while nickel remains in solution. When the viscosity of the organic phase increases, diffusivity decreases, slowing mass transfer of both ions; however, cobalt's stronger binding still ensures preferential extraction. Thus, the separation process is fundamentally governed by the interplay of coordination geometry, ligand field stabilization, and mass transfer dynamics [14].

During solvent extraction, the viscosity of the organic phase does not remain constant but undergoes distinct stepwise increases as metal loading progresses. This rheological change directly impedes the rate of mass transfer, since higher viscosity suppresses diffusivity and slows the migration of solute species across the liquid-liquid interface. To maintain efficient extraction, the organic phase loading must be restricted to below approximately 70%, beyond which viscosity rises sharply and compromises separation efficiency [11] [15]. The observed decline in mass transfer coefficients with increasing viscosity has been attributed to structural phenomena within the organic phase, notably polymerization of extractant-metal complexes and the formation of reverse micelles. The reverse micelle technique refers to the formation of nanoscale aggregates in the organic phase, where surfactant molecules such as Cyanex 272 organize around small pools of water. In these structures, the hydrophilic head groups of the extractant face inward toward the water core, while the hydrophobic tails extend into the organic solvent. This arrangement creates dynamic non-reactors that encapsulate hydrated metal ions, facilitating their transport across the organic phase [13].

In the context of cobalt-nickel separation, the technique plays a significant role in enhancing selectivity and mass transfer efficiency. Cobalt(II) ions, which more readily shed water molecules due to lower hydration energy, are stabilized within reverse micelles and transferred efficiently into the organic phase. Nickel(II) ions, by contrast, retain stronger hydration shells and octahedral coordination, making them less compatible with micellar encapsulation and thus less likely to migrate. These supramolecular assemblies hinder molecular mobility and reduce interfacial transport. Fundamentally, the transfer of solute from the aqueous to the organic phase is governed by extraction reactions that establish liquid-liquid equilibrium; however, the kinetics of this equilibrium are strongly modulated by the physical properties of the organic medium, with viscosity emerging as a critical determinant of overall separation performance phase [13]. A general equation for an increase in organic phase loading polymer formation is as follows:

$$M^{n+} + MA_nHA_{2org} + H_2A_{2org} \rightarrow (MA_2)_n H_2A_{2org} + nH^+ \quad (1)$$

where: $M^{n+}$ represents the metal

A represents 2,4,4-trimethyl phosphinic conjugate base in the organic phase.

Due to Cyanex 272 having a high selectivity over the other extractants for high Ni: Co ratios in aqueous solutions, it has been adapted as the main extractant for cobalt and nickel in sulphate solutions. A recovery of 99.7% cobalt has been reported using Cyanex 272. It was also reported that the purified nickel sulphate using Cyanex 272 contains <0.001% Co, <0.0001% Zn <0.000055% Fe, <0.00005% Cu and <0.00005% Mn [11]. This reflects the potential of Cyanex 272 as an extactant. A further practical advantage of Cyanex 272 extractant is that calcium uptake is much lower than that found in other extractants such as D2EPHA or PC-88A at the same pH and this minimizes serious loss of solvent.

Stoichiometric experiments suggested that the metal extraction is through the dimerized form of the extractant and the following equation has been proposed [16] [17].

$$M^{n+} + (p+2)H_2A_{2org} \rightarrow MA_n(HA_2)_{porg} + nH^+ \quad (2)$$

where, $p = 0$ for Co and $p = 1$ for Ni.

The extraction of metals by dimeric dialkyl esters of phosphoric, phosphonic, phosphinic acids $(H_2A_2)_{(org)}$ is usually represented by the extraction reaction Equation (2), and the following extraction reaction equations can be adapted for cobalt and nickel [9]:

$$Co^{2+} + 2(H_2A_2)_{org} \rightarrow CoA_2(H_2A_2)_{org} + 2H^+ \quad (3)$$

$$Ni^{2+} + 3(H_2A_2)_{org} \rightarrow NiA_2(H_2A_2)_{2org} + 2H^+ \quad (4)$$

The equilibrium constant of Equation (2) can be represented as follows:

$$K_e = \frac{\left[M(HA_2)_n(H_2A_2)_{m-n}\right]_{org}\left[H^+\right]^n}{\left[M^{n+}\right]\left[H_2A_2\right]_{org}^m} \quad (5)$$

The distribution of solute M (equilibrate between an aqueous phase and an organic solvent) can be described by an equilibrium equation. The distribution coefficient, D, is given by the ratio of the total metal content in the organic phase to the metal content in the aqueous phase as follows:

$$D = \frac{(M)_{org}}{(M)} = \frac{\left[M(HA_2)_n(H_2A_2)_{m-n}\right]_{org}}{\left[M^{n+}\right]} \quad (6)$$

It was also noted that with phosphorous based extractant cobalt forms a tetrahedral complex whilst nickel forms an octahedral complex. The cobalt complex is hydrophobic and is more readily extracted than the hydrophilic nickel complex.

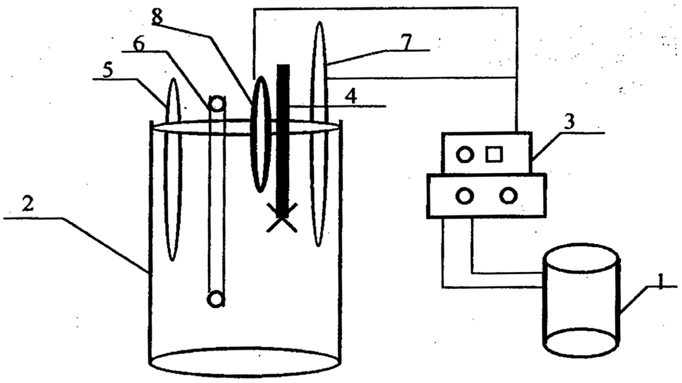
## 3. Experimental Schemes and Procedures

### 3.1. Method

To ensure repeatability and verifiability, the experimental conditions were carefully controlled and documented with precise control of solution concentrations, temperature, stirring rate, and other operating parameters. Cobalt and nickel sulphate solutions were prepared from $CoSO_4 \cdot 7H_2O$ (99.5% purity, Mw = 281.10) and $NiSO_4 \cdot 6H_2O$ (98.5% purity, Mw = 262.85), respectively, using deionized water produced by electrodialysis. The concentrations of the prepared solutions were adjusted to reflect those typically encountered in industrial leach liquors, ensuring practical relevance. Viscosity measurements were conducted in a thermostatically controlled water bath maintained at ±0.10˚C. Bath temperature was monitored using a calibrated platinum resistance thermometer, while the control panel ensured precise regulation of both the thermostat and mixer rotation frequency to maintain consistent stirring rates. Mass transfer coefficient experiments were performed using a flanged column apparatus (0.10 m diameter, 0.60 m height) with a plexiglass base, equipped with a Cole-Parmer 74900-10 multi-channel syringe pump and a computerized video imaging system to monitor and record droplet movement within the extraction column. All experiments were carried out at ambient temperature, consistent with industrial hydrometallurgical practice, to ensure miscibility between aqueous and organic phases. The extractant, bis (2,4,4-trimethylpentyl) phosphinic acid (Cyanex 272, 85% purity, Mw = 290), was supplied by CYTEC Canada Inc. and used without further purification. Analytical-grade reagents were obtained from Beijing Shuan Yuan Chemical Plant, and deionized water prepared by electrodialysis was used for solution preparation. Kerosene (99.5% purity) served as the diluent, while iso-octanol (99.5% purity, Mw = 130.23) was employed as a phase modifier. Sodium hydroxide (96.0% purity) was used for saponification, and hydrochloric acid (36 - 38% concentration) for stripping the organic phase. Metal sources included cobalt sulphate heptahydrate ($CoSO_4 \cdot 7H_2O$, 99.5% purity, Mw = 281.10) and nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$, 98.5% purity, Mw = 262.85), supplied by Bindura Nickel Refinery. The concentrations of cobalt and nickel in prepared solutions were representative of typical leach liquors. Ethanol (Mw = 46.07, 99.6% analytical grade, $\rho_{20}$˚C = 0.789 - 0.791 $g \cdot cm^{-3}$) was used for viscosity calibration. All other chemicals were of analytical reagent grade. Metal concentrations in aqueous and organic phases were determined using a Perkin Elmer AAnalyst-400 atomic absorption spectrometer (AAS). By carefully controlling solution concentration, bath temperature, stirring rate, and analytical procedures, the study ensured that results were reproducible and verifiable, providing a reliable foundation for understanding the effect of viscosity on mass transfer coefficients during cobalt-nickel extraction and separation.

### 3.1.1. Viscosity Experiments

**Figure 2** shows the experimental set-up for all viscosity experiments were the water-bath is equipped with a thermostastically controlled system to ±0.10˚C.



1. Voltmeter (TDGC 2 j-2); 2. Water—bath; 3. Control panel (SY 706); 4. Mixer; 5. Thermometer; 6. Viscometer; 7. Thermostat; 8. Heater.

**Figure 2.** Viscosity experimental set-up.

Solutions of known compositions for determining the effect of diluent (75, 80, 85, 90% v/v) and modifier (5% v/v iso-octanol) on the viscosity of Cyanex 272 (20, 15, 10, 5% v/v) were prepared and mixed together and these runs were carried out at different temperatures. These solutions were shaken for 2 min manually to ensure homogeneity before placed in a water bath. The viscosity was calculated using the following expression:

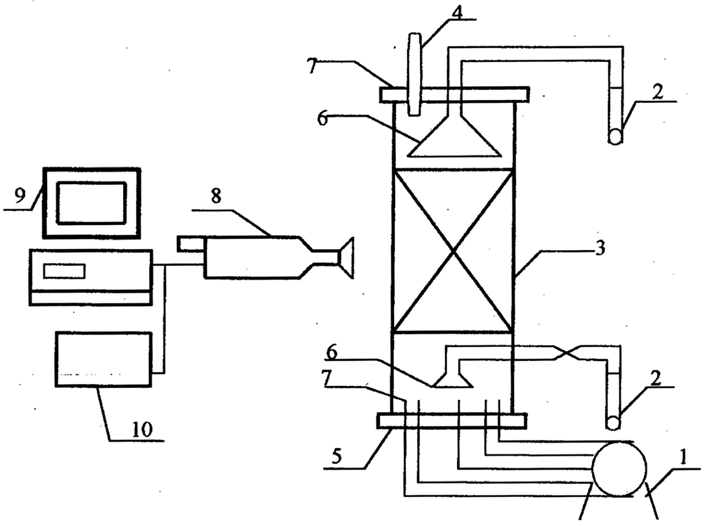
$$\mu_2 = \frac{(\mu_1 \rho_2 t_2)}{(\rho_1 t_1)} \tag{7}$$

where; $\mu_1$ = viscosity of standard solution (ethanol), cP
$\mu_2$ = viscosity of solution, cP
$\rho_1$ = density of standard solution (ethanol), g/cm$^3$
$\rho_2$ = density of solution, g/cm$^3$
$t_1$ = time taken by the standard solution (ethanol), sec
$t_2$ = time taken by the solution, sec

### 3.1.2. Mass Transfer Coefficient Experiments

A flanged column apparatus of 0.10 m diameter, 0.60 m height, having a bottom made of plexiglass equipped with a 74900-10 multi-channel precise syringe pump provided by Cole-Parmer Instrument Company and a computerized video imaging system to help monitor and capture the movement of drops in the extraction column was used (**Figure 3**). The pump was used to provide drop swarms as well as single drop. Medical hypodermic needles of seven different gauges were used in the experiments. Teflon pipe was implored as connector between needles and syringe pump. Flow rate of pump was controlled to ensure that producing time of each drop was constant (2 - 3 seconds). All experiments were carried out at room temperature (25 ± 2˚C). Cobalt and nickel sulphate solutions were maintained at

1 mol/L. The A/O for all runs was kept at unity. The loaded organic phases was accomplished by double stripping of the organic phase with 1 mol/L HCl. Aqueous feed and raffinate solutions and loaded organic phase were analyzed by AAS using closely matched standards.



1. Syringe pump; 2. Sample collector; 3. Extraction column; 4. Syringe; 5. Flange; 6. Funnel; 7. Needle; 8. Video camera; 9. PC Computer; 10. Video tape recorder.

**Figure 3.** Mass transfer experimental set-up.

The overall drop mass transfer coefficient ( $K_{od}$ ) for the experiments was calculated using the following equation:

$$K_{od} = -\frac{d_p}{6\tau \ln(1-E)} \tag{8}$$

$$E = \frac{(y_2 - y_1)}{(y^* - y_1)} \tag{9}$$

$$d_p = \left(\frac{6Qt}{n\pi}\right)^{1/3} \tag{10}$$

$$u_t = \frac{H}{t} \tag{11}$$

where:

$d_p$ = diameter of drops (mm).

$y_1$ = concentration of bottom organic phase.

$y_2$ = concentration of top organic phase.

$y^*$ = equilibrium concentration of continuous phase.

$t$ = time taken for formation of n drops.

$\tau$ = time taken for a drop to reach a height of 0.45 m of the column.

$n$ = number of drops formed (≈10 drops).

$u_t$ = terminal drop velocity.

$H$ = height of the column taken by a drop to reach in time, $\tau\left(H = 0.45m\right)$.
$Q$ = flow rate, mL/min.
$E$ = Murphy Efficiency.

## 4. Results and Analysis

### 4.1. Results on the Effect of Viscosity

Experiments were designed to evaluate the effect of viscosity on different organic phase systems used in cobalt-nickel solvent extraction. Three mixtures were investigated: (i) kerosene as diluent with Cyanex 272 as the extractant, (ii) kerosene as diluent with iso-octanol as modifier and Cyanex 272 as extractant, and (iii) a saponified mixture of kerosene, iso-octanol, and Cyanex 272. The saponified system was further loaded with cobalt, nickel, and combined cobalt-nickel solutions to simulate realistic extraction conditions. Each system was studied under varying concentrations and temperatures, as detailed in the corresponding tables and figures, to establish the operating parameters for mass transfer experiments. Viscosity measurements were performed under controlled thermal conditions, while mass transfer coefficients were determined using a drop swarm apparatus equipped with a precise syringe pump and video imaging system. The systematic variation of solution composition, temperature, and loading provided a comprehensive dataset for assessing how viscosity influences diffusivity and, consequently, the efficiency of cobalt-nickel separation.

In solvent extraction processes, organic extractants are rarely employed in their pure form; instead, they are dissolved in suitable diluents whose properties strongly influence extraction performance. The choice of diluent is particularly critical in hydrometallurgy, where the aromatic or aliphatic nature of the diluent can markedly affect metal separation. A diluent serves multiple functions: reducing the viscosity and density of the organic phase, ensuring an appropriate concentration of extractant relative to the feed solution, minimizing emulsification with the aqueous phase, and enhancing dispersion and coalescence [1] [7]. To be effective, a diluent must also meet stringent criteria, including broad miscibility with the extractant, high solvency for metal-extractant complexes, low aqueous solubility, low volatility, high flash point, low surface tension, and minimal toxicity, while remaining inexpensive and readily available. Kerosene satisfies most of these requirements, making it an ideal choice in this study.

Experimental results (**Table 2**; **Figure 4**) demonstrate that increasing the concentration of Cyanex 272 extractant leads to higher viscosity, while increasing temperature reduces viscosity. Maintaining relatively low viscosity (<10 cP) is essential to facilitate efficient mass transfer between aqueous and organic phases. Operating at moderate temperatures (<30˚C) is equally important, as excessively high temperatures can lead to miscibility of the two phases, eliminating the separation interface and rendering extraction ineffective. These findings underscore the importance of carefully balancing extractant concentration, diluent properties, and operating temperature to optimize cobalt-nickel separation. By systematically investigating viscosity effects, this research provides critical insights into the physical limitations of solvent extraction systems and contributes to the development of more reliable models for industrial hydrometallurgical applications.

**Table 2.** Effect of diluent on Cyanex 272 viscosity at different concentrations and temperatures ($\mu$, cP) without metal loading.

| Concentration of cyanex 272 (% v/v) | Diluent (kerosene: % v/v) | Temperature (˚C) | | |
|---|---|---|---|---|
| | | 25 | 30 | 50 |
| 5 | 95 | 1.380 | 1.272 | 0.916 |
| 10 | 90 | 1.496 | 1.383 | 0.970 |
| 20 | 80 | 1.870 | 1.684 | 1.132 |
| 40 | 60 | 3.152 | 2.799 | 1.704 |
| 50 | 50 | 4.594 | 3.936 | 2.289 |

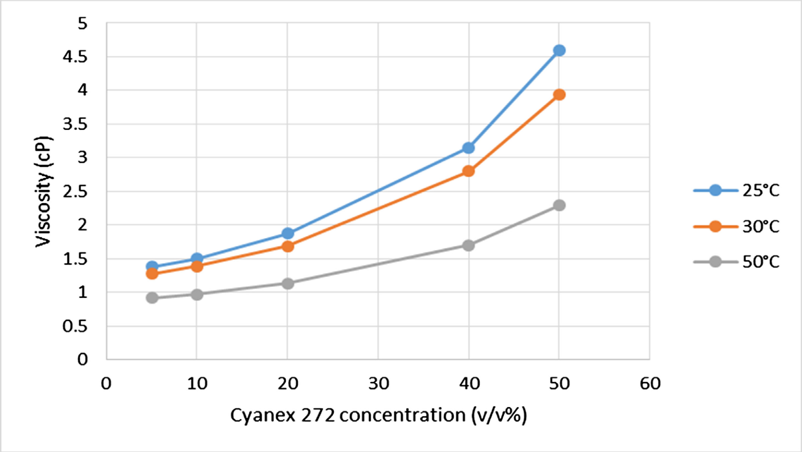


**Figure 4.** Effect of viscosity on Cynaex 272 extractant at different concentrations and temperature

Phase modifiers are commonly incorporated into solvent extraction systems to prevent the formation of a third phase, which can destabilize the separation process. For extractants such as PC-88A or Cyanex 272, the addition of a phase modifier becomes particularly important at high organic phase loadings, as it enhances mass transfer rates of solutes into the organic phase [1] [7]. Experimental observations (**Table 3**; **Figure 5**) confirm that increasing temperature reduces the viscosity of the organic phase, thereby improving its flow properties and facilitating solute transfer. Based on systematic evaluation, the combination of 15% Cyanex 272 with kerosene as diluent and 5% iso-octanol as modifier was identified as the optimum operating conditions at ambient temperature. This formulation not only minimizes the amount of extractant required, reducing costs but also achieves lower viscosity values, which directly increase the mass transfer coefficient of metal ions into the organic phase. Importantly, operating at ambient or relatively low temperatures is essential, since elevated temperatures can lead to miscibility of the aqueous and organic phases, eliminating the phase boundary necessary for extraction. At such high temperatures, the system behaves more like a distillation process rather than a solvent extraction system, undermining the separation efficiency. These findings highlight the critical role of phase modifiers and viscosity control in optimizing cobalt-nickel separation, ensuring both economic viability and technical effectiveness in hydrometallurgical applications.

**Table 3.** Effect of the mixture of diluent + modifier on Cyanex 272 viscosity at different concentrations and temperatures ($\mu$, cP) without metal loading.

| Concentration of cyanex 272 (% v/v) | 5% v/v Iso-octanol + kerosene | | Temperature (˚C) | | |
|---|---|---|---|---|---|
| | | | 25 | 30 | 50 |
| 5 | 5 | 90 | 1.454 | 1.289 | 0.916 |
| 10 | 5 | 85 | 1.585 | 1.417 | 0.992 |
| 15 | 5 | 80 | 1.751 | 1.569 | 1.063 |
| 20 | 5 | 75 | 1.947 | 1.749 | 1.169 |

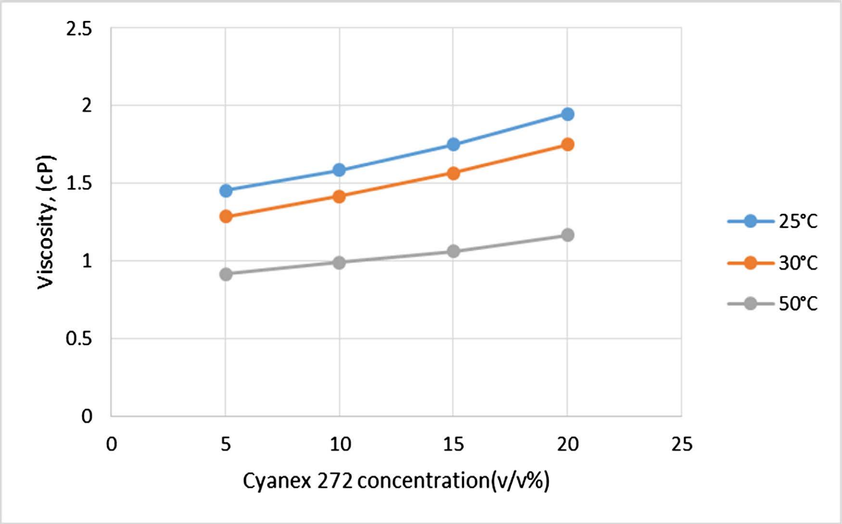


**Figure 5.** Effect of viscosity on the mixture of kerosene + iso-octanol (5 v/v%) on Cyanex 272 extractant at different concentrations and temperatures ($\mu$, cP) without metal loading.

The effect of the saponification ratio, expressed as the proportion of sodium salt formed, on the viscosity of the metal-loaded organic phase was systematically investigated using 15% v/v Cyanex 272 solutions. Experiments were conducted with 1 mol/L sulphate solutions of cobalt, nickel, and mixed cobalt-nickel to simulate realistic extraction conditions. Results (Table 4; Figure 6) clearly demonstrate that increasing the saponification ratio leads to a corresponding increase in both organic phase viscosity and metal loading capacity. This relationship is particularly pronounced in the cobalt and cobalt-nickel systems, where viscosity rises sharply once the saponification ratio approaches 70%. The observed viscosity increase at higher saponification levels is significant because it directly impacts diffusivity and mass transfer rates, thereby reducing extraction efficiency. These findings highlight the need to carefully optimize saponification ratios in order to balance metal loading capacity with acceptable viscosity levels, ensuring efficient cobalt-nickel separation under practical hydrometallurgical operating conditions. The increase is attributed to the degree of aggregation taking place in the organic phase as shown by the equations below:

*General equation:*

$$M^{2+}\,MA_{n-1}HA_{2(org)} + H_2A_{2(org)} \rightarrow \left(MA_2\right)_n H_2A_{2(org)} + 2H^+ \tag{12}$$

*For Cobalt*:

$$Co^{2+} + \left(CoA_2\right)_{n-1} H_2A_{2(org)} + 2H_2A_{2(org)} \rightarrow \left(CoA_2\right)_n H_2A_{2(org)} + 2H^+ \tag{13}$$

*For Nickel*:

$$Ni^{2+} + \left(NiA_2H_2A_2\right)_{n-1} H_2A_{2(org)} + 2H_2A_{2(org)} \rightarrow \left(NiA_2H_2A_2\right)_n H_2A_{2(org)} + 2H^+ \tag{14}$$

The sharp increase in viscosity observed at higher saponification ratios is attributed to the formation of large cobalt-Cyanex complexes and micellar structures within the organic phase [16] [17]. Long-chain alcohols and water molecules are also believed to participate in polymeric associations, further contributing to viscosity buildup. This phenomenon is critical because excessive viscosity reduces diffusivity and mass transfer rates, thereby limiting extraction efficiency. To mitigate this effect, viscosity must be controlled either by operating at lower extractant concentrations or by carefully regulating organic phase loading through the use of diluents and modifiers. Experimental results show that nickel-loaded organic phases exhibit higher viscosity compared to cobalt-loaded or mixed cobalt-nickel systems at saponification ratios below 70%. However, once the saponification ratio exceeds 70%, cobalt and cobalt-nickel systems display a dramatic rise in viscosity, underscoring the need to avoid excessive saponification. Operating near 70% saponification provides a practical balance: it maximizes metal loading while maintaining viscosity at levels that still permit efficient mass transfer. Importantly, in mixed systems cobalt is preferentially extracted, suppressing nickel uptake, which highlights the selectivity advantage of Cyanex 272. These findings emphasize the industrial relevance of optimizing saponification ratios, extractant concentrations, and phase modifiers to achieve efficient cobalt-nickel separation while minimizing viscosity-related limitations.

**Table 4.** Effect of different saponification ratios on the metal-loaded organic phase viscosity at different temperatures.

| | 80% Saponification ratio (SR) | | | 70% Saponification ratio (SR) | | | 60% Saponification ratio (SR) | | | 50% Saponification ratio (SR) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **T˚C** | **Ni** | **Co** | **Co + Ni** | **Ni** | **Co** | **Co + Ni** | **Ni** | **Co** | **Co + Ni** | **Ni** | **Co** | **Co + Ni** |
| 25 | 3.662 | 8.369 | 5.751 | 3.536 | 3.144 | 2.975 | 3.358 | 2.948 | 2.807 | 3.048 | 2.789 | 2.722 |
| 30 | 2.287 | 6.899 | 4.689 | 2.765 | 2.741 | 2.569 | 2.671 | 2.393 | 2.417 | 2.582 | 2.334 | 2.391 |
| 40 | 2.112 | 4.642 | 3.180 | 2.049 | 2.005 | 1.897 | 1.995 | 1.799 | 1.821 | 1.996 | 1.781 | 1.795 |
| 50 | 1.711 | 3.484 | 2.342 | 1.687 | 1.687 | 1.572 | 1.659 | 1.489 | 1.518 | 1.594 | 1.468 | 1.492 |

The viscosity experiments were conducted to establish reliable operating conditions for mass transfer coefficient studies in cobalt-nickel solvent extraction. Based on systematic evaluation, the optimum parameters were identified as 15% v/v Cyanex 272 as the extractant, kerosene as the diluent, and 5% v/v iso-octanol as the phase modifier, with a saponification ratio of 70% at 25˚C. These conditions are significant because they minimize extractant consumption, thereby reducing costs, while simultaneously maintaining low viscosity and ambient operating temperature to maximize diffusivity and mass transfer coefficients. The results highlight that cobalt-Cyanex complexes form aggregates that solubilize less water compared to nickel complexes, accounting for the lower viscosity observed in cobalt-loaded organic phases at saponification ratios below 70%. In contrast, nickel-loaded phases consistently exhibit higher viscosity, which directly impedes mass transfer. Importantly, once the saponification ratio exceeds 70%, both cobalt and mixed cobalt-nickel systems show a sharp increase in viscosity, underscoring the need to operate near but not beyond this threshold (**Figure 6**). These findings are highly relevant for hydrometallurgical practice, as they provide a clear operating window that balances extractant efficiency, viscosity control, and cost reduction, ultimately enhancing the separation performance of Co-Ni systems.

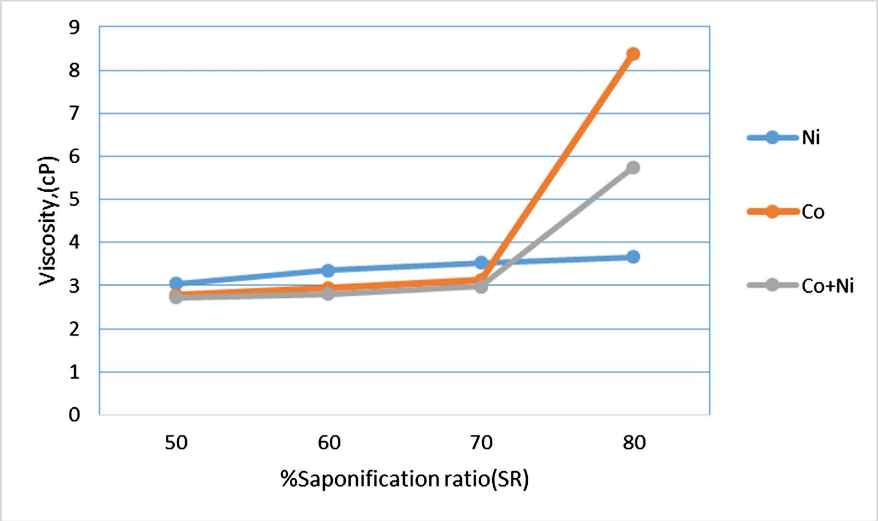


**Figure 6.** Effect of saponification ratio (SR) on the loaded organic phase viscosity at 25˚C (15% v/v Cyanex 272 using kerosene as diluent and 5% v/v iso-octanol as modifier).

### 4.2. Results on the Effect of Viscosity on Mass Transfer Coefficient

Mass transfer coefficient experiments were conducted under carefully optimized conditions to ensure reproducibility and industrial relevance. The organic phase consisted of 15% v/v Cyanex 272 as the solvent extractant, 5% v/v iso-octanol as the phase modifier, and kerosene as the diluent, with a saponification ratio maintained at 70% and experiments performed at 25˚C. These conditions were selected to minimize extractant consumption, reduce viscosity, and maintain ambient operating temperatures, thereby maximizing diffusivity and mass transfer coefficients.

Cobalt sulphate heptahydrate ($CoSO_4 \cdot 7H_2O$) and nickel sulphate hexahydrate ($NiSO_4 \cdot 6H_2O$) were used as metal sources, with solution concentrations adjusted to reflect those typically encountered in industrial leach liquors. This approach ensured that the experimental system closely simulated real hydrometallurgical conditions, providing results that are both scientifically rigorous and practically applicable to large-scale cobalt-nickel separation processes. The influence of organic phase viscosity on the mass transfer coefficient during cobalt-nickel extraction with Cyanex 272 can be explained through the interplay of fluid dynamics and molecular transport. In solvent extraction systems, mass transfer occurs primarily at the interface between the aqueous and organic phases, where solute ions migrate across the boundary and form coordination complexes with the extractant. When the organic phase viscosity is high, droplet mobility is reduced, interfacial renewal slows, and the diffusivity of solute complexes through the organic medium decreases. This leads to lower mass transfer coefficients because the rate of solute transport is limited by resistance within the viscous organic layer. Conversely, reducing viscosity with diluents such as kerosene and modifiers like iso-octanol enhances droplet circulation and interfacial turbulence, thereby increasing diffusivity and accelerating solute transfer.

Mass transfer coefficient measurements were carried out at varying Cyanex 272 concentrations (15, 20, and 25% v/v), with 5% v/v iso-octanol as modifier, kerosene as diluent, and a saponification ratio of 70% at 25˚C. The viscosity of the organic phase increased significantly with extractant concentration, rising from 5.347 cP at 15% Cyanex 272 to 15.291 cP at 20% and 30.679 cP at 25% (**Table 5**). Correspondingly, the mass transfer coefficients decreased, confirming the inverse relationship between viscosity and diffusivity. Although larger droplet diameters ($d_p$) produced slight increases in the mass transfer coefficient ($K_{od}$), the overall trend demonstrates that higher viscosity strongly suppresses solute transfer across the phase boundary. Mechanistically, viscosity affects three critical aspects of mass transfer. First, it governs droplet dynamics: lower viscosity allows droplets to deform, circulate, and renew their interface more effectively, which increases the available surface area for solute exchange. Second, it influences diffusion rates: solute complexes such as tetrahedral cobalt-Cyanex 272 species diffuse more rapidly in a less viscous medium, while octahedral nickel complexes, already hindered by stronger hydration, are further slowed in viscous conditions. Third, viscosity impacts interfacial resistance: a thinner, less viscous organic boundary layer reduces the barrier to solute migration, thereby raising the overall mass transfer coefficient. These findings are consistent with literature reports that elevated viscosity in the organic phase reduces mass transfer rates, thereby limiting extraction efficiency. The results underscore the importance of optimizing extractant concentration to maintain viscosity at levels conducive to effective cobalt-nickel separation, directly supporting the research objective of identifying operating conditions that maximize mass transfer performance while minimizing process limitations. These results align with established literature, reinforcing that viscosity control is critical for optimizing cobalt-nickel separation efficiency.

**Table 5.** Mass transfer coefficients results for the loaded organic phase.

| 15% v/v Cyanex 272; $\mu = 5.347$ cP | | | | | 20% v/v Cyanex 272; $\mu = 15.291$ cP | | | | | 25% v/v Cyanex 272; $\mu = 30.679$ cP | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $d_p$ (mm) | $u_t$ (m/s) | $Q$ (mL/min) | $E$ | $K_{od} \cdot 10^5$ (m/s) | $d_p$ (mm) | $u_t$ (m/s) | $Q$ (mL/min) | $E$ | $K_{od} \cdot 10^5$ (m/s) | $d_p$ (mm) | $u_t$ (m/s) | $Q$ (mL/min) | $E$ | $K_{od} \cdot 10^5$ (m/s) |
| 2.81 | 0.0927 | 0.24 | 0.0717 | 0.797 | 3.06 | 0.0821 | 0.30 | 0.0411 | 0.434 | 3.47 | 0.0792 | 0.35 | 0.0296 | 0.338 |
| 2.91 | 0.0946 | 0.26 | 0.0692 | 0.813 | 3.17 | 0.0876 | 0.32 | 0.0458 | 0.536 | 3.63 | 0.0813 | 0.38 | 0.0306 | 0.378 |
| 3.00 | 0.0967 | 0.28 | 0.0701 | 0.867 | 3.26 | 0.0908 | 0.34 | 0.0549 | 0.696 | 3.73 | 0.0828 | 0.40 | 0.0317 | 0.409 |
| 3.19 | 0.0990 | 0.32 | 0.0706 | 0.951 | 3.41 | 0.0924 | 0.36 | 0.0586 | 0.783 | 3.81 | 0.0845 | 0.42 | 0.0397 | 0.532 |
| 3.30 | 0.1012 | 0.35 | 0.0694 | 0.988 | 3.59 | 0.0938 | 0.38 | 0.0552 | 0.788 | 3.98 | 0.0863 | 0.44 | 0.0413 | 0.597 |
| 3.66 | 0.1072 | 0.40 | 0.0631 | 1.052 | 3.86 | 0.0978 | 0.44 | 0.0541 | 0.864 | 4.48 | 0.0898 | 0.52 | 0.0394 | 0.665 |
| 3.91 | 0.1098 | 0.44 | 0.0613 | 1.118 | 4.20 | 0.1022 | 0.48 | 0.0500 | 0.906 | 4.89 | 0.0970 | 0.58 | 0.0382 | 0.761 |

**Figure 7** demonstrates that mass transfer coefficients are significantly higher at lower viscosity values compared to systems with elevated viscosity. This trend highlights the critical role of viscosity control in optimizing solute diffusion across the phase boundary. Additionally, the results show that increasing droplet diameter ($d_p$) enhances mass transfer coefficients, as larger drops provide greater interfacial area for solute transfer. From the experimental data, the most favorable operating conditions are achieved at 15% v/v Cyanex 272, corresponding to a viscosity of approximately 5.347 cP, with droplet diameters in the range of 3.30 - 3.90 mm. Under these conditions, mass transfer rates and overall coefficients are maximized, ensuring efficient diffusion of metal ions into the organic phase. These findings are directly relevant to the research objectives, as they establish practical operating parameters that balance extractant concentration, viscosity, and droplet size to achieve high solvent extraction efficiency and effective separation of cobalt-nickel systems.

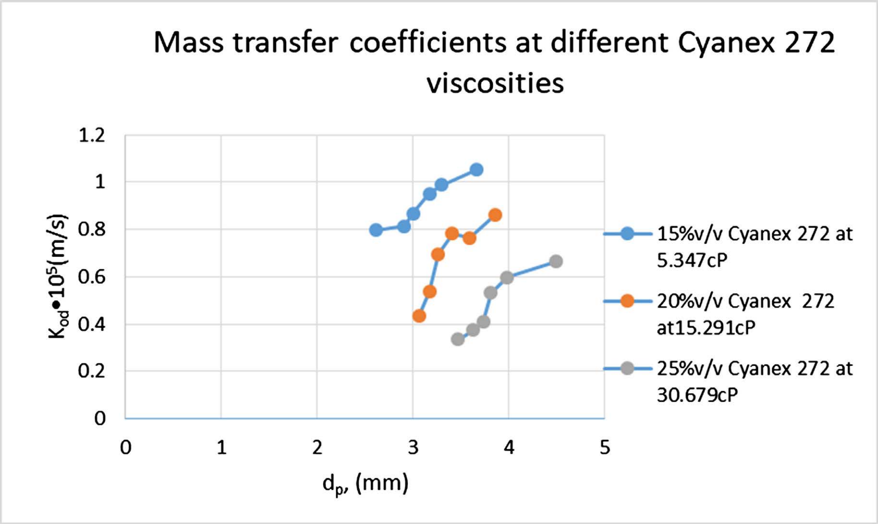


**Figure 7.** Mass transfer coefficients at different Cyanex 272 concentrations and viscosities during Co-Ni solvent extraction and separation.

The systematic control of viscosity provides a direct operating window for optimizing cobalt-nickel separation. By lowering viscosity below 10 cP at 15% v/v Cyanex 272, diffusivity is maximized, enabling preferential extraction of cobalt due to its hydrophobic tetrahedral complexes, while nickel remains in the aqueous phase with its hydrophilic octahedral complexes. Thus, viscosity is not merely a physical property but a mechanistic determinant of extraction efficiency, directly linking fluid dynamics to coordination chemistry. This insight underscores the novelty of the research: demonstrating how viscosity control enhances mass transfer coefficients and cobalt selectivity, offering practical guidance for industrial hydrometallurgical operations.

The results presented in Figure 8 clearly demonstrate that cobalt is preferentially extracted over nickel when using Cyanex 272, confirming the higher loading of Co compared to Ni in the organic phase. This difference in extractive behaviour is explained by fundamental coordination chemistry. Cobalt ions form tetrahedral complexes with organophosphorous acid reagents, while nickel ions form octahedral complexes. The tetrahedral geometry of cobalt complexes allows for tighter packing and reduced steric hindrance, making cobalt extraction less sensitive to structural variations in the extractant [9] [16] [17]. In contrast, nickel's octahedral complexes are more affected by steric hindrance introduced by branching in the alkyl chains of Cyanex 272, which reduces its extractability. Additionally, the degree of hydration of the extracted complexes plays a critical role. Cobalt complexes are less hydrated compared to nickel complexes, further enhancing their stability and affinity for the organic phase. This strong coordination affinity of Cyanex 272 for cobaltous ions results in a higher separation factor in Co-Ni systems, directly favouring cobalt uptake while suppressing nickel extraction. The experimental observations (Figure 8, Figure 9) are in full agreement with these mechanistic insights, showing consistently higher cobalt loading relative to nickel under identical conditions. From a practical standpoint, these findings are highly relevant to the research objectives: they establish that Cyanex 272 provides

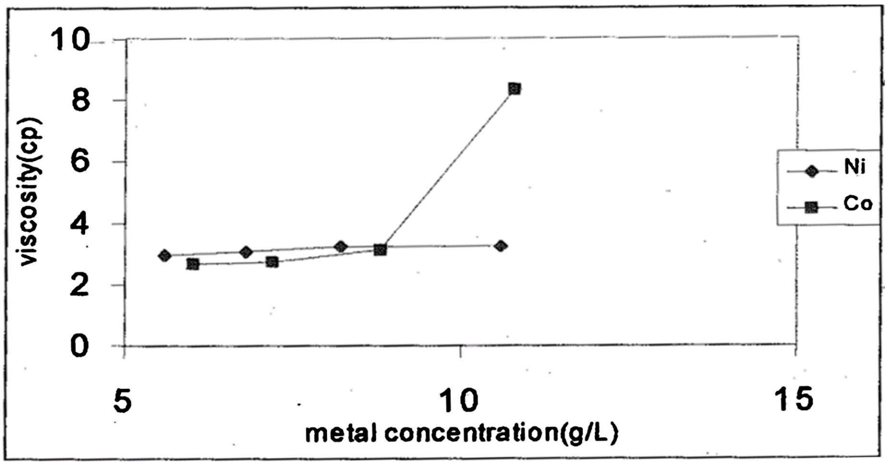


Figure 8. Metal loading on organic phase (15% v/v Cyanex 272, 5% v/v iso-octanol as modifier in kerosene as diluent and 70% SR at 5.347cP with drop diameter ranging from 3.30 to 3.90 mm at 25˚C) during Co-Ni separation.

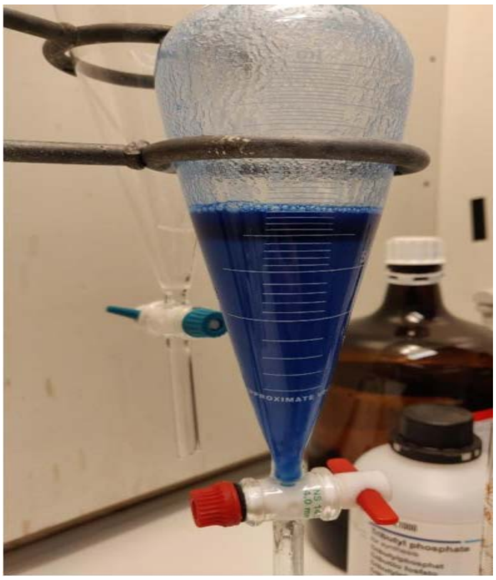


**Figure 9.** Coronal, sagittal and axial views of plain CT scan of the abdomen showing a diffuse collection of gas in the bladder wall.

selective extraction of cobalt over nickel, which is essential for efficient separation in hydrometallurgical processes. By understanding the structural and hydration differences between Co and Ni complexes, process engineers can optimize solvent extraction conditions to maximize cobalt recovery while minimizing nickel co-extraction. This selectivity not only improves separation efficiency but also reduces downstream purification requirements, thereby lowering operational costs and enhancing the overall sustainability of cobalt-nickel extraction systems.

Figure 9 shows the blue color indicating cobalt ions in both phases, thus the organic phase which is at the top being darker in color and the organic phase at the bottom being lighter in color.

## 5. Conclusion

The study investigated the influence of organic phase viscosity on mass transfer coefficients during cobalt-nickel separation using Cyanex 272 and established viscosity as a key mechanistic factor governing solvent extraction efficiency. The research aimed to determine how viscosity, coordination chemistry, and micellar mechanisms collectively affect cobalt selectivity and extraction performance. A systematic experimental methodology was employed using different diluents, modifiers, and saponification conditions, with optimum operating parameters identified as 15% v/v Cyanex 272 in kerosene, 5% v/v iso-octanol, and 70% saponification at 25˚C. Advanced experimental equipment, including a drop swarm column fitted with precision syringe pumps and video imaging systems, enabled accurate analysis of droplet dynamics, interfacial behavior, and mass transfer performance. The findings demonstrated that reducing the viscosity of the organic phase to below 10 cP significantly enhanced diffusivity, lowered interfacial resistance, and increased mass transfer coefficients, thereby improving cobalt extraction and cobalt-nickel separation efficiency. The preferential extraction of cobalt was attributed to its formation of tetrahedral hydrophobic complexes with lower water retention, whereas nickel forms octahedral hydrophilic complexes that retain more water molecules and therefore transfer less readily into the organic phase. The study's novelty lies in integrating fluid dynamics, coordination chemistry, and reverse micelle mechanisms to explain selective extraction behavior. These insights provide practical strategies for more efficient, cost-effective, and sustainable hydrometallurgical processes, particularly for producing high-purity battery-grade cobalt and nickel for energy storage technologies.

## Acknowledgements

The research team thanks the National University of Science and Technology (Bulawayo, Zimbabwe) and Tsinghua University (China) for providing the resources and sponsorship for the success of the research.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

[1] Rodrigues, I.R., Deferm, C., Binnemans, K. and Riaño, S. (2022) Separation of Cobalt and Nickel via Solvent Extraction with Cyanex-272: Batch Experiments and Comparison of Mixer-Settlers and an Agitated Column as Contactors for Continuous Counter-Current Extraction. *Separation and Purification Technology*, **296**, Article ID: 121326. https://doi.org/10.1016/j.seppur.2022.121326

[2] Belhadj, N., Benabdallah, T., Coll, M.T., Fortuny, A., Hadj Youcef, M. and Sastre, A.M. (2019) Counter-Current Separation of Cobalt(II)-Nickel(II) from Aqueous Sulphate Media with a Mixture of Primene JMT-Versatic 10 Diluted in Kerosene. *Separation Science and Technology*, **55**, 513-522. https://doi.org/10.1080/01496395.2019.1577271

[3] Mudono, S., Tshuma, J., Manhongo, T.T., Madzokere, T.C., Tsorai, P. and Witika, L.K. (2018) The Use of Nano- Synthesis Methodology on Electrochemical Performance of $LiMn_2O_4$ Cathode at Elevated Temperature. *MRS Advances*, **3**, 2589-2602. https://doi.org/10.1557/adv.2018.297

[4] Leon, G., Martinez, G., Leon, L. and Guzman, M.A. (2016) Separation of Cobalt from Nickel Using Novel Ultrasound-Prepared Supported Liquid Membranes Containing Cyanex 272 as Carrier. *Physicochemical Problems of Mineral Processing*, **52**, 77-86.

[5] Ghonem, E.A., Hamed, M.M., Mohamad, Y.T., El-Reefy, S.A., Hegazy, M. and Abd El-Wahed, A. (2015) Extraction of Cobalt (II) from Sulphate Medium and Possible Separation from Nickel (II). *Arab Journal of Nuclear Science and Applications*, **48**, 17-21.

[6] Adekola, F., Baba, A.A. and Ayanda, O.S. (2010) Solvent Extraction of Cobalt and Nickel from Nigeria Lateritic Soil. *Journal of Chemical Society of Nigeria*, **35**, 123-128.

[7] Liu, Y., Nam, S. and Lee, M. (2015) A Study on the Separation of Co(II), Ni(II), and Mg(II) by Solvent Extraction with Cationic Extractants. *Bulletin of the Korean Chemical Society*, **36**, 2646-2650. https://doi.org/10.1002/bkcs.10535

[8] Wang, J., Fu, J., Yu, F., Xu, W. and Wang, H. (2020) An Efficient Extractant (2-Ethylhexyl)(2,4,4'-Trimethylpentyl)Phosphinic Acid (USTB-1) for Cobalt and Nickel Separation from Sulfate Solutions. *Separation and Purification Technology*, **248**, Article ID: 117060. https://doi.org/10.1016/j.seppur.2020.117060

[9] Ichlas, Z.T. (2015) Development of a Solvent Extraction Process for the Recovery of Nickel and Cobalt from Nitrate Solutions. Master's Thesis, Curtin University.

[10] Hereijgers, J., Vandermeersch, T., Van Oeteren, N., Breugelmans, T. and De Malsche, W. (2016) Separation of Co(II)/Ni(II) with Cyanex 272 Using a Flat Membrane Microcontactor: Stripping Kinetics Study, Upscaling and Continuous Operation. *Chemical Engineering Research and Design*, **111**, 305-315. https://doi.org/10.1016/j.cherd.2016.05.025

[11] Flett, D.S. (2004) Cobalt-Nickel Separation in Hydrometallurgy: A Review. *Chemistry for Sustainable Development*, **12**, 81-91.

[12] Ayanda, O.S., Adekola, F.A., Baba, A.A., Ximba, B.J. and Fatoki, O.S. (2013) Application of Cyanex Extractant in Cobalt/Nickel Separation Process by Solvent Extraction. *International Journal of Physical Sciences*, **8**, 89-97. https://doi.org/10.5897/ijps12.135

[13] Yu, S., Zhang, J., Li, S., Chen, Z. and Wang, Y. (2023) Mass Transfer and Droplet Behaviors in Liquid-Liquid Extraction Process Based on Multi-Scale Perspective: A Review. *Separations*, **10**, Article 264. https://doi.org/10.3390/separations10040264

[14] Vušak, D., Smrečki, N., Muratović, S., Žilić, D., Prugovečki, B. and Matković-Čalogović, D. (2021) Structural Diversity in the Coordination Compounds of Cobalt, Nickel and Copper with *n*-Alkylglycinates: Crystallographic and ESR Study in the Solid State. *RSC Advances*, **11**, 23779-23790. https://doi.org/10.1039/d1ra04219j

[15] Fugleberg, S., Hultholm, S., Rosenback, L. and Holohan, T. (1995) Development of the Hartley Platinum Leaching Process. *Hydrometallurgy*, **39**, 1-10. https://doi.org/10.1016/0304-386x(95)00021-8

[16] Kursunoglu, S. and Kaya, M. (2019) Hydrometallurgical Processing of Nickel Laterites—A Brief Overview on the Use of Solvent Extraction and Nickel/Cobalt Project for the Separation and Purification of Nickel and Cobalt. *Bilimsel Madencilik Dergisi*, **58**, 131-144. https://doi.org/10.30797/madencilik.580147

[17] Wang, L.Y. and Lee, M.S. (2017) Synergistic Extraction of Co(II) over Ni(II) from Chloride Solutions by a Mixture of Cyanex 301 and LIX 63. *Geosystem Engineering*, **20**, 311-317. https://doi.org/10.1080/12269328.2017.1323680