

**IMPROVED LIQUID-LIQUID EJECTOR PERFORMANCE
FOR EMULSION GENERATION APPLICATION**

BY

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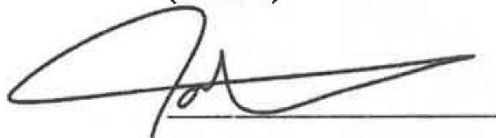
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**Dedicated to My Beloved Mother and Father,
My Beloved Elder Brother Abdullah,
My Beloved Brothers and Sisters,
My Beloved Nephews and Nieces.**

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LIST OF ABBREVIATIONS AND NUMENCLATURE

<i>Symbol</i>	<i>Definition</i>	<i>Dimension</i>	<i>Unit</i>
A_{ME}	Mixing Chamber Area Ratio	$M^0L^0T^0$	-
C	Density Ratio	$M^0L^0T^0$	-
DR	Drag Reduction	$M^0L^0T^0$	-
D_n	Nozzle Diameter	L	m
D_t	Throat Diameter	L	m
H_m	Motive/Primary Flow Head	L	m
H_s	Suction Flow Head	L	m
H_d	Discharge Flow Head	L	m
K_p	Primary Flow Loss Coefficient	$M^0L^0T^0$	-
K_s	Suction Flow Loss Coefficient	$M^0L^0T^0$	-
K_m	Mixing Chamber Flow Loss Coefficient	$M^0L^0T^0$	-
K_d	Discharge Flow Loss Coefficient	$M^0L^0T^0$	-
$K_{f,m}$	Primary Flow Friction Loss Coefficient	$M^0L^0T^0$	-
$K_{f,s}$	Suction Flow Friction Loss Coefficient	$M^0L^0T^0$	-

$K_{f,d}$	Discharge Flow Friction Loss Coefficient	$M^0L^0T^0$	-
M	Entrainment Ratio	$M^0L^0T^0$	-
N	Pressure Ratio	$M^0L^0T^0$	-
P_d	Discharge Pressure	$ML^{-1}T^{-2}$	Kg/cm^2
P_s	Suction Pressure	$ML^{-1}T^{-2}$	Kg/cm^2
P_m	Motive Pressure	$ML^{-1}T^{-2}$	Kg/cm^2
Q_d	Discharge Flow Rate	$M^0L^3T^{-1}$	GPM
Q_p	Primary/Motive Flow Rate	$M^0L^3T^{-1}$	GPM
Q_s	Suction Flow Rate	$M^0L^3T^{-1}$	GPM
R	Area Ratio	-	-
V_d	Discharge Flow Velocity	LT^{-1}	m/s
V_m	Primary/Motive Flow Velocity	LT^{-1}	m/s
V_n	Nozzle Flow Velocity	LT^{-1}	m/s
V_s	Suction Flow Velocity	LT^{-1}	m/s
X	Flow Rate Fraction	-	-
$\Delta P_{with\ DRA}$	Pressure Drop with Drag Reducing Agent	$ML^{-1}T^{-2}$	Kg/cm^2
$\Delta P_{without\ DRA}$	Pressure Drop without Drag Reducing Agent	$ML^{-1}T^{-2}$	Kg/cm^2
η_{A1}	Analytical Type 1 Efficiency	$M^0L^0T^0$	-
η_{A2}	Analytical Type 2 Efficiency	$M^0L^0T^0$	-

η_{EX}	<i>Experimental Efficiency</i>	$M^0L^0T^0$	-
η_{HR}	<i>Head Ratio Efficiency</i>	$M^0L^0T^0$	-
θ_d	<i>Divergence Angle</i>	$M^0L^0T^0$	<i>deg</i>
ρ_p	<i>Primary Fluid Density</i>	ML^{-3}	Kg/m^3
ρ_s	<i>Secondary Fluid Density</i>	ML^{-3}	Kg/m^3
DRA	<i>Drag Reducing Agents</i>		
DRP	<i>Drag Reducing Polymers</i>		
EAS	<i>Emulsified Acid System</i>		
EOR	<i>Enhanced Oil Recovery</i>		
NXP	<i>Nozzle Exit Position</i>		
SFR	<i>Suction Flow Rate</i>		
SP	<i>Suction Pressure</i>		

ABSTRACT

Full Name : Abdulelah Kassar Eid Al-Shammari
Thesis Title : Improved Liquid-Liquid Ejector Performance for Emulsion Generation Application
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Emulsion generation is a crucial process for enhanced oil recovery (EOR) and other applications where two immiscible liquids need to be mixed. One method to generate emulsions is using controlled ejector devices, which can be inefficient due to friction losses. To address this, drag reducing additives (DRAs) can be added to reduce friction and improve the performance of the ejector. This approach is not only cost-effective but also efficient, resulting in improved productivity and lower energy consumption. This study aims to improve the efficiency and suction capacity of an ejector for emulsion generation. The specific objectives include investigating the impact of different flow rates and DRA concentrations on the performance of the ejector. By understanding the factors that influence the ejector's performance, this work aims to find ways to improve its ability to generate emulsions. The expected outcome is a better understanding of how to optimize the performance of the ejector and generate emulsions more efficiently, contributing to advancements in EOR and other applications.

ملخص الرسالة

الاسم الكامل: عبدالاله كسار عيد الشمري

عنوان الرسالة: تحسين أداء المضخة النفائثة سائل-سائل في تطبيق إنتاج المستحلبات.

التخصص: هندسة ميكانيكية

تاريخ الدرجة العلمية: مايو 2024

يعد توليد المستحلب عملية مهمة في مجال الاستخلاص المعزز للنفط والتطبيقات الأخرى حيث يلزم خلط سائلين غير قابلين للامتزاج. تتمثل إحدى طرق توليد المستحلبات في استخدام أجهزة المضخات القاذفة التي يمكن التحكم فيها، والتي يمكن أن تكون غير فعالة بسبب فقد الاحتكاك. ولمعالجة هذه المشكلة، يمكن إضافة إضافات تقليل السحب لتقليل الاحتكاك وتحسين أداء القاذف. وهذا النهج ليس فعالاً من حيث التكلفة فحسب، بل يتسم بالكفاءة أيضاً، مما يؤدي إلى تحسين الإنتاجية وانخفاض استهلاك الطاقة. تهدف هذه الدراسة إلى تحسين كفاءة وقدرة الشفط للقاذف لتوليد المستحلب. وتشمل الأهداف المحددة دراسة تأثير معدلات التدفق المختلفة وتركيزات مبلورات تقليل السحب على أداء القاذف. ومن خلال فهم العوامل التي تؤثر على أداء القاذف، يهدف هذا العمل إلى إيجاد طرق لتحسين قدرته على توليد المستحلبات. والنتيجة المتوقعة هي فهم أفضل لكيفية تحسين أداء القاذف وتوليد المستحلبات بشكل أكثر كفاءة، والمساهمة في التقدم في الاستخلاص المعزز للنفط والتطبيقات الأخرى.

CHAPTER 1

INTRODUCTION

1.1 Introduction:

Among all compressors and vacuum pumps, jet ejectors are the most straightforward equipment. Since they don't have any moving parts, lubricants, or seals, they are thought of as very dependable machines with low initial and ongoing expenditures. Additionally, the motive fluid for the majority of jet ejectors is steam or compressed air, both of which may be found in chemical plants. Jet ejectors are employed often in chemical industrial processes because of their simplicity and excellent reliability; however, they are inefficient. Among the many variables that determine jet ejector performance are the Reynolds number, the primary flow velocity, fluid temperature, throat characteristics, length of the mixing chamber, placement of the nozzle, molecular weight, and the ratios of the specific heat and pressure[1]. An earlier study tried to investigate how the position of the nozzle affected the effectiveness of the jet ejector. Kumar V, Subbarao P and Singhal G came to the conclusion that the nozzle placement, which influences the length over which the primary and secondary streams are fully merged, had a significant impact on the jet ejector efficiency. Before entering the throat region, the nozzle is supposed to be positioned between 0.5 and 1.0 lengths of throat diameter away[2]. Holton and Schultz investigated the impact of fluid temperature, the influence of fluid molecular weight studied

briefly by Work L, Haedrich V[3]. Many of researchers did an effort to investigate the influence of jet ejector parameters on jet ejector efficiency. For instance, Hamedi-Estakhrsar M et al.[4] investigated the effect of divergence, convergence, length, and half-angles on of the throat section, also kroll[5] did an effort to investigate nozzle placement, secondary fluid entrance, and primary velocity.

1.2 Problem Statement:

Emulsion generation is a process in which two immiscible liquids, such as oil and water, are mixed together to form a stable mixture known as an emulsion. This process is important in enhanced oil recovery (EOR), as it can help to increase the amount of oil that can be extracted from an oil reservoir. One way to generate emulsions is by using controlled ejector devices which they work by controlling the valves that regulate the flow rates of fluid entering or exiting the ejector. The valves can be adjusted to increase or decrease the flow of fluid, allowing for precise control of the ejector's operation. However, the efficiency of these devices can be low due to various losses, including friction. To improve the efficiency of the ejector and increase its suction capacity, we propose here the use of drag reducing additives (DRA). These additives are typically polymers that are added to the oil-water mixture in order to reduce the friction between the two liquids, which can significantly improve the performance of the ejector. Using additives to improve the performance of an ejector is a technique that offers several benefits. One of the main advantages of this approach is that it is economically viable, meaning that it is cost-effective and affordable.

Additionally, this technique is also more efficient, meaning that it can help to improve the overall performance and productivity of the ejector. By reducing friction and improving the flow of the working fluid, the ejector can operate more efficiently, requiring less energy and resources to achieve the same level of output. Overall, this technique offers a cost-effective and efficient way to improve the performance of an ejector.

1.3 Objectives:

The main goal of this work is to improve the efficiency and suction capacity of an ejector. To achieve this, the following specific objectives have been identified:

- To study the impact of different flow rates on the performance of the ejector when no drag reducing polymer (DRP) is used.
- To examine the effect of flow rates on the performance of the ejector when DRP is used.
- To investigate the influence of the concentration of DRP on the performance of the ejector.

The main focus of this work is to understand how different variables, including flow rates and the concentration of drag reducing polymer (DRP), can affect the performance of an ejector. Moreover, the ultimate goal of this work is to find ways to improve the efficiency and suction capacity of the ejector, specifically with regard to its ability to generate emulsions. By studying the impact of these different factors on the performance of the

ejector. Overall, the aim of this work is to improve the performance of the ejector for emulsion generation through a thorough understanding of the factors that influence its performance.

1.4 Study Motivation:

In conventional applications, the jet pump has been extensively studied in the literature to optimize its performance. Previous research primarily focused on designing and enhancing the jet pump to maximize its efficiency and overall performance. These studies aimed at achieving higher levels of suction, better fluid entrainment, and improved overall energy efficiency.

The existing literature offers valuable insights into the various design parameters and operational factors that influence the jet pump's performance. Researchers have explored the impact of factors such as nozzle geometry, diffuser angles, mixing chamber length, motive flow rate, and fluid properties on the pump's efficiency.

While much of the research has concentrated on improving the jet pump's performance through design modifications, there remains a notable gap in the literature regarding other potential enhancements and operational aspects. Specifically, limited attention has been given to exploring alternative ways to improve the performance of the jet pump using drag reducing polymers (DRPs) without changing its design. Additionally, studies focusing on the optimization of the pump's performance under varying operational conditions, such as fluctuating flow rates, are relatively scarce.

One important application of the jet pump, where DRPs can play a key role, is in mixing and emulsion generation. Emulsion is widely used in several industries, including the

petroleum industry, where the production of oil and gas from subsurface reservoirs involves the use of emulsion. In particular, emulsified acid is used to stimulate hydrocarbon wells completed across carbonate reservoirs. In this type of emulsion, hydrochloric acid serves as the inner phase, while diesel acts as the outer continuous phase. This emulsion delays the direct contact of the acid with the reservoir rock, retarding the reaction rate and achieving deeper penetration in the hydrocarbon reservoir. Typically, this emulsion is prepared using a combination of mixing tanks, agitators, and c-pumps. The emulsification process using this equipment and the standard procedure is operationally time-consuming and results in an emulsion associated with high friction pressure.

Jet pumps provide an excellent alternative for preparing emulsion on the fly with a smaller surface footprint. By incorporating DRPs, the friction pressure from emulsified associated with the conventional mixing method can be reduced. This serves as an additional motivation to improve the efficiency of jet pumps with DRPs.

In response to the identified literature gap and industrial requirement, this research study was undertaken to comprehensively investigate the influence of drag-reducing polymers on the performance of a liquid jet pump. The study aims to fill the existing knowledge void by examining the effects of these polymers under various operational conditions, including the partial closure of the suction flow rate valve. The motivation behind this research lies in the potential benefits that drag-reducing polymers can offer to enhance the efficiency and effectiveness of liquid jet pumps. Previous literature has provided limited insights into the utilization of such polymers in this specific context. Therefore, this study seeks to address this deficiency and contribute to a more profound understanding of the impact of these additives on the jet pump's overall performance.

CHAPTER 2

LITERATURE REVIEW

Engineers employed "rule-of-thumb" or "trial-and-error" methods in the past to create jet ejectors. Both methods could produce inefficient results, necessitating additional energy, materials, and effort. The characteristics of the convergence region are used to characterize conventional jet ejectors. Two categories exist:

1. Jet ejector with constant area.
2. Jet ejector with constant pressure.

According to recent findings, the ejector operating at a constant pressure demonstrates greater efficiency in comparison to the ejector with a constant area. The reason for this is that the efficiency of turbulent mixing in the jet-ejector is higher under a negative pressure gradient[6], and this effect is more pronounced in the constant-area jet ejector than in the constant-pressure jet ejector. Increased turbulent mixing results in a reduction in the ejector efficiency. Mathematical functions that apply to both categories of ejectors have been provided by DeFrate and Hoerl[6]. The functions encompass two key aspects:

- 1.The relationship between the area ratio (D_n/D_t).
- 2.The correlation between the optimal motive and secondary-stream velocity and molecular weight and temperature. **(Fig.1)** illustrates how the two categories differ from one another.

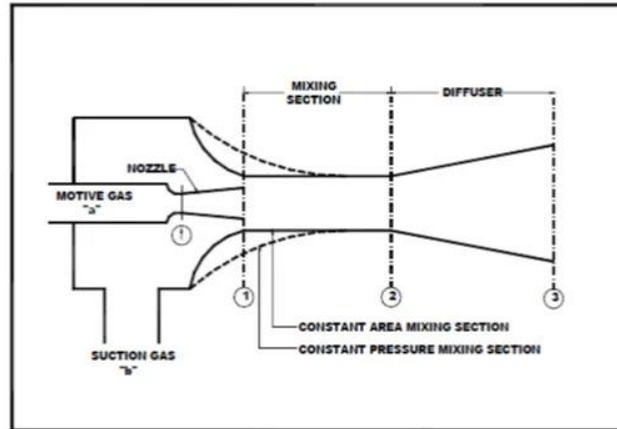


Figure 1 Jet ejectors differences

The primary factors influencing the efficiency of the jet ejector are mixing, turbulence, friction, separation, and energy expenditure in the Secondary stream's suction. The main objective should be to improve turbulent mixing in order to improve jet ejector efficiency. To increase the tangential shear contact between the secondary and primary stream, the literature suggests that the nozzle shape should be well-designed. Furthermore, the two streams must totally converge inside the throat. To minimize the impacts of turbulence, the jet ejector needs to be appropriately engineered. The following section provides an explanation of each component of a jet ejector. The geometric symbols used in the current part are shown in **Figure 2**).

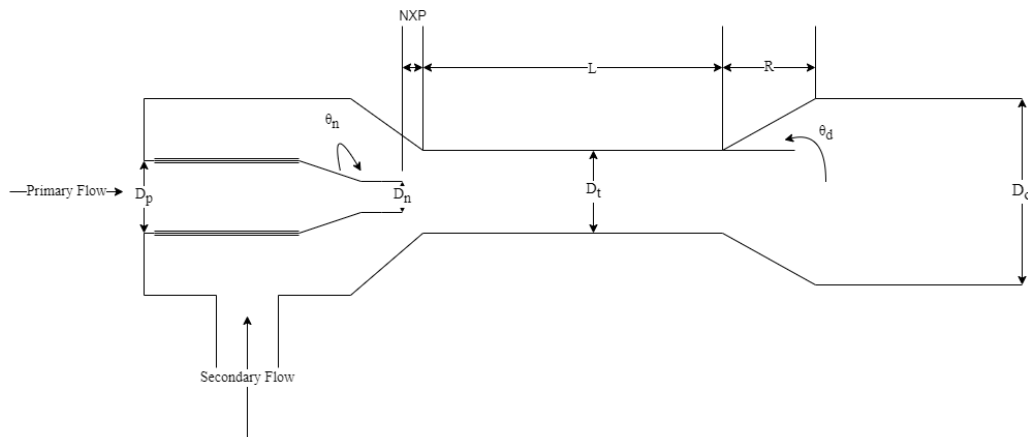


Figure 2 Jet ejector geometric symbols

2.1 Ejector Efficiency Influenced by Design Factors:

A larger maximum vacuum was created by ejectors with cylindrical throats than by those with progressive constriction tapering off to the outlet, according to experimental results from Mellanby[7]. Additionally, he said that a jet's ability to entrain a fluid is independent of the point along the jet where the entrained fluid enters. No justification was provided for potential causes. The efficiency of an ejector is significantly influenced by the distance between the diffuser throat and the nozzle exit. The maximum value of this length, according to Watson[8] was shown to decrease with rising nozzle supply pressure and increase with rising vacuum. Additionally, he said that it is crucial to position the nozzle such that it is concentric with the throat's axis and that even a very minor adjustment in the size of the throat can have a significant impact on the amount of air entrained. Choking will happen if the throat is too small (the liquid will fill the throat and the absorbed gas will be unable to pass through), and air leakage into the system will happen if the throat is too large.

For pressure recovery, a long, slowly diverging diffuser is preferred. Additionally, it has been shown that a well-rounded entry is the ideal shape for the entrance to the diffuser throat[9]. In order to prevent the nozzle jet, which also has an angle of around 20 degrees, from causing unfavorable shock and eddy losses at the intake, they determined that a conical or tapered entry should have an angle greater than 20 degrees.

The angle of the diverging section, θ_d is typically 4 to 10 degrees. It is not counseled to deviate too quickly just after the throat[5]. For pressure recovery, a divergent length of, say, four to eight times the throat diameter is preferred. However, if necessary, the length might be cut to only twice the throat diameter. It was found that removing the divergence

segment resulted in a 20% reduction in the entrainment ratio (Q_s/Q_p).

Fewer studies have investigated how the design of the nozzle influences the efficiency of the jet ejector. Hence, two factors of the nozzle influence the ejector efficiency:

- 1- The location of nozzle.
- 2- The design of nozzle.

It has been investigated how nozzle design affected the efficiency of jet ejectors[10]. Two conically diverging nozzles with different divergence angles were examined in their experiment. Both times, the nozzle's exit and throat sizes were set. The experimental findings demonstrate that the nozzle design had no impact on the overall performance of the jet ejector. Kroll[5] claimed that research conducted by Engdahl and W . C. Holton [9] supports the aforementioned claim. They discovered that at pressures up to 170 psig, the nozzle, which was created using traditional techniques for a specified pressure, performed just marginally better than a straightforward straight-hole nozzle.

According to Kroll[5], an inefficient jet ejector is the result of shock losses and wasteful lateral expansion brought on by an improperly designed nozzle. For pressures up to 100 psi, a small pipe-cap nozzle produced by drilling a hole in a typical pipe cap performed just 3 to 6% better than a machined nozzle with a convergence section and an angle of 11 divergence. However, the primary stream speed can be changed by modifying the nozzle's design. Berkeley[11] has done much research on this topic. In addition, he discovered that the primary stream expansion in the ejector of a properly constructed nozzle is typically a rather efficient element of the flow process under most conditions. That's why the nozzle wastes so little power in the first place. However, energy is lost in the process of transforming velocity back into pressure, making this a challenging operation.

To put it simply, the nozzle exit position (NXP) is the distance from the primary nozzle outlet to the intake of the mixing chamber. Upstream of the entrance to the mixing chamber, the NXP value is negative, while downstream, it is positive[12]. By influencing both the entrainment ratio and the critical back pressure, primary NXP is a crucial geometrical component that significantly affects the ejector's efficiency. The critical back pressure and entrainment ratio are also affected by it. It has been demonstrated that ejector efficiency can vary depending on whether the nozzle exit position (NXP) is oriented inwardly or outwardly in the mixing chamber, influencing the entrainment and pressure lift ratio[13]. Many studies employ the entrainment ratio as an important metric in their investigations[14]. The entrainment ratio, M is calculated by dividing the secondary flow rate by the primary flow rate. Three distinct ways of operation are available for ejectors. Initially, a constant mass flow rate is produced by choking of both the main and secondary flows if the back pressure is less than the critical back pressure. Therefore, the critical mode is defined as the region where the entrainment ratio is stable despite variations in back-pressure. Second, the lack of secondary flow choking causes the entrainment ratio to decrease significantly if the backpressure is increased above the critical pressure, reaching subcritical mode. Finally, a situation called back flow or malfunction mode might emerge if the back pressure is increased to the point in which the entrainment ratio is minimal, and the flow direction is reversed[15]. **(Fig.3)** illustrates the relation between back pressure and entrainment ratio (M).

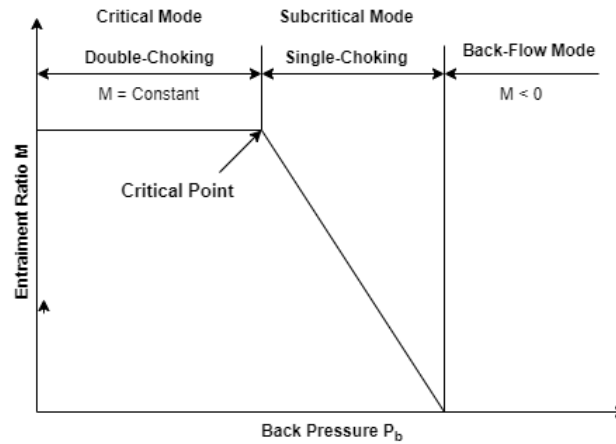


Figure 3 Operational modes for gas ejector [19].

2.2 The ejector components Losses:

Frictional and pressure losses are common in liquid-liquid ejectors, which can impact their performance and efficiency. Frictional losses occur due to the resistance to flow caused by the interaction between the fluids and the walls of the ejector[16]. Pressure losses occur when there is a drop in pressure along the flow path, which can be caused by factors such as turbulence, separation, and obstructions [17]. To mitigate these losses and improve the performance of liquid-liquid ejectors, researchers have explored strategies such as optimizing the design and operating conditions, using advanced materials and coatings to reduce friction, and incorporating mixing aids or additives to enhance mixing [18]. The dimensionless loss coefficients are values used to account for the various losses that occur within the components of an ejector, Primary nozzle, Secondary inlet, Mixing Chamber and Diffuser. These losses can include frictional losses, pressure drop losses, and other types of losses that occur as the fluid flows through the ejector. The loss coefficients are

used to represent the magnitude of these losses and are used in the design and analysis of the ejector.

2.2.1 Primary nozzle

One way to express the loss coefficient is in terms of the difference in pressure that exists across the nozzle.

$$V_n = \frac{Q_p}{A_n} \quad (1)$$

$$K_p = \frac{P_1 - P_n}{0.5 \rho_p V_n^2} - 1 \quad (2)$$

Where:

P_1, P_n : Primary flow and nozzle pressures respectively as in **(Fig.4)**.

A_n : The nozzle exit area

V_p, V_n : Primary and nozzle flow velocities

ρ_p : The primary fluid density

2.2.2 Secondary inlet

The loss could be handled similarly to give:

$$V_3 = \frac{MR}{1-R} V_n \quad (3)$$

$$K_s = \frac{P_2 - P_3}{0.5 \rho_s V_3^2} - 1 \quad (4)$$

Where:

ρ_s : The primary fluid density, other geometries illustrated in **(Fig.4)**.

V_3 : Mixing chamber entry flow velocity.

2.2.3 Mixing Chamber

In order to calculate the mixing chamber loss coefficient:

$$V_4 = R(1 + M)V_n \quad (5)$$

$$f = \frac{P_3 - P_4}{\frac{L}{4D} 0.5 \rho_m V_4^2} \quad (6)$$

$$K_m = \frac{4fL}{D} \quad (7)$$

Where:

P_3, P_4 : Mixing chamber entry and exit pressures respectively as in **(Fig.4)**.

L, D : The mixing chamber length and diameter.

V_4 : Mixing chamber exit flow velocity.

ρ_m : The mixing chamber fluid density.

f : The usual pipe friction factor.

2.2.4 Diffuser

The diffuser's loss coefficient is defined as

$$K_d = \frac{P_4 - P_5}{0.5 \rho_d V_4^2} \quad (8)$$

After identifying the area ratio (R), pressure ratio (N), and entrainment ratio (M) for each application, the primary nozzle's diameter can be calculated. R can be optimized by trial and error. The nozzle's size is then determined by the following equation.

$$D_n = \sqrt{\frac{4V_p}{\pi C_D} \sqrt{\frac{\rho_p}{2(P_1 - P_2)}}} \quad (9)$$

For well-designed nozzles, the coefficient of discharge (CD) can be taken to be 0.95. The nozzle's edge should be rounded, and the angle θ_n should be between 5 and 10°. The outlet edge should be 0.1 D_n thick, and the inner and outer convergence curves should be 16 D_n and 17 D_n , respectively. Those geometries are illustrated in **(Fig.5)**. Nozzle efficiency is unaffected by the shape of the section at the nozzle output.

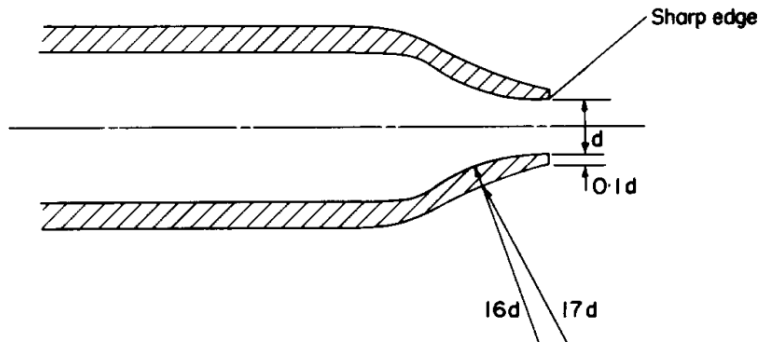


Figure 4 Optimal design for liquid ejector nozzle [2].

If flow separation from the boundary occurs, which is determined by the divergence angle and the inlet velocity profile, there will be a significant loss in the diffuser. Due to the closeness of the secondary (low energy) fluid to the diffuser wall, there is a risk of separation when significant mixing continues into the diffuser intake. There will be an uneven velocity profile at the diffuser intake when the mixing chamber length is insufficient to finish mixing. The diffuser with the wider angle will be more negatively impacted by a non-uniform velocity profile for two diffusers of the same length because of the bigger axial static pressure gradient. For maximum effectiveness, it is advised that the diffuser angle θ_d be between 6 and 8 degrees[2].

2.3 Ejector Classifications:

There are three primary ways to classify ejectors: (1) by the type of nozzle used, (2) by the location of the nozzle, and (3) by the number of working fluid phases. The efficiency of an

ejector is significantly impacted by the nozzle's design and geometry. For a convergent nozzle, the ejector typically operates in subsonic settings, and the maximum can reach a sonic regime at the suction outlet; a convergent-divergent nozzle, on the other hand, can produce a supersonic flow at the exit. It is possible for the flow to enter the supersonic region while using convergent-divergent ejectors. Finally, ejectors can be divided into single-phase ejectors (Gas-Gas or Liquid-Liquid) and two-phase ejectors (Air-Gas or Air-Liquid) according to the conditions of the primary and secondary streams.

2.3.1 Liquid-Liquid Jet Pumps:

Jet Pumps are the name given to liquid-liquid ejectors; the maximum amount of vacuum that can be attained by these pumps is proportional to the pressure of the primary liquid, while the maximum amount of discharge pressure that can be achieved is proportional to the inlet pressure of the primary liquid.

Entrainment ratio (M), pressure ratio (N), and area ratio of diameters (R) are the three most important characteristics to consider while dealing with a liquid-liquid ejector.

1a. Experimental Efficiency:

The experimental efficiency (η_{EX}) is determined based on the pressure ratio. This efficiency calculation involves taking direct pressure readings obtained during the experiments and incorporating them into a well-established formula. This formula serves as a comprehensive and widely applicable approach where the direct pressure and flow

measurements are directly utilized. To calculate the experimental efficiency, precise pressure readings will be gathered from the experimental setup. These readings will be combined with the corresponding flow measurements obtained during the experiments. This approach provides valuable insights into the overall efficiency and effectiveness of the system, enabling us to make informed decisions regarding system optimization and improvement. The experimental efficiency model is derived from the mathematical relationships presented below, which serves as the foundation for quantifying and analyzing the efficiency of the system:

$$M = \frac{Q_s}{Q_p} \quad (10)$$

$$N = \frac{P_d - P_s}{P_m - P_d} \quad (11)$$

$$N = \frac{2R + \frac{2CM^2R^2}{1-R} - R^2(1+CM)(1+M)(1+K_m+K_d) - \frac{CM^2R^2}{(1-R)^2}(1+K_s)}{(1+K_p) - 2R - \frac{2CM^2R^2}{1-R} + R^2(1+CM)(1+M)(1+K_m+K_d)} \quad (12)$$

This statement becomes when the primary and secondary fluids have the same density:

$$N = \frac{2R + \frac{2M^2R^2}{1-R} - R^2(1+M)^2(1+K_m+K_d) - \frac{M^2R^2}{(1-R)^2}(1+K_s)}{(1+K_p) - 2R - \frac{2M^2R^2}{1-R} + R^2(1+M)^2(1+K_m+K_d)} \quad (13)$$

Where:

Q_s, Q_p : The secondary, Primary flow rates.

P_m, P_s, P_d : Total pressures, as indicated in **(Fig.4)**.

C: Density ratio (primary to secondary fluid).

R: Area ratio of diameters (D_n/D_p).

K_d , K_m , K_s , and K_p : The diffuser, mixing chamber, secondary nozzle flow inlet, and primary nozzle flow intake are each accounted for by their respective loss coefficients.

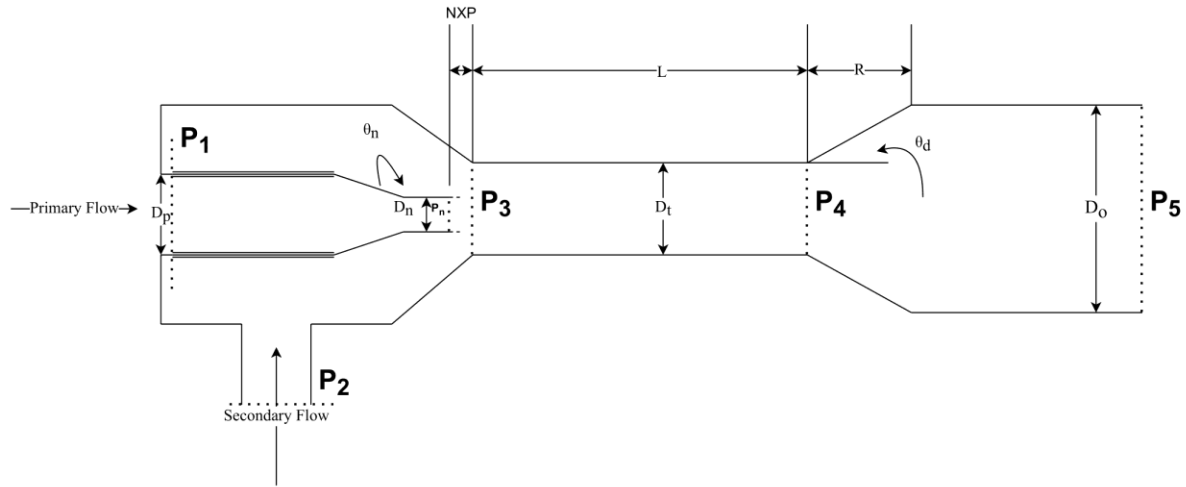


Figure 5 Liquid ejector parameters pressures [2].

The efficiency of the device can be calculated from the following Equation:

$$\eta = M \times N \quad (14)$$

(Fig.6) illustrates the efficiency curve for a Liquid-Liquid ejector as a function of Entrainment and pressure ratio, with results from Equation (14) clearly displayed. With a peak efficiency of about 29%.

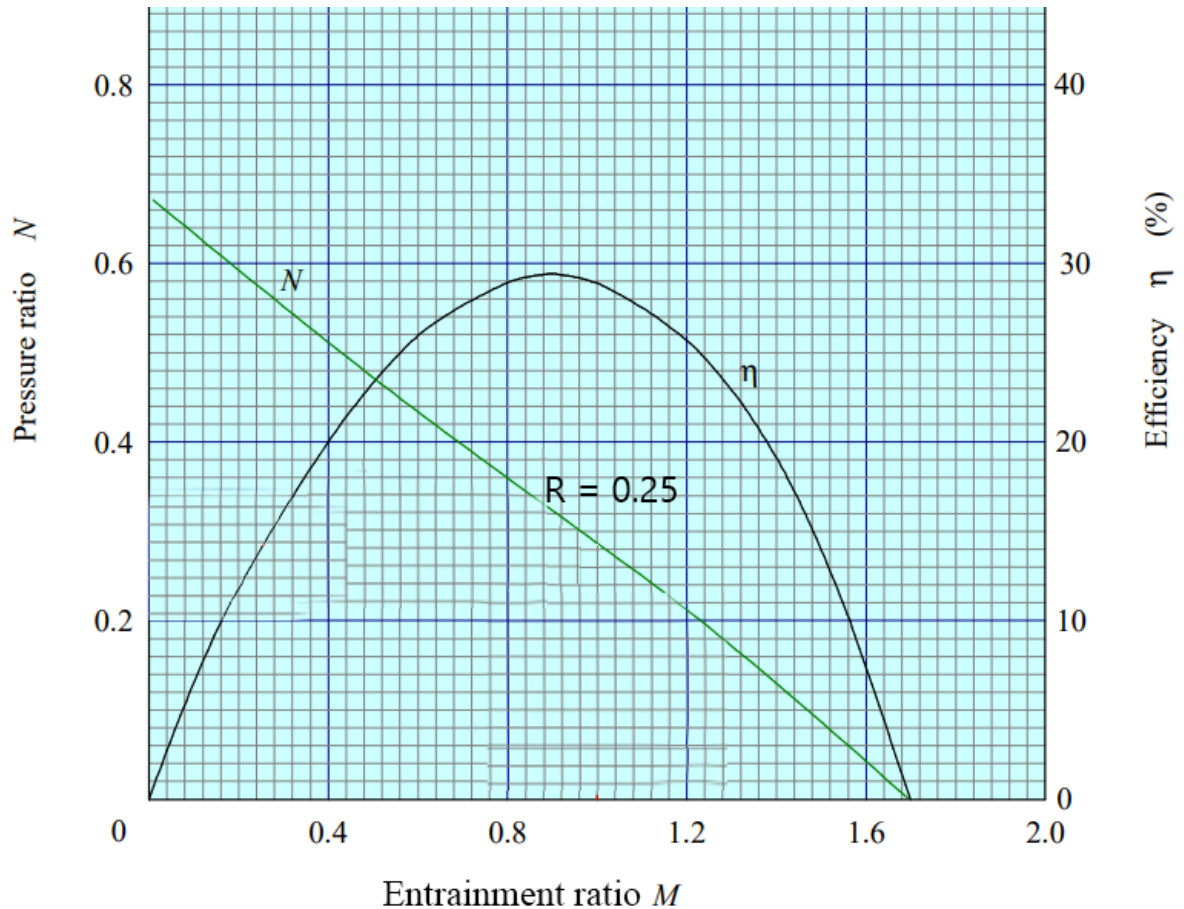


Figure 6 Liquid ejector efficiency compared to pressure ratio N , Entrainment ratio M [2].

1b. Analytical Type 1 Efficiency:

An alternative efficiency formula we referred to as the Analytical type 1 efficiency (η_{A1}), which was developed by ESDU 85032 [2], is worth considering. However, it is important to note that this formula is not universally applicable to all liquid-liquid ejectors due to several underlying assumptions. One significant assumption of this formula is that the

nozzle outlet is located at the beginning of the mixing chamber, resulting in a (NXP) value of zero. The nozzle exit position (NXP) is the distance from the primary nozzle outlet to the intake of the mixing chamber. Upstream of the entrance to the mixing chamber, The NXP value exhibits a negative value when measured upstream, whereas it demonstrates a positive value when measured downstream [3]. By influencing both the entrainment ratio and the critical back pressure, primary NXP is a crucial geometrical component that significantly affects the ejector's efficiency. The critical back pressure and entrainment ratio are also affected by it. It has been demonstrated that ejector efficiency can vary depending on whether the nozzle exit position (NXP) is oriented inwardly or outwardly in the mixing chamber, influencing the entrainment and pressure lift ratio [4]. Additionally, it assumes that the mixing chamber has a constant area, which may not hold true in all cases, including our specific scenario. While the Analytical efficiency formula provides a useful framework for evaluating ejector performance, its limitations in accommodating variations in nozzle outlet positioning and mixing chamber geometry must be acknowledged. These assumptions may restrict the formula's accuracy and applicability to specific ejector configurations. As such, it is crucial to consider the specific design and operational characteristics of the liquid-liquid ejector under investigation when assessing its efficiency. Furthermore, the formula fails at very low motive flow rate,

In our case, where the positioning of the nozzle outlet and the varying geometry of the mixing chamber are factors of interest, it becomes essential to explore alternative efficiency measures that account for these specific conditions. This allows for a more accurate evaluation of the ejector's performance and provides insights into its efficiency in converting the motive fluid's energy into useful work. By considering these factors and

exploring alternative efficiency formulas tailored to our specific ejector design, we can obtain a more comprehensive understanding of its performance and make informed decisions regarding optimization and operational considerations. To proceed with the application of the equations, it is necessary to assign specific values to the parameters, which are commonly referred to as the loss coefficients. These coefficients, namely K_p (loss coefficient of the primary or motive flow), K_s (loss coefficient of the suction flow), K_m (loss coefficient of the mixing chamber), and K_d (loss coefficient of the diffuser or discharge), are assigned values of 0.7, 0.12, 1.36, and 0.43 respectively. These values are crucial for the analysis of the system. By utilizing the following equations, the analytical efficiency model (η_{A1}) can be derived. These equations provide a systematic approach to obtain and evaluate the efficiency of the system.

$$P_d - P_s = \frac{1}{2} \rho_p V_n^2 \left[2R + \frac{2CM^2R^2}{1-R} - R^2(1 + K_m + K_d)(1 + CM)(1 + M) - C(1 + K_s) \left(\frac{MR}{1-R} \right)^2 \right]. \quad (15)$$

$$P_m - P_d = \frac{1}{2} \rho_p V_n^2 \left[-2R - \frac{2CM^2R^2}{1-R} + R^2(1 + M)(1 + CM)(1 + K_m + K_d) + (1 + K_p) \right]. \quad (16)$$

$$N = \frac{P_d - P_s}{P_m - P_d}. \quad (17)$$

$$\eta_{A1} = M \times N. \quad (18)$$

Where (V_n) represents the velocity of the flow through the nozzle, while (R) denotes the area ratio between the mixing chamber area and the nozzle area, which has a specific value of 0.11169. Moreover, in our case, where both the motive and suction fluids are water, the variable (C) represents the density ratio between these fluids. The assigned value of (C) is 1, indicating that the density of the motive fluid is equal to the density of the suction fluid.

1c. Analytical Type 2 Efficiency:

To address the limitations of the assumptions made in the Analytical type 1 efficiency model (η_{A1}), a new efficiency model which we will refer to as the Analytical type 2 efficiency (η_{A2}) was developed, as described in ESDU 93022 [19]. The Analytical type 2 efficiency takes into account the variable area of the mixing chamber, recognizing its crucial role and geometric characteristics that significantly impact the ejector's performance. It is worth noting that the Analytical type 2 efficiency model assumes a nozzle exit position (NXP) of zero. While this assumption may slightly deviate the Analytical type 2 efficiency from the actual efficiency observed in practice. Our objective is to evaluate the performance and efficiency of the liquid ejector while considering the introduction of drag reducing polymers (DRPs). Specifically, we will compare the efficiencies at two different motive flow rates, namely 1 and 1.45 GPM using the Analytical type 2 efficiency (η_{A2}). By conducting this analysis, we aim to understand the impact of DRPs on the ejector's efficiency and identify any improvements or changes in its performance. The following equations represent the model.

$$P_d - P_s = 0.5 \cdot \rho \cdot V_n^2 \cdot \left[2 \cdot R + C \cdot M^2 \cdot \left[\frac{R \cdot A_{ME}}{1 - R \cdot A_{ME}} \right]^2 \cdot \left[2 \cdot \left[\frac{1 - R \cdot A_{ME}}{A_{ME}} \right] - (1 + K_s) \right] - \left((X \cdot R^2 \cdot (1 + C \cdot M) \cdot (1 + M)) \cdot (1 + K_m + K_d) \right) \right] \quad (19)$$

$$P_m - P_d = 0.5 \cdot \rho \cdot V_n^2 \cdot \left[1 + K_p - 2 \cdot R - 2 \cdot C \cdot M^2 \cdot R \cdot R \cdot \left[\frac{A_{ME}}{1 - R \cdot A_{ME}} \right] + (X \cdot R^2 \cdot (1 + C \cdot M) \cdot (1 + M)) \cdot (1 + K_m + K_d) \right] \quad (20)$$

$$N = \left| \frac{P_d - P_s}{P_m - P_d} \right| \quad (21)$$

$$\eta_{A2} = M \times N. \quad (22)$$

Where (A_{ME}) represents the area ratio between the mixing chamber inlet and outlet, in our case it is assigned with 0.21 value. While (X) stands for the flow rate fraction between the discharge to the motive and suction flow rates (Q_d/Q_m+Q_s), and in our case it equals to 1. The remaining loss coefficients (K_p , K_s , K_m , and K_d) are assigned with the values 0.7, 0.12, 1.36, and 0.43. The remaining parameters are assumed to be consistent with the previous models, meaning that they are kept unchanged and not subject to modification.

1d. Analytical Type 1 Efficiency:

One of the developed formulas, referred to as the Head ratio efficiency (η_{HR}), accounts for factors such as kinetic energy, primary and secondary friction losses attributable to the ejector design. By incorporating these factors into the head ratio efficiency model, a comprehensive assessment of the ejector's performance can be obtained. The head ratio efficiency is a performance metric that assesses the effectiveness of a system in converting the available head into useful work or energy. Moreover, it provides insights into how efficiently the system utilizes the pressure energy of the motive fluid.

Frictional and pressure losses are common in liquid-liquid ejectors, which can impact their performance and efficiency. Frictional losses occur due to the resistance to flow caused by the interaction between the fluids and the walls of the ejector or even due to the lack of the optimal design of the ejector's components. The loss coefficients are used to represent the magnitude of these losses and are used in the design and analysis of the ejector's components, Motive, suction, discharge and friction which referred as K_p , K_s , and

K_d assigned with the values of 0.7, 0.12, and 1.88 respectively, K_{fm}, K_{fs}, K_{fd} are the friction losses coefficients for each component of the ejector with the values of 0.336, 0.37 and 0.56. By incorporating the coefficients of losses into the following equations:

$$N = \left| \frac{H_d - H_s}{H_m - H_d} \right|. \quad (23)$$

$$H_m = \frac{P_m}{9810} + (1 + K_m + K_{f,m}) \cdot \frac{V_m^2}{2 \cdot 9.81}. \quad (24)$$

$$H_s = \frac{P_s}{9810} + (1 + K_s + K_{f,s}) \cdot \frac{V_s^2}{2 \cdot 9.81}. \quad (25)$$

$$H_d = \frac{P_d}{9810} + (1 + K_d + K_{f,d}) \cdot \frac{V_d^2}{2 \cdot 9.81}. \quad (26)$$

$$M = \frac{Q_s}{Q_m}. \quad (27)$$

$$\eta_{HR} = M \cdot N. \quad (28)$$

Where V_m, V_s and V_d are the velocities of motive, suction and discharge. Q_s and Q_m are the flow rates of suction and motive. P_m, P_s and P_d are the pressures for motive, suction and discharge. The variable "M" denotes the entrainment ratio, specifically defined as the ratio of the suction flow rate (Q_s) to the motive flow rate (Q_m). This parameter quantifies the effectiveness of the propelling process within the system. On the other hand, the variable "N" signifies the pressure ratio of the ejector, which characterizes the relationship between the discharge pressure, the motive and suction pressures.

2.3.2 Gas-Gas Ejectors:

Small pressure ratios allow for the treatment of gas-gas ejectors as liquid-liquid ejectors, but large pressure differences emphasize the influence of compressibility. Equation (x) can be used to determine how flow through the nozzle changes to be independent of secondary pressure.

$$M_1 = C_D P_1 S_{TH} \sqrt{\frac{\gamma}{R_1 T_1} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)(\gamma-1)}} \quad (29)$$

(S_{TH}) stands for throat area, (γ) for specific heat ratio, (R) for specific gas constant, and (C_D) for discharge coefficient. The primary flow is controlled by the high-pressure nozzle, which causes a sequence of supersonic shocks to expand the flow until the pressures of the two streams (high and low) are equal and mixing takes place. Amin A et al. 2019[20], studied the entrainment ratio role in the gas ejector efficiency and he concluded that No relationship exists between the primary nozzle convergent angle and throat length and the entrainment ratio, The secondary nozzle agitation angle has just a minor impact, according to the results. The ideal primary nozzle convergence and divergence angles are, respectively, 11.2 and 7.06. While 6.47, 2.9, 8.82, and 13.5 mm, respectively, are the ideal throat length, main nozzle exit location, and nozzle incitation angle. Additionally, the ideal diffuser angle is 5.57, the ideal mixing tube diameter is 8.3, and the ideal mixing tube length is 72.4 mm.

2.3.3 Gas-Liquid Ejectors:

Since they are so effective in mass transfer applications, gas-liquid ejectors are utilized generally for mass transfer. In reality, the efficiency of gas-liquid nozzles is improved by

the quantity of gas-induced in the ejector. The quantity of mass transfer is directly associated with the amount of gas flow rate. To guarantee that the so-called optimal blending tube and nozzle position geometries achieve optimum efficiency, the configuration dependency of entrainment efficiency for gas-liquid ejectors is investigated by Li C et al. 2012[21] under given operating circumstances. It is clear that the length of the blending tube for N_2 - H_2O and He - LO_2 ejectors is a critical design factor and can have a huge impact on ejector efficiency. The ideal blending tubes for N_2 - H_2O ejectors are between one and two times their diameter. When the blending tube length is increased from zero to the ideal value, which is 1-2 times the blending tube diameter, it is evident that the ejector performance is significantly improved, and that further increases in the blending tube length lead to a progressive but noticeable decline in the entrainment efficiency. In conclusion, it has been discovered that optimal blending tube length greatly depends on the working fluids and causes the incidence of highest entrainment ratio. A blending tube that is either long or short might restrict pressure recovery or result in extra viscous losses, both of which reduce the ejector's ability to entice working fluids of the gas-liquid kind. The primary nozzle location subsequently becomes crucial for pressure restoration. To guarantee maximum entrainment efficiency under these circumstances, negative NXP is necessary. However, it should be noted that when the blending tube is longer than the recommended length, the impact of NXP is less noticeable.

2.3.4 Liquid-Gas Ejectors:

Due to the density difference between the flows, which also results in a difference in effective momentum, this type of ejector has a liquid primary fluid and gas as a secondary fluid flow. This difference in density makes the mixing process more challenging than with single-phase ejectors, necessitating the use of a longer mixing tube (usually between 10 and 15 radius). The following formula (17) can be used to describe how well these ejectors perform:

$$\dot{V}_g = B(\dot{V}_L - \dot{V}_{L-Minimum}) \quad (30)$$

Where $\dot{V}_g$ is the secondary gas flow rate, $\dot{V}_L$ is the primary liquid flow rate, $\dot{V}_{L-Minimum}$ is the minimum liquid flow rate when no gas flow will be there.

2.4 Drag Reducing Polymers:

There are multiple techniques to stop ejector pressure loss effects from happening. It is really difficult for the fluid to stream because of friction and pressure drops caused by the contact between eddies and the mixing chamber wall. Pumping is the most straightforward approach to raise the fluid's pressure, which is important to reduce friction. However, due of the high energy consumption and associated costs, employing several pumps via the line has certain limitations. Implementing additives known as drag-reducing agents is among the greatest approaches. Practically, increasing the capacity of the tunnel by injecting a low amount of such chemicals to such stream decreases friction in the fluid and keeps tunnel conditions the same. To put it another way, the majority operational systems call for

pumping streams at huge flowrates, that leads to high frictional pressure drops by lowering the skin-friction of the stream; DRA may lower the amount of power consumption for the pressurization to compensate the pressure drops[22].

Long-chain, high-molecular-weight polymers known as drag-reducing polymers (DRPs) include polymethyl methacrylate (PMMA), polyethylene oxide (PEO), and polyisobutylene (PIB), Polyacrylamide (PA). Toms (1948) [23] is credited with making the formal discover of drag reduction utilizing polymers while conducting tests on the breakdown of polymers in pumps. Since then, there has been a huge amount of research to better understand and make use of this phenomena, leading to possibly hundreds of publications in both single- and multiphase phase flows for both practical and basic goals. An oil-water two-phase flow's flow rate may be significantly increased, and friction reduced with the use of DRPs. The Trans-Alaska pipeline was the first significant use of DRPs as a huge scale real application[24]. It has been shown that the buffer layer is the only one to undergo the impacts of drag reduction; neither the viscous sublayer nor the log-law layer is impacted. DRPs increase the thickness of the buffer layer and reduce turbulence within it[25].

Few research has been done on DRA for liquid-liquid flows[26], but those that have been done demonstrate that little quantities of polymer introduced to the water phase may greatly increase overall area of stratified flow and reduce pressure drop by around 65%. Additionally, it was discovered that adding polymers changed the flow patterns map, liquid fraction, and interface height as well as dampened interfacial waves[27].

The DRA chemical structure somehow doesn't typically withstand the intense shear

stresses created into pumps. As a result, the DRA must be introduced following each pumping station. The efficiency of the DRA is affected by various elements, including viscosity, diameter of the pipe, and velocity of the flow, all of which are affected by the Reynolds number. Drag reduction is often only efficient in turbulence and increases as the pipe diameter and flow viscosity decrease or as Reynolds number increases.

Chang and Darby [28] investigated the effects of shear degradation of polyacrylamide DRA solutions in 0.0046 m diameter pipes and discovered that the DRA both ages, losing efficiency after a few days, and degrades when subjected to shear. They also found that the freshly added DRA solutions demonstrated lower friction factors than both the solvent alone as well as those that had been exposed to pump shear.

Experimental research[29] was done on the impact of DRP on the oil-water flow patterns map and pressure loss in horizontal 1-inch acrylic pipe. It was shown how molecular weights and polymer concentrations affected flow behavior and pressure decreases. DRP's effectiveness was examined in relation to how much salt is in the water phase. The following observations were made:

- The inclusion of PDRA lowers the level of turbulent mixing at higher mixture velocities when a dispersed flow regime occurs and can avoid the phase inversion peak shown by pressure gradient.
- The pressure gradient is greatly decreased, and the amount of the reduction depends on the molecular weight of the DRP, concentration, mixture velocity and water percentage.
- At higher mixture velocities in a dispersed flow regime, the inclusion of DRP minimizes the intensity of turbulent mixing also can eliminate the pressure

gradient-indicated phase inversion peak.

The drag-reducing polymer's efficiency is affected by the method employed to introduce the polymer into the flow. The master polymer solution should be made gently and introduced further into surface film in a way that spreads it over the circle[30]. High shear pumps should not be used for transfer to the pipe.

The polymer's efficiency is measured in terms of drag-reduction (DR), which is defined as:

$$DR = \frac{\Delta P_{without\ DRA} - \Delta P_{with\ DRA}}{\Delta P_{without\ DRA}} \quad (31)$$

Where:

$\Delta P_{without\ DRA}$, the pressure drop without adding the drag reducing agent .

$\Delta P_{with\ DRA}$, the pressure drop with adding the drag reducing agent .

2.5 Emulsion Definition:

Emulsion is a thermodynamically unstable system composed of two or more phases that will finally separate to diminish the interfacial area in between phases[31]. One of the liquids is dispersed in the other, which is immiscible; the first is known as the dispersed phase, and the second as the continuous phase[32]. Emulsion is generated in using some types of emulsifying agents (Mayonnaise, lanolin, diglycerides etc.)[31]. There are four kinds of emulsions, oil immersed into water (O/W), water immersed into oil (W/O), oil immersed into water and both immersed into oil (O/W/O), water immersed into oil and both immersed into water (W/O/W). The four kinds are illustrated in **(Fig.7)**. The

emulsifying agent has two properties which the balance between them is a very important to determine the type of the emulsion[32]– [34].

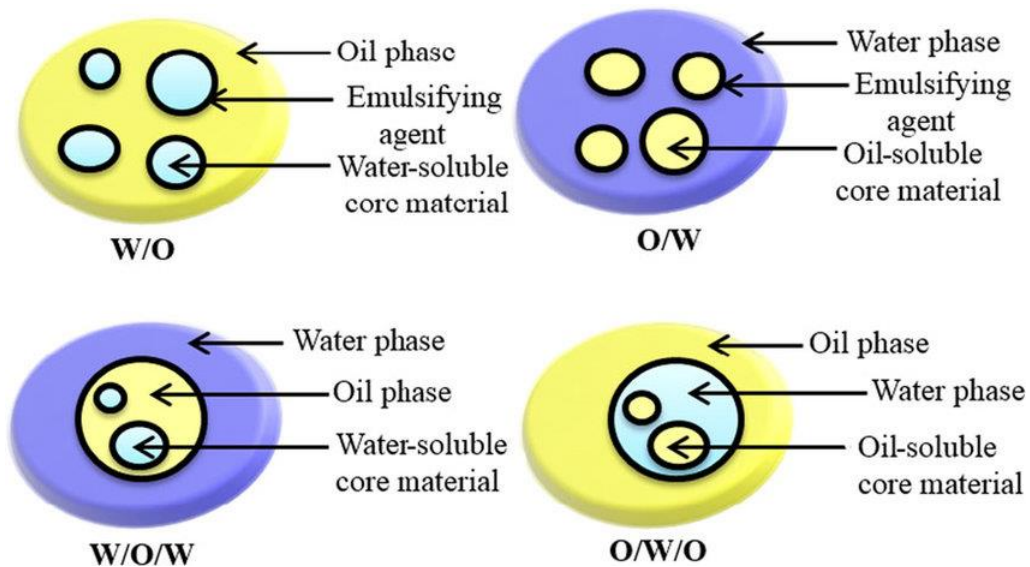


Figure 7 The four emulsion systems W/O ,O/W ,W/O/W ,and O/W/O [37].

2.5.1 Rheology of Emulsion:

The study of fluid flow and deformation in the presence of various forms of shear stress and strain is known as rheology. The study of emulsion rheological behavior is critical for efficiently treating 7 emulsions. Depending on the fluid composition, a fluid could exhibit Newtonian or Non-Newtonian behavior. The connection of shear stress and rate, temperature and time may be used to study the rheological characteristics of emulsions. As a result, the viscosity of emulsions is strongly temperature dependent, shear rate, water cut, the existence of solid materials, and so on. Emulsion viscosities are greater above oil and water viscosities since emulsions are heavier substances that exhibits non-Newtonian

behavior [36].

Al-Yaari and Al-Sarkhi et al. 2013[37] investigated the influence of DRP (drag reducing polymers) on the flow properties of surfactant stabilized water in oil emulsions. They discovered that introducing Polyisobutylene polymer with varying molecular weights enhanced emulsion viscosity at low DRP concentrations (50 ppm). However, when DRP concentration grew, so did the shear thinning impact, which was accentuated as the molecular weight of DRP increased.

2.5.2 Emulsified Acid System (EAS):

Hydrochloric acid (HCl), a commonly employed acidizing fluid for enhancing carbonate reservoir productivity, exhibits noteworthy attributes including its robust acidity and swift reactivity with scales and fines proximate to the wellbore. Nevertheless, it poses operational challenges at elevated temperatures, potentially affecting tubing, casing, gravel pack screens, and downhole pumps. Additionally, it is advised to refrain from using HCl at temperatures surpassing 93 °C due to its detrimental impact on the reservoir formation, as highlighted by Huang et al. in 2013[38]. To mitigate these concerns, alternative acid systems, such as blends of tricarboxylic acids, amino carboxylic acids, and dicarboxylic acids, can be deployed at elevated temperatures without causing harm to downhole equipment, as suggested by Huang et al. in their study.

An emulsion is characterized by the combination of two fluids that do not readily mix, with one being referred to as the internal or dispersed phase and the other as the external or continuous phase. In the context of Emulsified Acid Systems (EAS), diesel serves as the continuous phase enveloping HCl droplets, creating an emulsion known as acid-in-diesel.

Typically, the oil and gas industry utilize a concentrated HCl acid solution, typically ranging from 15 to 28 percent [39], [40]. EAS finds extensive application in the enhancement of formation permeability and the augmentation of oil and gas production in carbonate reservoirs through fracturing and acidizing operations. It's important to note that EAS tends to slow down reaction rates due to the oil's presence in the external phase, leading to the formation of deeper and more narrow wormholes.

An emulsifying agent is employed to facilitate the combination of aqueous acid and oil, enhancing the stability of the EAS (Emulsified Acid System) when subjected to varying temperatures. In some cases, minuscule particles, such as colloidal clay particles or nanoparticles, are utilized in the creation of the emulsion. This stabilized emulsified acid system comprises at least one type of oil, a solution of aqueous acid containing at least one acid, at least one emulsifying agent, and acid-insoluble nanoparticles with an average particle size of one thousand nanometers or less [38]. The acids, when emulsified with oil, typically diesel, serve the purpose of minimizing corrosion of pumping and downhole equipment and reducing the rates of reaction with carbonate formations at elevated temperatures. This results in the deep penetration of active acid into the geological formation. It's important to note that the physical properties of emulsified acids are significantly affected by the methods of preparation. Therefore, analyzing emulsified acids based on their droplet size distribution provides a comprehensive understanding of their chemical composition, offering a specific description and thereby ensuring reproducible properties [39].

CHAPTER 3

METHODOLOGY AND PROCEDURE

3.1 Flow Loop Description:

Figure 8 The experimental Flow Loop illustrates the experimental flow loop; it is designed for investigating the performance of a liquid-liquid ejector generating water-in-oil or oil-in-water emulsions. The flow loop comprises three main components: a motive liquid tank, a suction liquid tank, and a discharge tank. A valve connects the discharge tank to a water outlet aperture to make sure that the drag reducing polymers concentration is constant. Conversely, when emulsion needs to be examined, the valve remains closed, enabling tank to operate based on the specific experiment being conducted. To achieve the desired flow rates for the experiments, one centrifugal pump is integrated into the flow loop. The pump is equipped with a control valve, facilitating the regulation of the motive stream's flow rate. Additionally, flow meters and pressure gauges are installed along the motive and suction lines to measure the flow rate and pressure of the primary and secondary liquid streams. The liquid-liquid ejector functions by drawing its primary stream from the motive tank. Utilizing the pressure energy of the motive stream, the ejector effectively suctions the secondary stream from the suction tank and combines them to generate the desired emulsion. The resulting emulsion is then discharged through the ejector's discharge line. This experimental setup provides a controlled environment for studying the performance of the liquid-liquid ejector for emulsion generation. By precisely controlling the flow rates, monitoring pressure, and incorporating drag reducing additives into the suction flow line to assess and study their influence on the performance of the ejector.

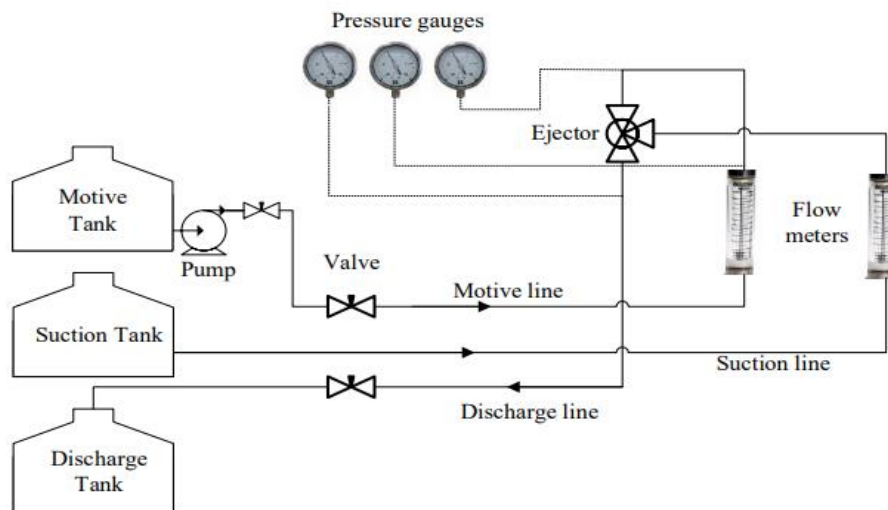
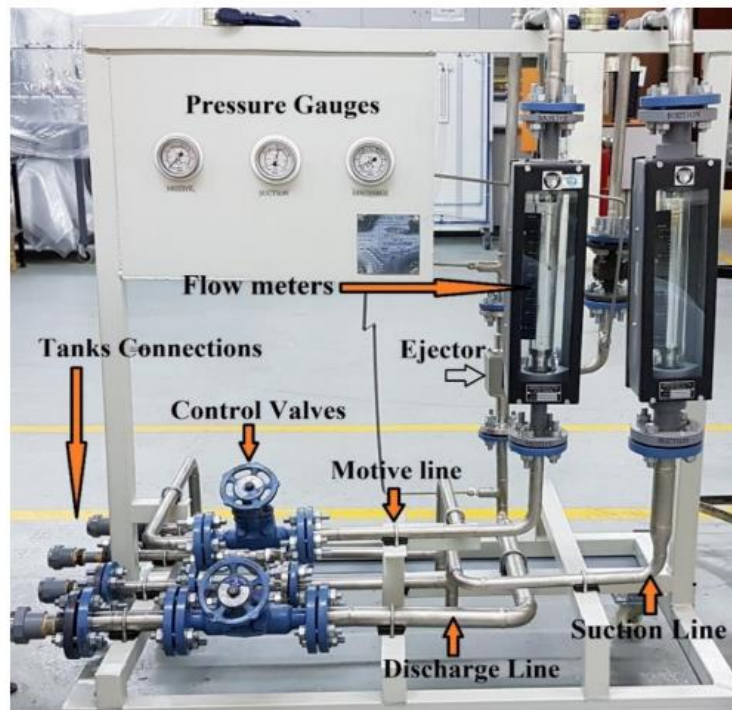


Figure 8 The experimental Flow Loop

3.2 Liquid Ejector Description:

The jet pump is distinguished from other pump types primarily by its operating principle, wherein energy is transferred to the secondary fluid by utilizing the kinetic energy of the driving (primary) fluid, rather than relying on mechanical components such as impellers or pistons. The main components of the ejector are the nozzle, mixing chamber, and diffuser. Furthermore, (

Table 1) indicate the ejector's components materials.

Table 1 Ejector's components materials.

Sr No.	ITEM	MATERIAL
1	EJECTOR BODY	SS 316/ SS 316L
2	NOZZLE	SS 316/ SS 316L
3	DIFFUSER	SS 316/ SS 316L
4	FLANGES	SS 316/ SS 316L
5	O-RINGS	Viton
6	GASKETS	Neoprene
7	BOLTING	Stainless Steel

3.3 Ejector Controlled Operational Modes:

The experimental procedure for the suction-controlled mode encompassed a series of sequential steps to ensure accurate data collection and analysis. Initially, both the suction

and motive tanks were filled with water to establish the necessary fluid volumes for the experiment. Next, the motive pump is activated while ensuring that all relevant valves are fully open to allow for unobstructed flow. To simulate varying suction flow rates, the suction flow rate control valve was gradually closed, thus reducing the influx of fluid from its maximum value to the minimum. Throughout this process, we meticulously recorded the corresponding flow rates and pressures for all interconnected lines within the experimental setup.

3.4 Procedure:

This section presents the outcomes of a parametric analysis, along with a comprehensive description of the procedure followed for each experiment. The analysis covers the impact of controlling the suction and discharge valves on the performance of the system. Furthermore, it explores the effect of drag reducing polymers on the suction flow capacity, including tests conducted at various concentrations of these polymers to optimize the suction flow capacity at different motive flow rates. At the conclusion, a detailed discussion and analysis of the results are provided. The analysis delves into the findings and their implications, shedding light on the observed outcomes and relationships between the variables studied. The discussion incorporates a thorough examination of the experimental data and its relevance to the research objectives. This comprehensive analysis allows for a deeper understanding of the investigated phenomena and provides insights into the performance and potential enhancements of the ejector-based emulsion generation system.

3.4.1 Incorporating Drag Reducing Polymers:

In the same procedure in suction-controlled mode experiment, an additional step was introduced to incorporate drag reduction polymers into the suction stream. This process involved mixing the polymers with 50 parts per million (PPM) and 100 (PPM) concentrations in a separate tank with a mixer equipped with a three-blade impeller. To ensure minimal degradation of the polymers, the mixing was conducted for a duration of one hour at a controlled speed of 85 Revolution Per minute (RPM). Following the polymer mixing process, the experiments proceeded in a similar manner to the suction-controlled experiment. The data collection process began by measuring the flow rates and pressures within the system. Careful attention was given to maintaining the integrity and effectiveness of the polymers throughout the experiment. By adhering to the specified mixing time, speed, and utilizing a dedicated tank, efforts were made to minimize any potential degradation or alteration of the polymers entanglements properties. Through these modified experimental steps, the impact of drag reducing polymers on flow rates and pressures could be accurately evaluated, providing valuable insights into the effectiveness of these additives in improving the performance and efficiency of the system. Additionally, **(Table 2)** illustrates the experimental parameters.

Table 2 Experimental Parameters

Parameter	Value
Water Temperature	24 C°
Water Density (ρ_w)	997 Kg/m ³
Water Dynamic Viscosity (μ_w)	0.0009096 Pa.s
Nozzle Diameter (D_n)	2.7 mm
Area Ratio (R)	0.11169
Density Ratio (C)	1
Loss Coefficients (K_p, K_d, K_m, K_d)	0.7, 0.12, 1.36, 0.43

3.5 Emulsified acid system (EAS) preparation Using Aramco Recipe and Ejector method:

Using the same method as we do for controlled valve ejectors operating at full capacity (with a 70% Suction and 30% Motive ratio), we mixed diesel and FA-1 emulsifier in the motive tank. We stirred this mixture at 1000 RPM for 15 minutes. Meanwhile, the contents of the suction tank changed to a solution containing HCL acid, water, and some chemicals to protect the pipes and stabilize the emulsion. This solution was mixed vigorously at 7000 RPM for 10 minutes. Then, a preliminary test using an ejector was conducted to obtain a stable emulsion with diesel as an external phase. Two trials have been conducted with different water salinity (1000 and 15000 PPM) using NaCl. However, both resulted in the water as an external phase, and the emulsion separated a few minutes after the test (unstable emulsion), it seems that the mixing level was low. The concentrations of these components

were used in the trail are shown in **(Table 3)**. The mentioned concentrations are in order to make 1 liter of the emulsion.

Table 3 ARAMCO EAS recipe.

Component Code	Functional Name	Concentration	Unit
Diesel	Diesel	300 ml per 1000 ml	mL
FA-1	Emulsifier	5ml per 1000 ml	mL
Water	Water	213 ml per 1000 ml	mL
31% HCl	Raw Acid	450 ml per 1000 ml	mL
Sodium Erythorbate	Iron Reducing Agents	0.8 g per 1000 ml	Gram
SR-1	Iron Stabilizer	1 g per 1000 ml	Gram
HTAI-6	Inhibitor Aid	20 ml per 1000 ml	mL
FTS-21	HT Corrosion Inhibitor	7 ml per 1000 ml	mL
SCA-101	H2S Scavenger	2.5 ml per 1000 ml	mL
SCA-108	H2S Scavenger	2.5 ml per 1000 ml	mL

CHAPTER 4

RESULTS AND CONCLUSION

4.1 Procedure:

The impact of drag reducing polymers on suction flow rate pressure within the water-water liquid jet was investigated. The suction flow rate decreases at different motive flow rates as the suction flow rate control valve is partially closed. This decrease in the suction flow rate is accompanied by a decrease in suction pressure, which drops from -0.1 kg/cm² until it reaches -0.51 kg/cm² at 1.45 GPM motive flow rate, 0.02 to -0.3 kg/cm² at 1 GPM motive flow rate. These changes in flow rate and pressure occur as the suction flow is controlled and adjusted through the partial closing of the suction control valve. Then drag reducing polymers (DRPs) were introduced with 50 and 100 parts per millions (ppm) concentration within the suction line, then the whole readings such as suction flow rates and suction pressures were taken again. Both experiments are presented in **(Figure 9)** which represents the variation between the suction flow rate and pressure.

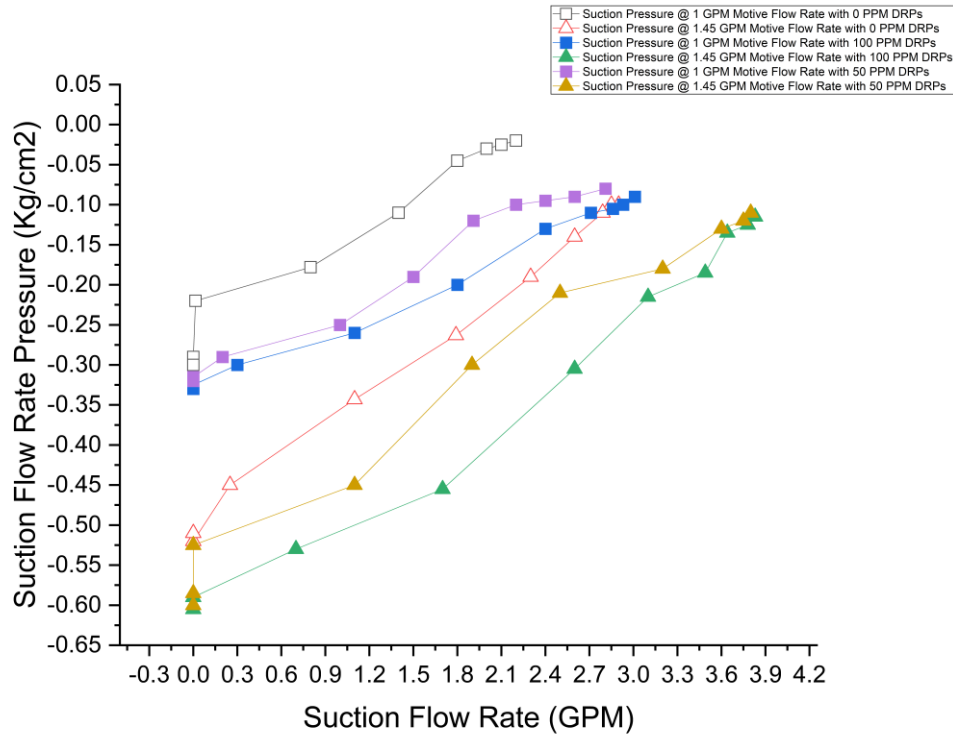


Figure 9 Variation of the suction flow rate pressure with the suction flow rate capacity at different motive flow rates and DRPs concentrations (100, 50 and 0 PPM).

One notable observation is the significant increase in suction flow rate capacity with the addition of drag reducing polymers (DRPs) with 50 ppm at the same motive flow rate. Specifically, when comparing the same motive flow rate, at 1.45 GPM motive flow rate, the suction flow rate capacity demonstrated a noteworthy increment of 0.9 gallons per minute (GPM), this increment translates to an increase of approximately 31% in the suction flow rate capacity, moreover, at 1 GPM motive flow rate, the suction flow rate increased to 2.81 GPM with 28% increment in the suction flow rate capacity. It is worth noting that the motive pressure remains unaffected by the presence of DRP. Additionally, there is a slight rise in the suction pressure with the incorporation of DRP. Although the increase is relatively small, it indicates a change in the pressure dynamics within the system. On the

other hand, the discharge pressure experiences a significant doubling effect. This is primarily due to the enhanced suction flow capacity resulting from the DRP addition and the reduction of the frictional pressure drop along the ejector. The increased suction flow rate ultimately leads to higher discharge pressure. Furthermore, as the concentration of drag reducing polymers increased to 100 ppm, the suction flow rate increased to 3.83 GPM at a motive flow rate of 1.45 GPM, slightly surpassing the flow rate observed at a concentration of 50 ppm. However, both concentrations (50 and 100 ppm) at a motive flow rate of 1.45 GPM exhibited nearly identical suction pressure levels.

Table 4 Suction flow rates and pressures comparison of the ejector at a motive flow rate of 1.45 GPM at different drag reducing polymers concentrations (0, 50 and 100 ppm).

Motive Flow Rate (GPM)	Suction Control Valve Capacity (%)	SFR (GPM) (0 ppm)	SFR (GPM) (50 ppm)	SFR (GPM) (100 ppm)	SP (kg/cm2) (0 ppm)	SP (kg/cm2) (50 ppm)	SP (kg/cm2) (100 ppm)
1	100	2.2	2.81	3.01	-0.02	-0.08	-0.08
1	90	2.2	2.6	2.93	-0.02	-0.09	-0.09
1	80	2.1	2.4	2.86	-0.025	-0.095	-0.095
1	70	2	2.2	2.71	-0.03	-0.1	-0.1
1	60	1.8	1.91	2.4	-0.045	-0.12	-0.12
1	50	1.4	1.5	1.8	-0.11	-0.19	-0.19
1	40	0.8	1	1.1	-0.178	-0.25	-0.25
1	30	0.015	0.2	0.3	-0.22	-0.29	-0.29
1	20	0	0	0	-0.29	-0.315	-0.315
1	10	0	0	0	-0.3	-0.32	-0.32

Table 5 Suction flow rates and pressures comparison of the ejector at a motive flow rate of 1 GPM at different drag reducing polymers concentrations (0, 50 and 100 ppm).

Motive Flow Rate (GPM)	Suction Control Valve Capacity (%)	SFR (GPM) (0 ppm)	SFR (GPM) (50 ppm)	SFR (GPM) (100 ppm)	SP (kg/cm2) (0 ppm)	SP (kg/cm2) (50 ppm)	SP (kg/cm2) (100 ppm)
1.45	100	2.9	3.8	3.83	-0.1	-0.1100	-0.1100
1.45	90	2.8					
		5	3.75	3.78	-0.1	-0.12	-0.12
1.45	80	2.7					
		9	3.6	3.64	-0.11	-0.13	-0.13
1.45	70	2.6	3.2	3.49	-0.14	-0.18	-0.18
1.45	60	2.3	2.5	3.1	-0.19	-0.21	-0.21
1.45	50	1.7					
		9	1.9	2.6	-0.263	-0.3	-0.3
1.45	40	1.1	1.1	1.7	-0.343	-0.45	-0.45
1.45	30	0.2					
		5	0	0.7	-0.45	-0.525	-0.525
1.45	20	0	0	0	-0.52	-0.585	-0.585
1.45	10	0	0	0	-0.51	-0.6	-0.6

4.2 Case 1 (Experimental Efficiency):

Using the experimental efficiency showed a significant improvement through the addition of Drag Reducing Polymers (DRPs) at varying concentrations at a fixed motive flow rate at 1 Gallon Per Minute (GPM). In the absence of DR/Ps, the experimental efficiency (η_{EX}) was measured at 6.5% with a suction flow rate of 2.2 GPM when the suction flow rate control valve was fully opened. In addition, the highest efficiency of 12.5% was achieved with 50% suction valve opening and a suction flow rate of 1.4 GPM. Subsequently, DRPs were introduced into the suction tank at a concentration of 50 ppm, resulting in a remarkable increase in the experimental efficiency (η_{EX}). The efficiency increased from 6.5% to 22.7% with a suction flow rate of 2.81 GPM when the suction valve was fully opened. With 50% suction flow rate control valve opening, the efficiency improved from 12.5% to 20.5% at a suction flow rate of 1.5 GPM. The concentration of DRPs was further increased to 100 ppm, leading to another substantial improvement in η_{EX} . At a suction flow rate of 3.01 GPM when the suction flow rate control valve was fully opened, the efficiency reached 31%. Similarly, with 50% suction flow rate control valve opening, the efficiency stood at 29.45% with a suction flow rate of 1.8 GPM. Furthermore, it is worth noting that when the suction flow rate control valve is partially closed, an increase in efficiency was observed only in the absence of drag reducing polymers (DRPs) at 40% and 50% opening of the valve, in comparison to when the valve was fully opened. However, when DRPs were introduced at different concentrations (50 and 100 ppm), closing the suction flow rate control valve only resulted in an efficiency increase at a 50% opening of the valve, as compared to a 60% opening. Nevertheless, even at a 50% opening of the suction flow rate control valve, the efficiency did not surpass that of the ejector when the valve was fully opened, as observed in the absence of DRPs. **(Fig.10) and (Fig.11)** illustrate the

Relationship between suction flow rate control valve capacity and the experimental efficiency, with varying concentrations of drag reducing polymers (DRPs) (0, 50, and 100 ppm), at a fixed motive flow rate of 1 GPM.

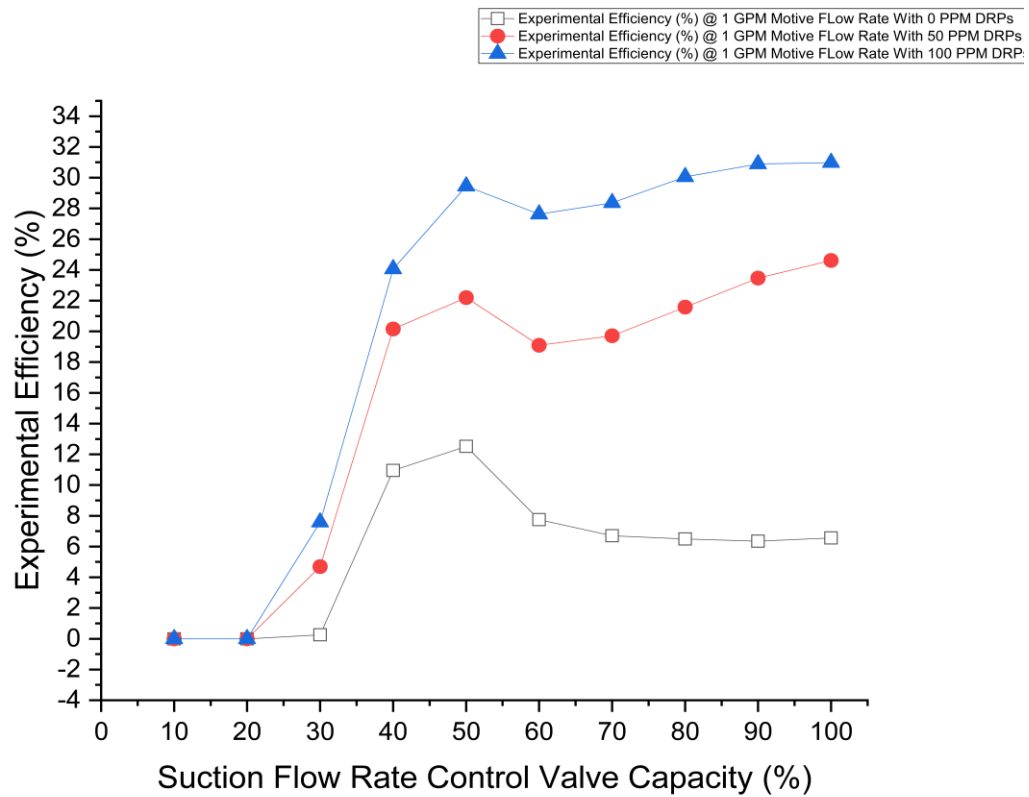


Figure 10 Experimental efficiency variation as a function of suction flow rate control valve capacity at a motive flow rate of 1 GPM, considering different concentrations of drag reducing polymers (DRPs) (0, 50, and 100 ppm).

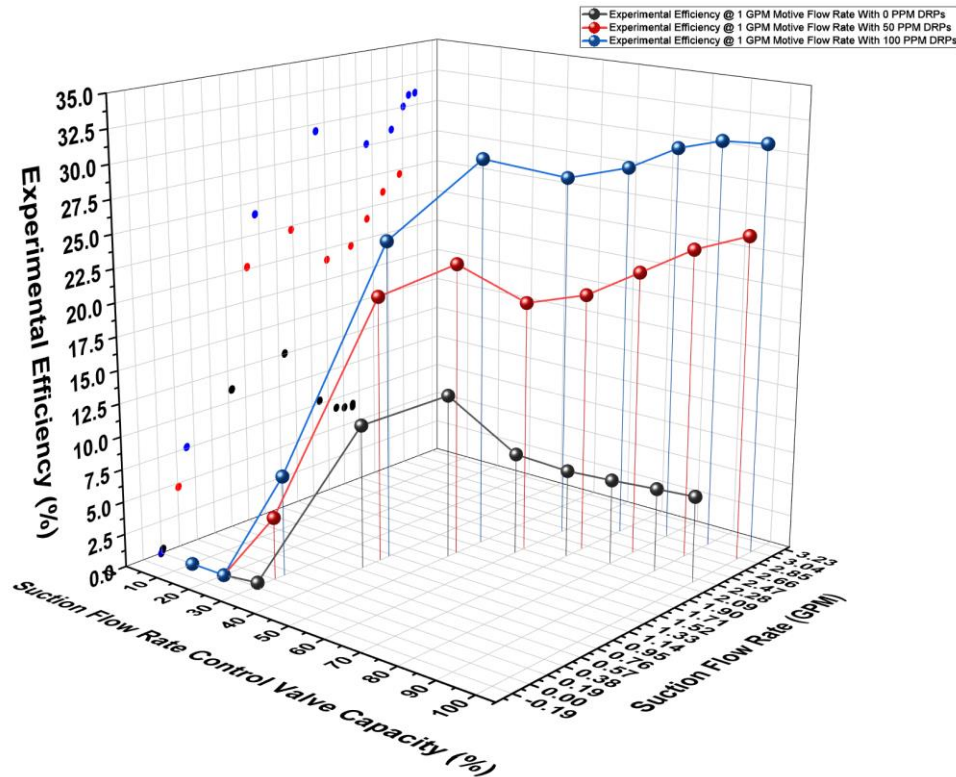


Figure 11 3D representation of the variation between the Experimental efficiency, the suction flow rate control valve capacity, and the suction flow rate at 1 GPM motive flow rate.

When the motive flow rate increased to 1.45 GPM, a significant improvement was observed when drag reducing polymers (DRPs) were introduced at different concentrations (50 and 100 ppm). When concentration of DRPs was set at 50 ppm, an interesting enhancement in experimental efficiency was observed. Specifically, with the suction flow rate control valve fully opened, the experimental efficiency increased from 13.8% to 25.3%. This increase also resulted in an elevation of the suction flow rate from 2.9 to 3.8 GPM. Additionally, at a suction flow rate control valve opening of 70%, a slightly better experimental efficiency of 27% was obtained compared to the fully open position. Furthermore, when the concentration of DRPs was increased to 100 ppm, the experimental efficiency continued to improve. At the fully open suction flow rate control valve, the

experimental efficiency increased to 26.7%, accompanied by a suction flow rate of 3.83 GPM. Interestingly, by reducing the suction flow rate control valve opening to 70%, the experimental efficiency further increased to 30.3% while maintaining a suction flow rate of 3.5 GPM. The observed increment in experimental efficiency during the closure of the suction flow rate control valve can be attributed to the decrease in suction pressure, which increases proportionally with the suction flow rate. This relationship suggests that controlling the suction flow rate through the valve can have a significant impact on the overall efficiency of the system, especially when combined with the introduction of drag reducing polymers. (Fig.12) and (Fig.13) depict the graphical representation of the relationship.

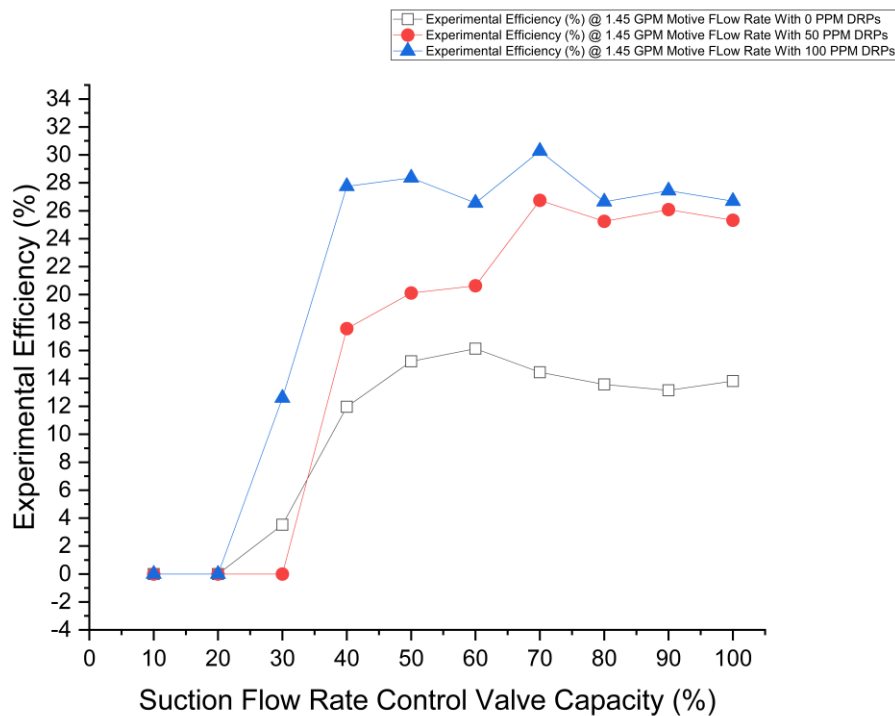


Figure 12 Relationship between the experimental efficiency and the suction flow rate control valve capacity for varying concentrations of drag reducing polymers (DRPs) (0 ppm, 50 ppm, and 100 ppm), at a fixed motive flow rate of 1.45 GPM.

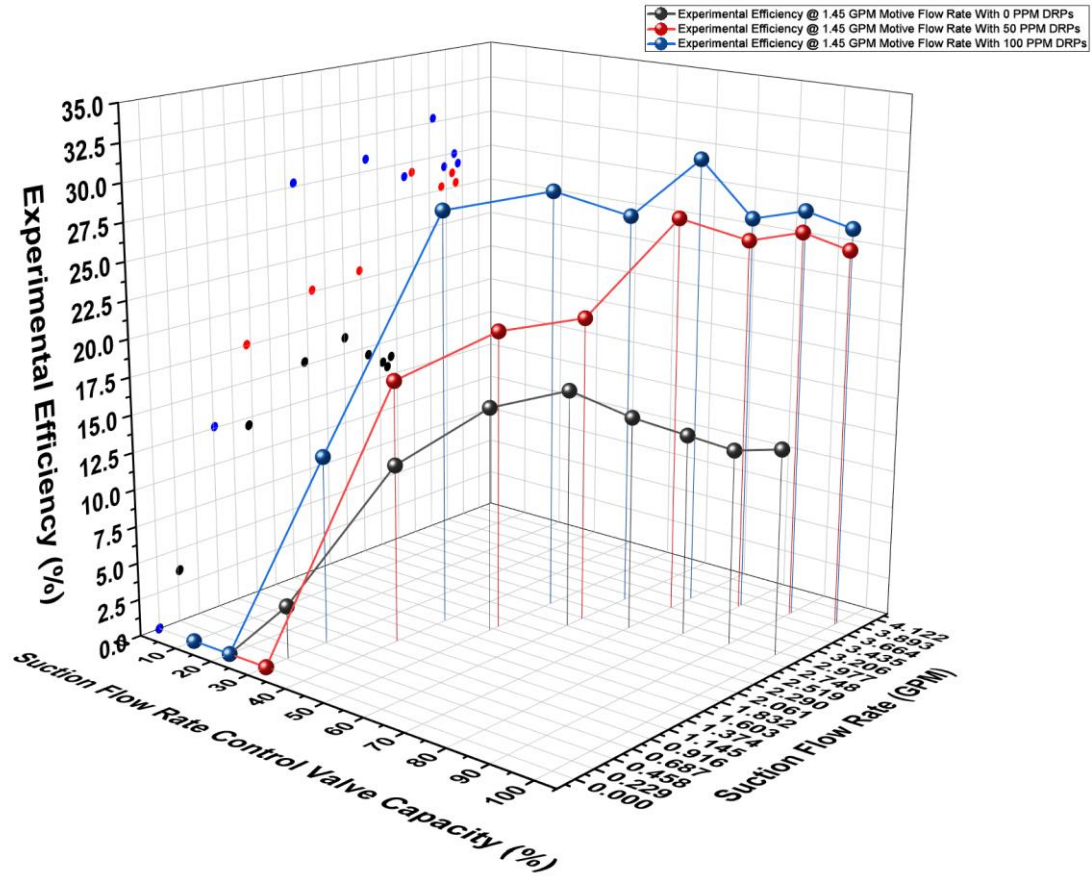


Figure 13 3D representation illustrating the relationship among the Experimental Efficiency, Suction Flow Rate Control Valve Capacity and Suction Flow Rate at 1.45 GPM motive flow rate.

4.3 Case 2 (Analytical Type 1 Efficiency):

The impact of drag reducing polymers (DRPs) on the Analytical type 1 efficiency (η_{A1}) was investigated at a motive flow rate of 1 and 1.45 GPM. (Fig.14) and (Fig.15) illustrate the results obtained from various experimental scenarios at 1 GPM motive flow rate. The addition of DRPs at concentrations of 100 ppm and 50 ppm resulted in higher η_{A1} values. The highest Analytical type 1 efficiency of 80.7% was achieved at a suction flow rate of 3.01 GPM with a concentration of 100 ppm DRPs. Subsequently, the DRPs concentration was reduced to 50 ppm, which led to an improvement in the efficiency of Analytical type 1 compared to the suction flow rate without any DRPs (0 ppm concentration). The

analytical type 1 efficiency increased from 46.5% at a suction flow rate of 2.2 GPM to 71% at a suction flow rate of 2.81 GPM. It is worth noting that the efficiency slope decreased noticeably at a concentration of 100 ppm DRPs compared to 50 ppm. Additionally, Examining the relationship between suction flow rate control valve capacity and analytical efficiency, as depicted in **(Fig.16)** and **(Fig.17)**, revealed variations observed at different concentrations of DRPs while maintaining a motive flow rate of 1.45 GPM. At 50 ppm, the suction flow rate increased from 2.9 GPM to 3.8 GPM, resulting in an improvement in analytical type 1 efficiency from 40% to 62.7%. Furthermore, when the concentration of DRPs was increased to 100 ppm, the suction flow rate reached 3.83 GPM, with an analytical type 1 efficiency of 63.7%. Comparing the analytical type 1 efficiencies at both DRP concentrations (50 ppm and 100 ppm), similar results were observed, with an approximate 23% enhancement in the system analytical type 1 efficiency compared to the system with no DRPs addition (0 ppm concentration).

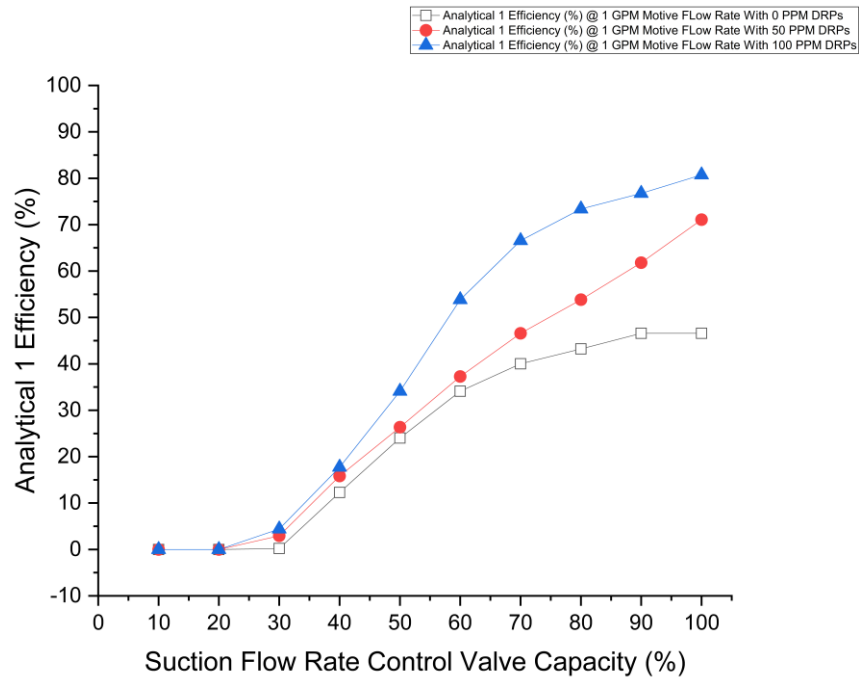


Figure 14 Variation of Analytical type 1 efficiency with respect to the capacity of the suction flow rate control valve at 1 GPM motive flow rate with different DRPs concentrations (0, 50 and 100 ppm)

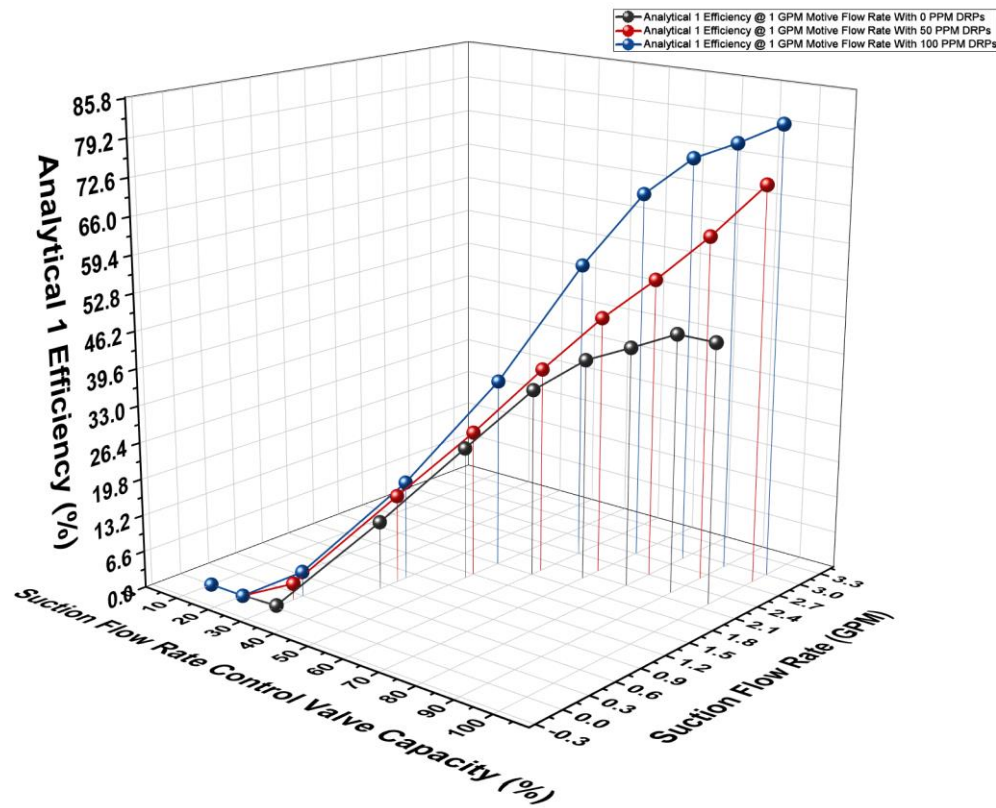


Figure 15 3D representation of the variation between the analytical type 1 efficiency, the suction flow rate control valve capacity, and the suction flow rate at 1 GPM motive flow rate.

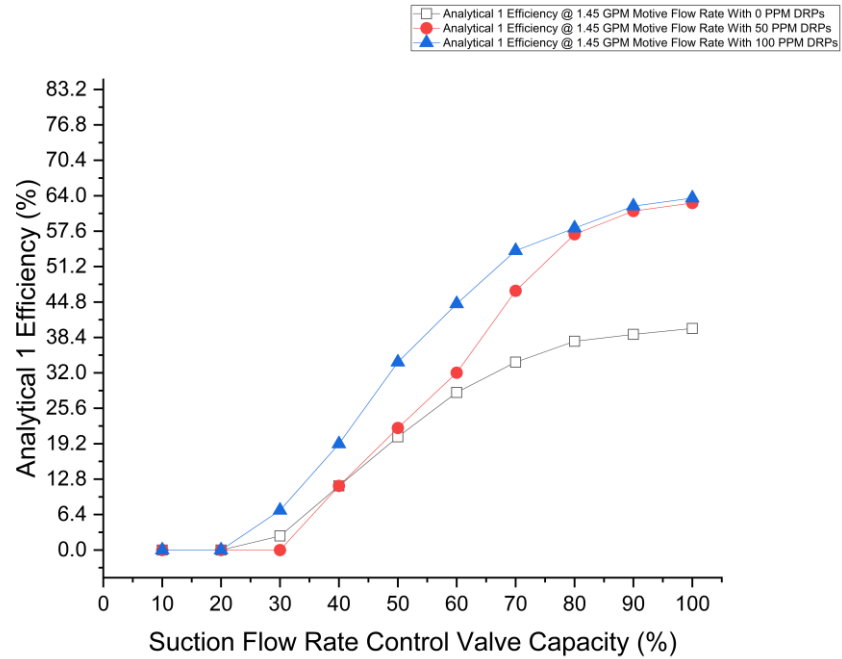


Figure 16 Variation of Analytical type 1 efficiency with respect to the capacity of the suction flow rate control valve at 1.45 GPM motive flow rate with different DRPs concentrations (0, 50 and 100 ppm)

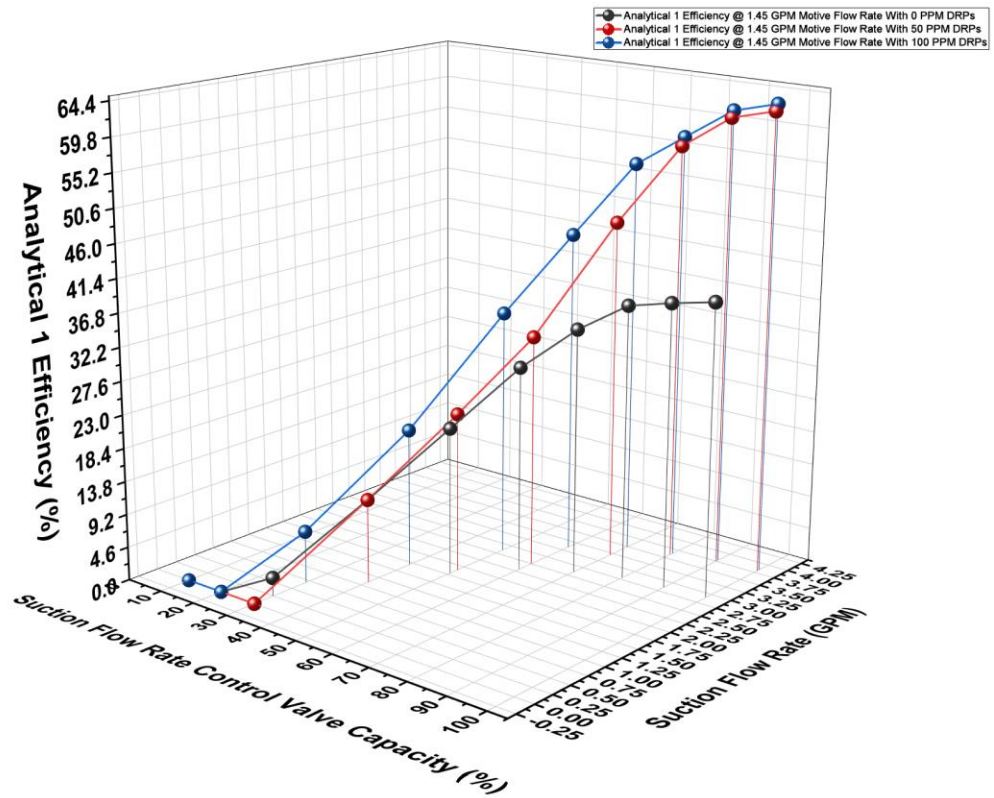


Figure 17 3D representation of the variation between the analytical type 1 efficiency, the suction flow rate control valve capacity and the suction flow rate at 1.45 GPM motive flow rate.

4.4 Case 3 (Analytical Type 2 Efficiency):

The variation of analytical type 2 efficiency (η_{A2}) with the capacity of the suction flow rate control valve was examined using **(Fig.18)** and **(Fig.19)**. The analysis using both figures was conducted at different concentrations of drag reducing polymers (DRPs) (0, 50, and 100 ppm), while maintaining a motive flow rate of 1 GPM. Introducing DRPs at a concentration of 50 ppm in the suction line resulted in a significant enhancement of the analytical type 2 efficiency (η_{A2}), increasing it from 13% to 35.4%. This improvement corresponded to an increase in the suction flow rate capacity from 2.2 to 2.81 GPM. Further increasing the concentration of DRPs to 100 ppm led to a substantial improvement in the analytical type 2 efficiency (η_{A2}), rising from 13% to 44.4%. This enhancement was accompanied by an increase in the suction flow rate capacity to 3.01 GPM. Furthermore, it was observed that the slope of the analytical type 2 efficiency (η_{A2}) appeared to be lower at a concentration of 100 ppm compared to 50 ppm. Additionally, at a lower suction flow rate control valve opening of 40%, the analytical type 2 efficiency yielded nearly identical results across the three different DRP concentrations (0, 50, and 100 ppm) with higher values compared to the 50% suction control valve opening. Furthermore, the analytical type 2 efficiency remained consistent across the three DRP concentrations (0, 50, and 100 ppm) at this lower valve opening, furthermore, the analytical type 2 efficiency (η_{A2})

demonstrated a higher value at a 40% opening of the suction control valve compared to a 50% opening of the suction flow rate control valve.

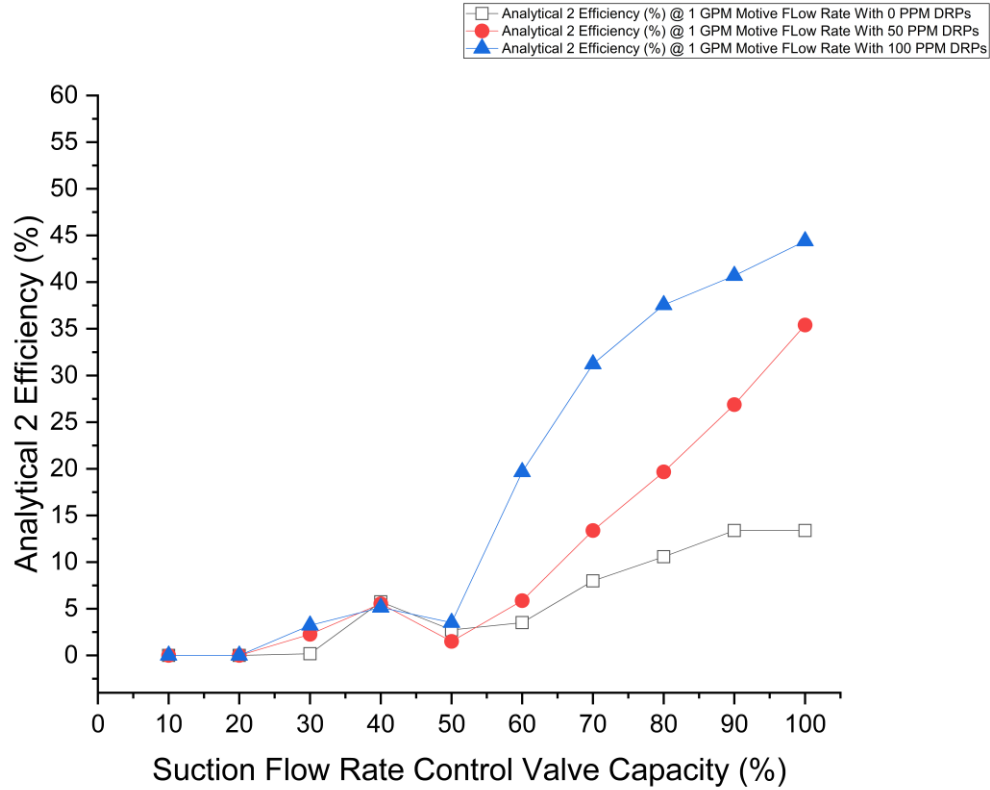


Figure 18 Analytical type 2 efficiency variation as a function of suction flow rate control valve capacity at a motive flow rate of 1 GPM, considering different concentrations of drag reducing polymers (DRPs) (0, 50, and 100 ppm).

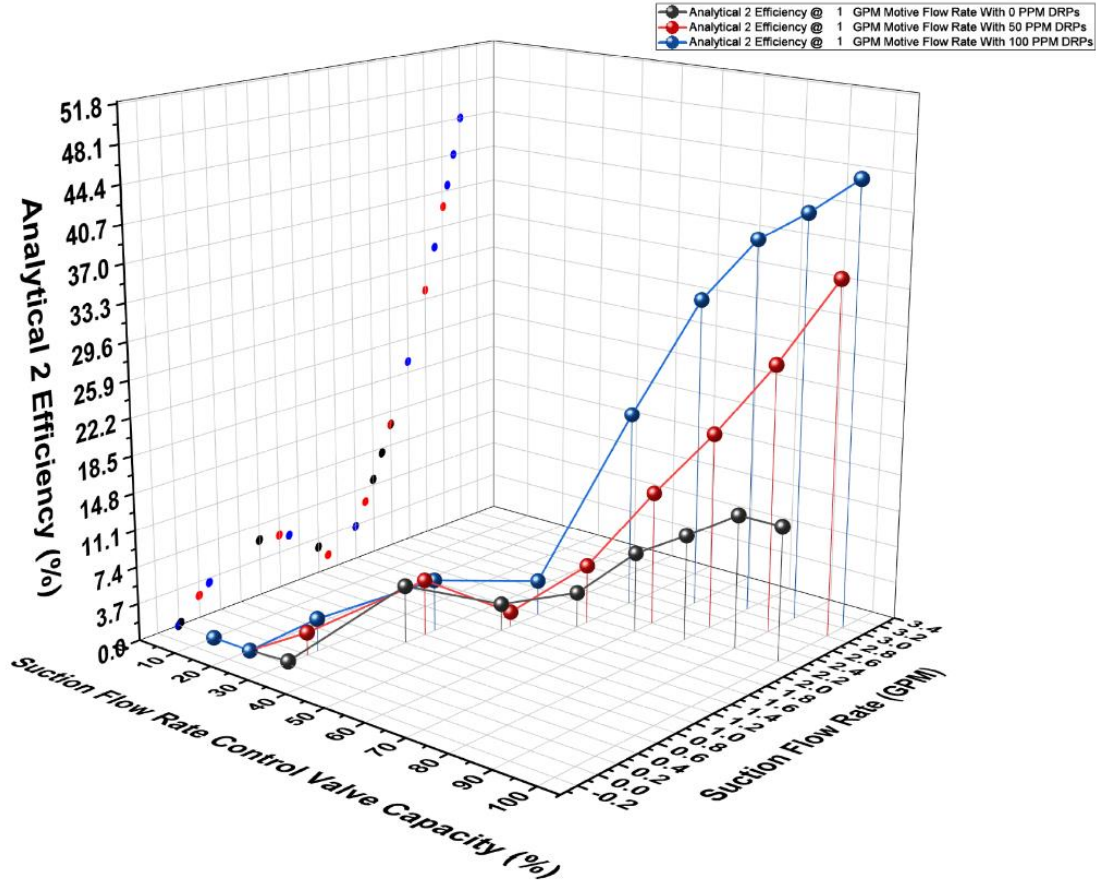


Figure 19 3D representation of the variation between the analytical type 2 efficiency, the suction flow rate control valve capacity and the suction flow rate at 1 GPM motive flow rate.

Moreover, under a constant motive flow rate of 1.45 GPM, the introduction of drag reducing polymers (DRPs) at a concentration of 50 ppm into the suction line yielded a noteworthy enhancement in the analytical type 2 efficiency (η_{A2}). It went from 8% to 27.7%, resulting in an increased suction flow rate capacity from 2.9 to 3.8 GPM. Elevating the DRPs concentration to 100 ppm exhibited a similar improvement in the analytical type 2 efficiency (η_{A2}), which increased from 8% to 28.5%. The suction flow rate capacity also increased to 3.83 GPM. Importantly, the slope of the analytical type 2 efficiency (η_{A2}) remained consistent between 100 ppm and 50 ppm DRPs concentrations. Furthermore, at a lower suction flow rate control valve opening of 40%, the analytical type 2 efficiency

showed higher values at a concentration of 50 ppm compared to 100 ppm. Additionally, it exhibited higher efficiency (η_{A2}) than at a 50% suction flow rate control valve opening. Moreover, the same behavior of 1 GPM is observed here, at a 40% lower valve opening, the efficiency (η_{A2}) was higher compared to when the suction flow rate control valve opening was set at 50%. The relationship between the capacity of the suction flow rate control valve and the analytical type 2 efficiency (η_{A2}) is illustrated in **(Fig.20)** and **(Fig.21)**.

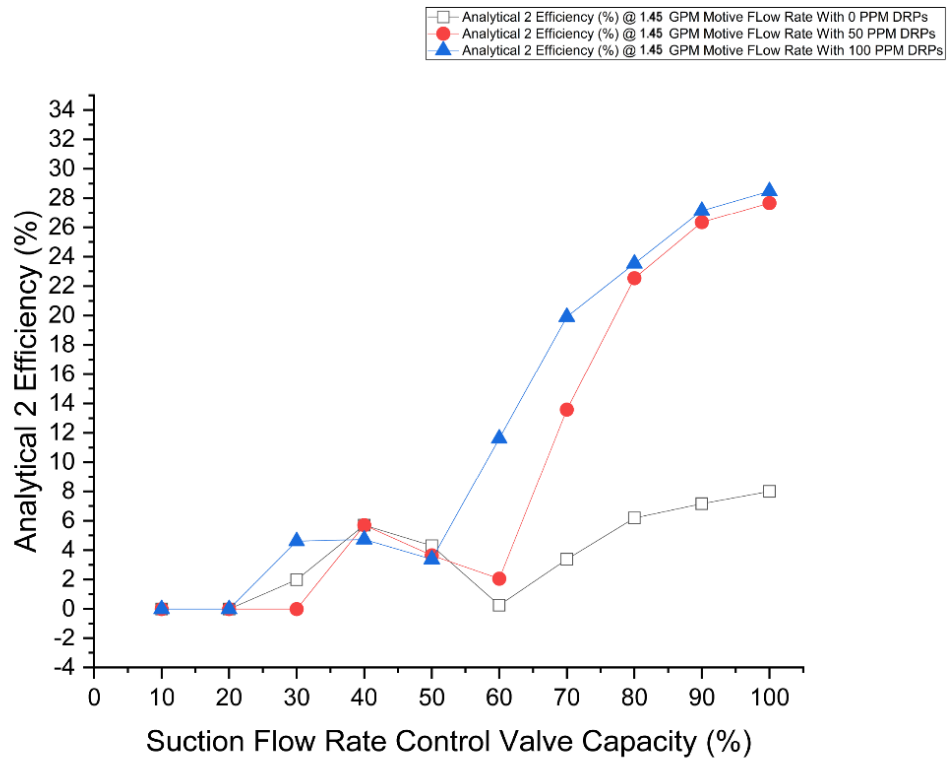


Figure 20 Analytical type 2 efficiency variation as a function of suction flow rate control valve capacity at a motive flow rate of 1.45 GPM, considering different concentrations of drag reducing polymers (DRPs) (0, 50, and 100 ppm).

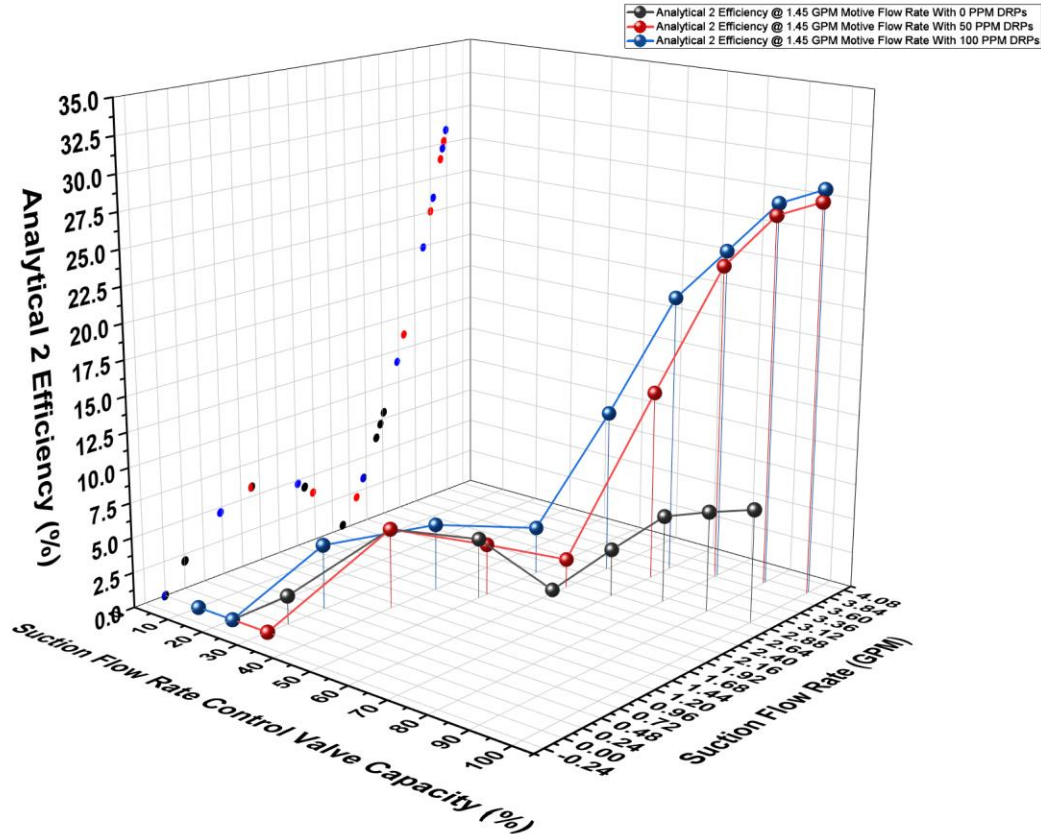


Figure 21 3D representation of the variation between the analytical type 2 efficiency, the suction flow rate control valve capacity, and the suction flow rate at 1.45 GPM motive flow rate.

4.5 Case 4 (Head Ratio Efficiency):

The application of Drag Reducing Polymers (DRPs) at a concentration of 100 ppm has demonstrated a significant enhancement in the Head Ratio efficiency at a motive flow rate of 1 gallon per minute (GPM), raising it from 22.3% to 50%. Additionally, when the DRP concentration was reduced to 50 ppm, the Head Ratio efficiency exhibited a noticeable improvement, reaching 41.5%. Notably, the slope of the head ratio efficiency is lower at 100 ppm DRPs concentration compared to 50 ppm, indicating a higher conservation of head ratio efficiency at higher suction flow rate control valve openings. Furthermore, reducing the opening of the suction flow rate control valve did not lead to an increase in

head ratio efficiency when compared to the analytical or experimental efficiencies. **(Fig.22)** and **(Fig.23)** provide a visual representation of the observed variations.

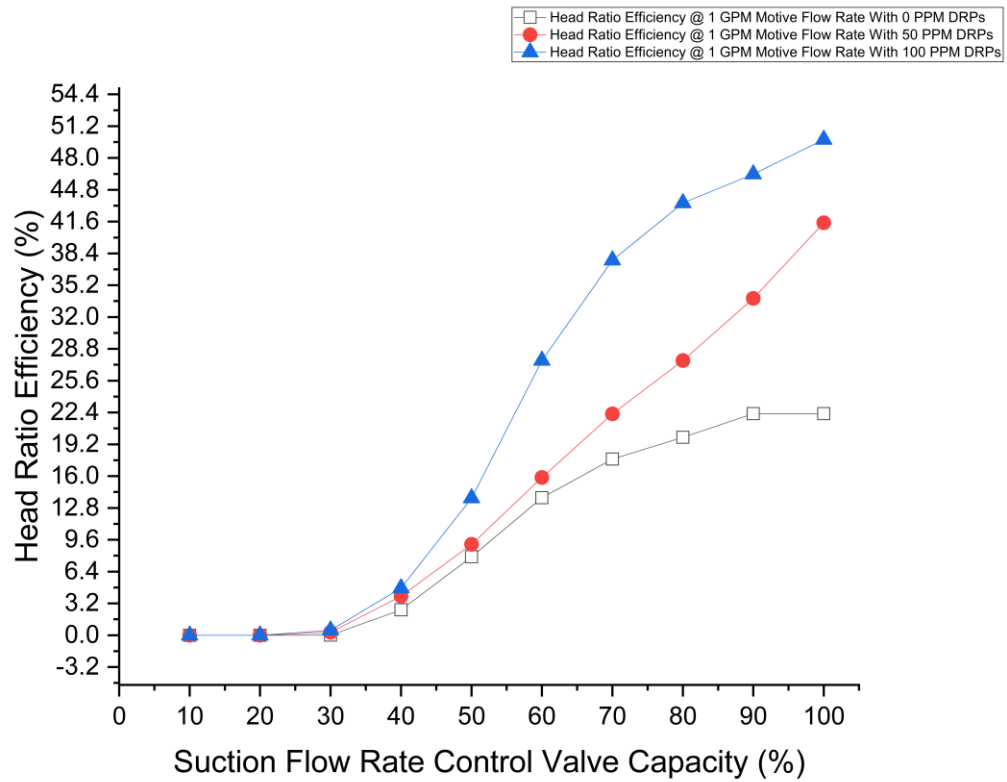


Figure 22 Variation of head ratio efficiency with respect to the capacity of the suction flow rate control valve at 1 GPM motive flow rate with different DRPs concentrations (0, 50 and 100 ppm)

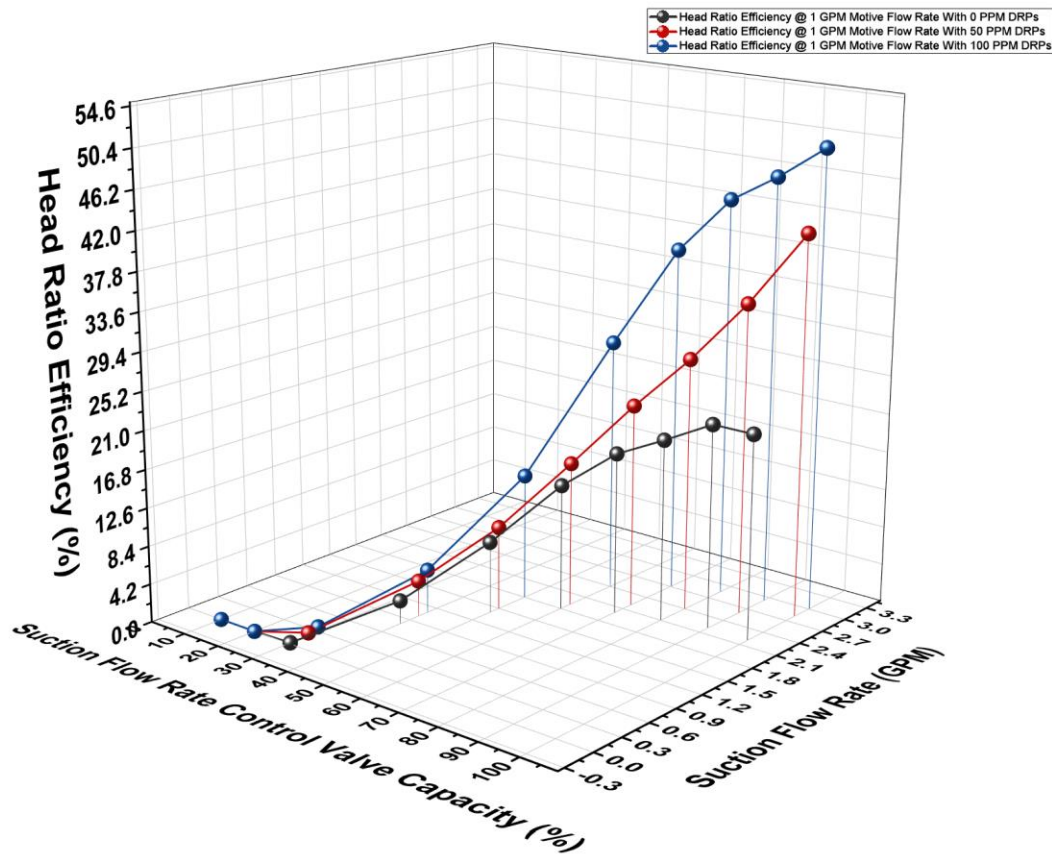


Figure 23 3D representation of the variation between the head ratio efficiency, the suction flow rate control valve capacity and the suction flow rate at 1 GPM motive flow rate.

A significant improvement in head ratio efficiency is observed with the introduction of a 100-ppm concentration of drag reducing polymers (DRPs) at a motive flow rate of 1.45 GPM, resulting in an increase from 17.7% to 35.3%. Interestingly, the effects of 100 ppm and 50 ppm concentrations on the capacity of the high suction flow rate control valve appear to be similar. However, when the suction flow valve is closed, the efficiency of the 100-ppm concentration surpasses that of the 50-ppm concentration. Furthermore, when the valve opening is significantly reduced, both the 100 ppm and 50 ppm concentrations show

comparable improvements in head ratio efficiency compared to the suction flow rate without DRPs (0 ppm). Observations depicted in **(Fig.24)** and **(Fig.25)**.

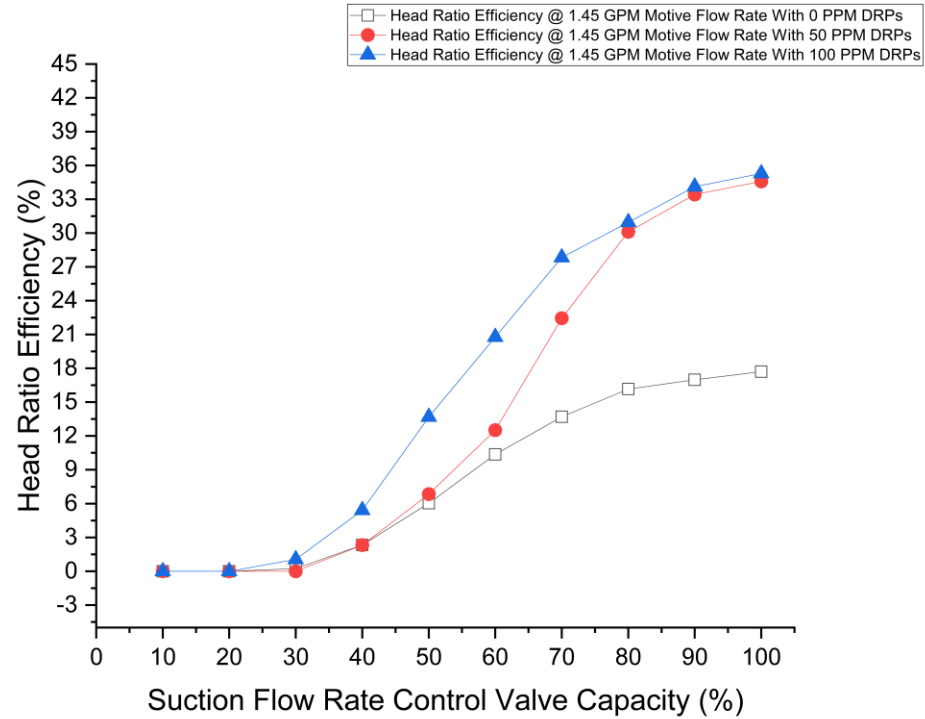


Figure 24 Variation of head ratio efficiency with respect to the capacity of the suction flow rate control valve at 1.45 GPM motive flow rate with different DRPs concentrations (0, 50 and 100 ppm)

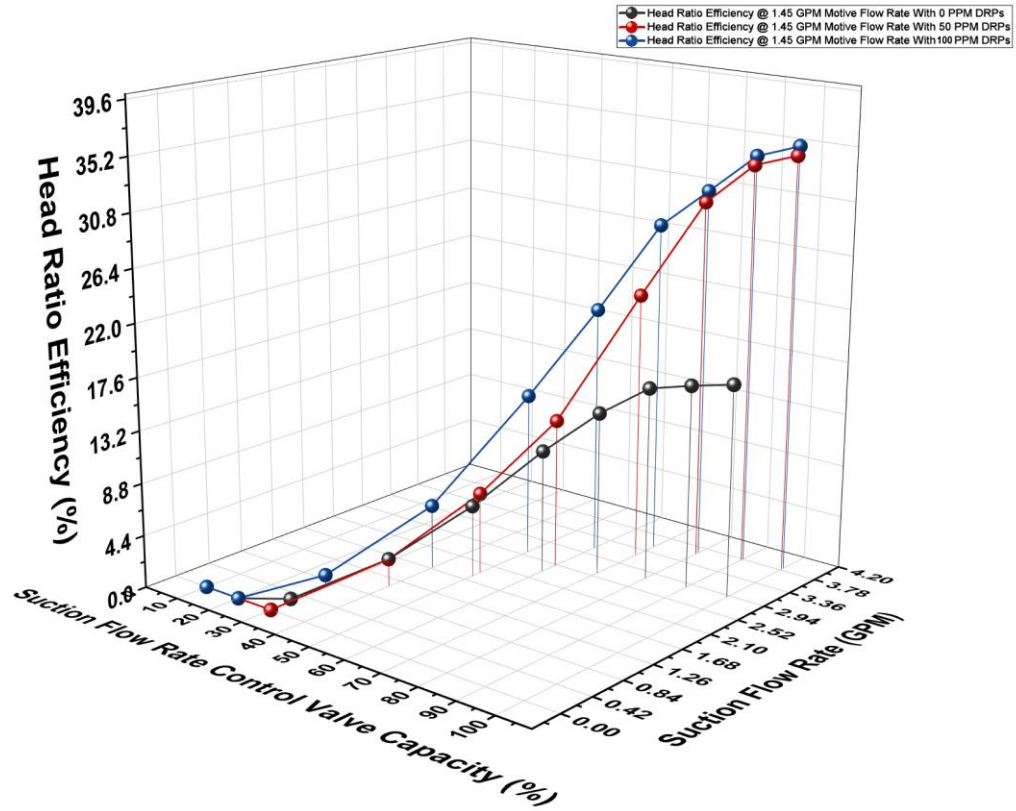


Figure 25 3D representation of the variation between the head ratio efficiency, the suction flow rate control valve capacity and the suction flow rate at 1.45 GPM motive flow rate.

4.6 Cases Efficiencies Comparison:

A comparison was conducted between the efficiencies of different cases at two motive flow rates (1 and 1.45 GPM), with the suction flow rate control valve fully open. It was observed that at a motive flow rate of 1.45 GPM, the head ratio, analytical type 2, and experimental efficiencies showed relatively close results, whereas the analytical type 1 efficiency differed. However, at a motive flow rate of 1 GPM, the experimental efficiency deviated from both the head ratio and analytical type 2 efficiencies. This deviation can be attributed to the models' dependence on the entrainment ratio (M), which tends to yield higher values at low motive flow rates, thereby increasing the efficiency of the system according to these models. (**Table 6**) effectively illustrates the comprehensive comparison.

Table 6 Comprehensive comparison between the different cases efficiencies at different motive flow rates (1 and 1.45 GPM) and DRPs concentrations (0, 50 and 100 ppm) at fully opened suction control valve.

Motive Flow Rate (GPM)	Concentration (PPM)	Suction Control Valve Capacity (%)	Suction Flow Rate (GPM)	η_{HR} (%)	η_{AN1} (%)	η_{AN2} (%)	η_{EX} (%)
1.45	100	100	3.83	35.3	63.58	30.51	26.69
1.45	50	100	3.8	34.59	62.7	29.67	25.33
1.45	0	100	2.9	17.71	40.03	9.203	13.82
1	100	100	3.01	49.86	80.72	46.97	30.99
1	50	100	2.81	41.49	71.07	37.67	24.61
1	0	100	2.2	22.29	46.58	14.83	6.56

4.7 Drag Reduction in Terms of Reynolds Number and Velocity:

After performing the experiments and collecting the data, we measured the drag reduction in each component in the ejector at different motive flow rates mainly for 1 and 1.45 GPM motive flow rates and different DRPs concentrations 50 and 100 PPM. And since the pressure was constant after the addition of the DRPs and the flow rate was the only variable, in accordance with Darcy-Weisbach equation:

$$dP = \lambda \frac{L}{4\pi^2 R_W^5} \rho Q^2 \quad (32)$$

Where, λ is the drag coefficient, R_W and L are the pipe radius and length, and Q , dP are the flow rate and the pressure drop.

From equation 32:

$$\lambda = \frac{4\pi^2 R_W^5}{L\rho} \frac{dP}{Q^2} \quad (33)$$

knowing that:

$$DR\% = \frac{\lambda_s - \lambda_p}{\lambda_s} \quad (34)$$

Substituting equation 33 in 34 knowing that $dP = \text{Constant}$:

$$DR\% = \frac{Q_s^2 - Q_p^2}{Q_s^2} \quad (35)$$

Where Q_s is flow rate without DRPs addition and Q_p is the flow rate with the DRPs addition. After utilizing equation 35 using our results collected before, Figures 26-29 show the drag reduction at 1 and 1.45 GPM motive flow rates and different DRPs concentrations for the different ejector's components.

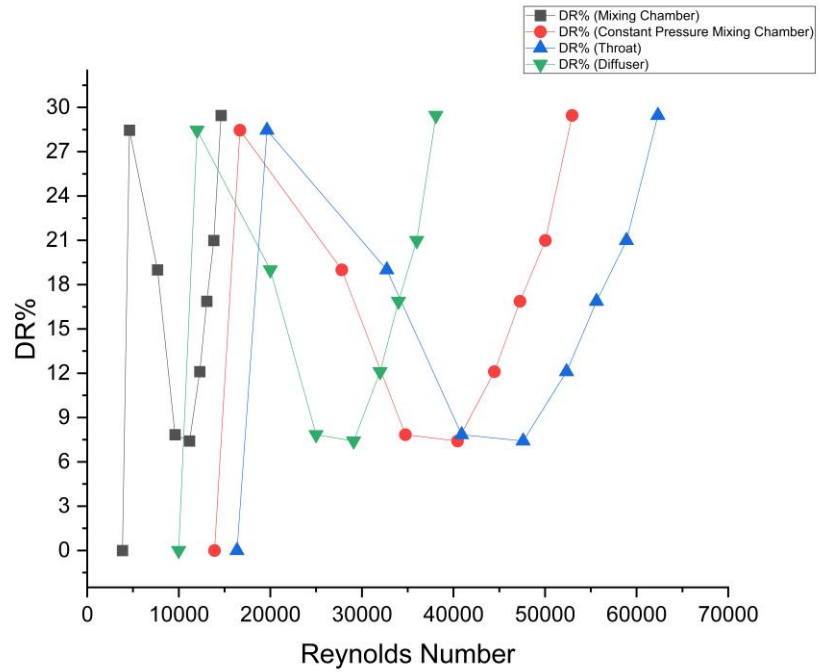


Figure 26 Drag reduction in the ejector's components using 1 GPM motive flow rate and 50 PPM DRP concentration.

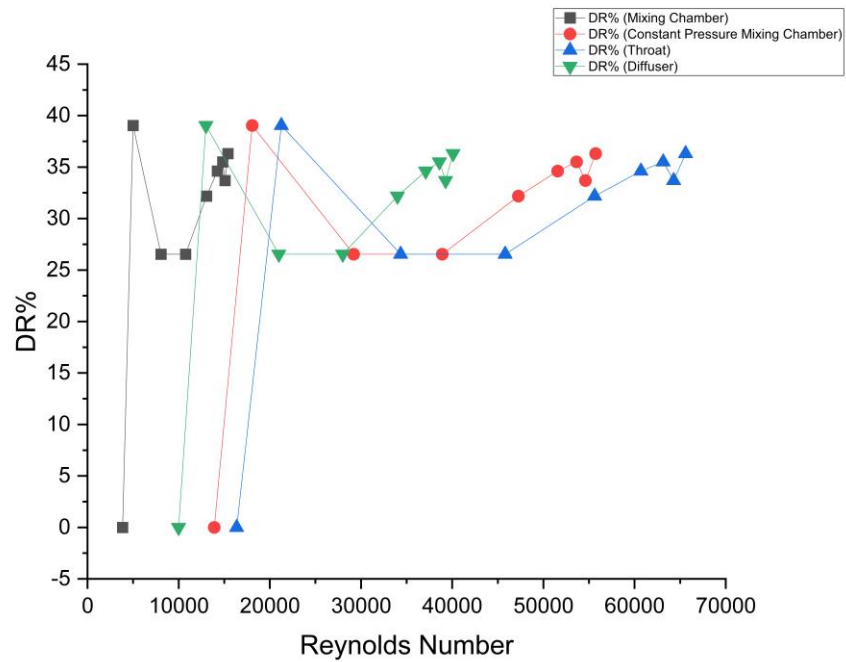


Figure 27 Drag reduction in the ejector's components using 1 GPM motive flow rate and 100 PPM DRP concentration.

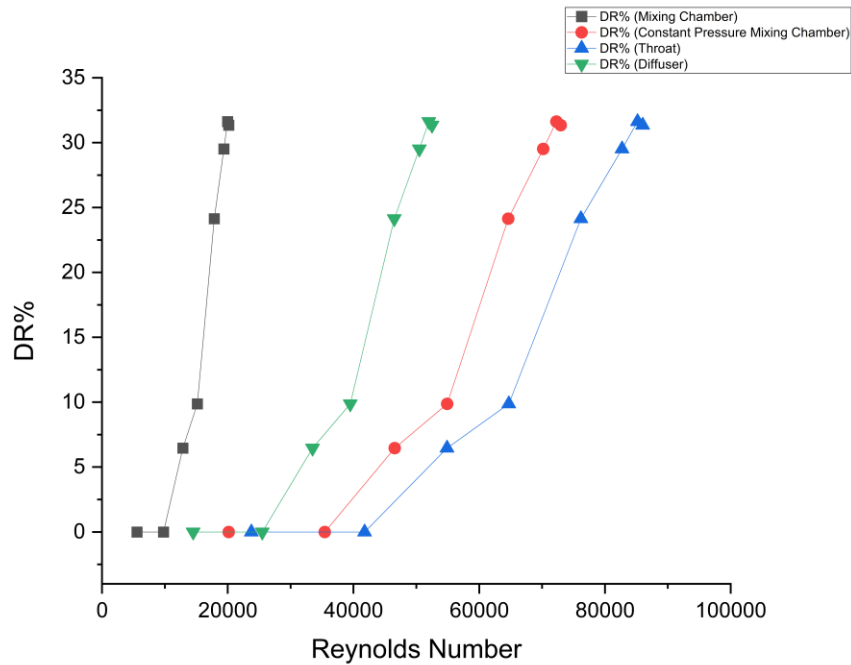


Figure 28 Drag reduction in the ejector's components using 1.45 GPM motive flow rate and 50 PPM DRP concentration.

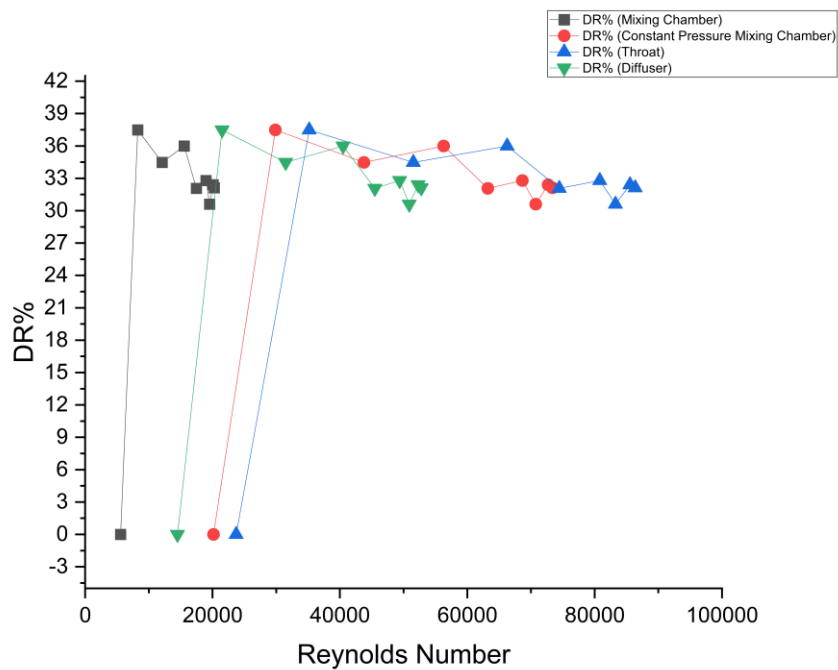


Figure 29 Drag reduction in the ejector's components using 1.45 GPM motive flow rate and 100 PPM DRP concentration.

From figures 26 and 28, when 50 PPM DRPs added, the drag reduction fluctuates especially at low suction flow rates, while 100 PPM DRPs did not experience the same behavior, moreover, the components showed the same drag reduction percentage whatever was the diameter of the component. Figures 30 and 31 have a comprehensive representation for the velocity and Reynolds number inside the ejector at any point within the X-Direction for both motive flow rates and both DRPs concentrations.

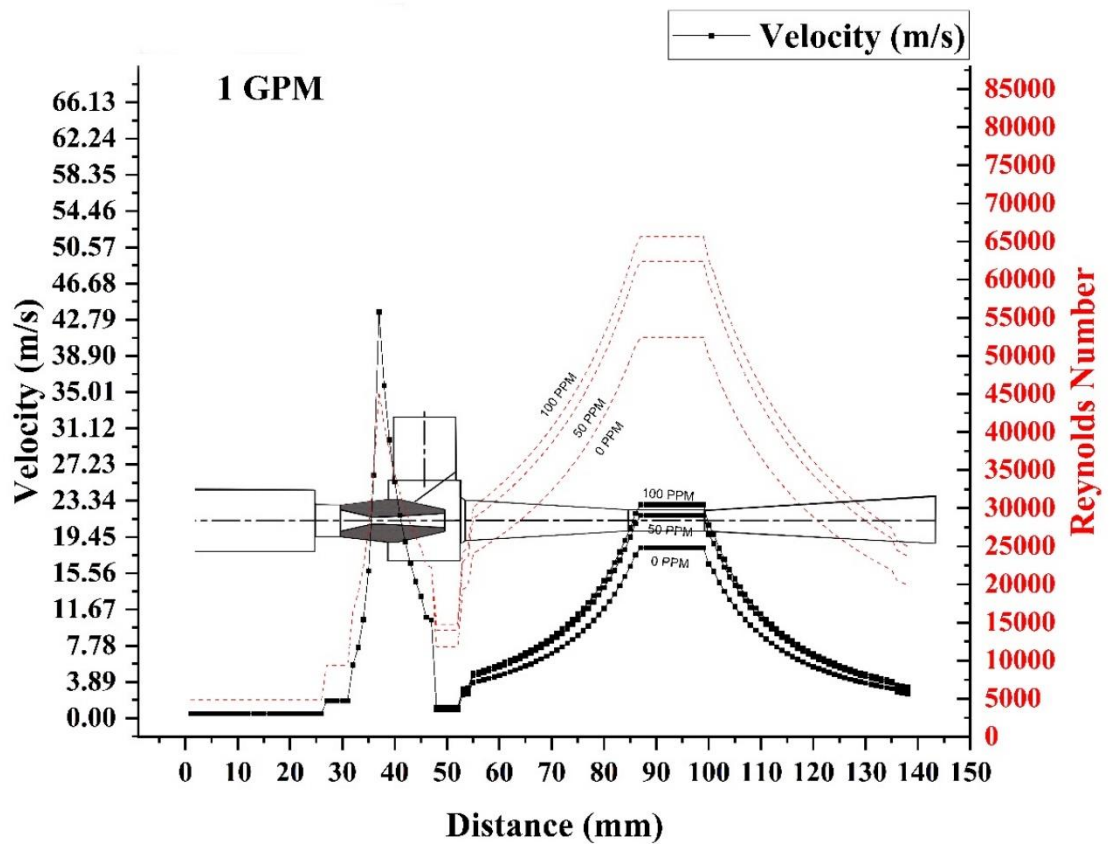


Figure 30 Velocity profile and Reynolds number in X-Direction at 1 GPM motive flow rate.

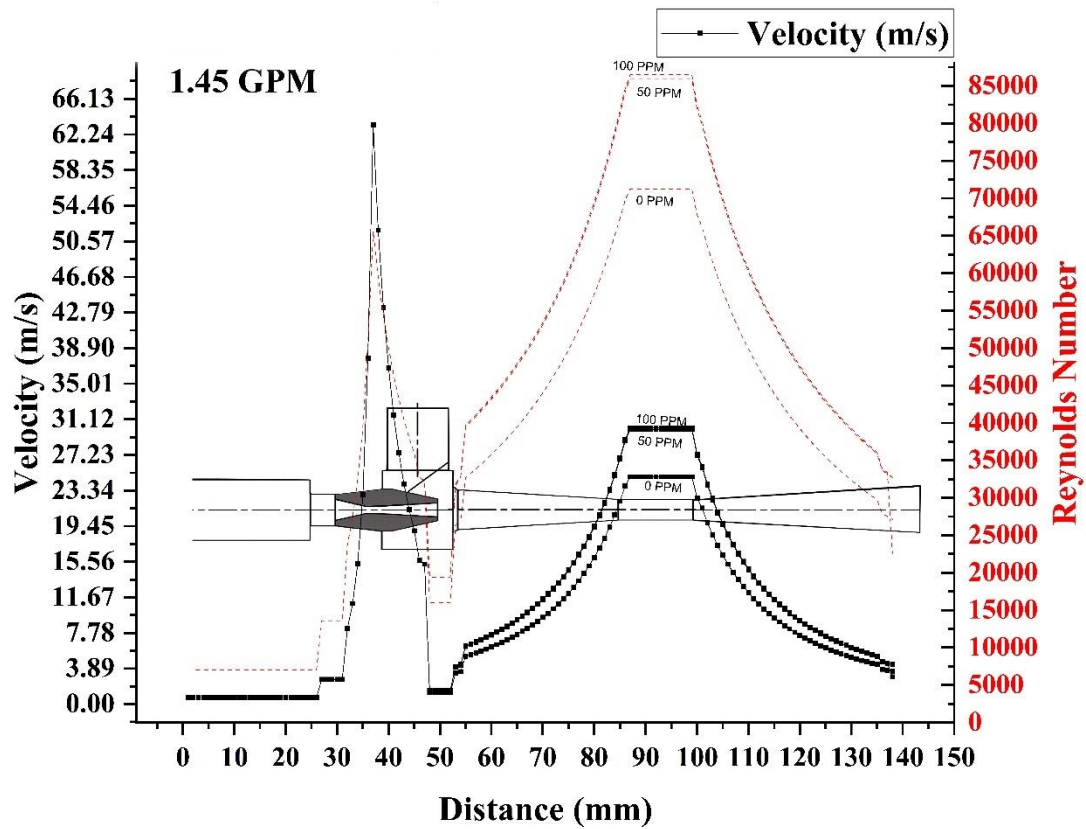


Figure 31 Velocity profile and Reynolds number in X-Direction at 1.45 GPM motive flow rate.

From the two figures above, it is obvious that Reynolds number at 1.45 GPM motive flow rate was much higher than 1 GPM with the value of 87000 compared to approximately 65000 at the throat zone which leads to a higher turbulence and higher mixing intensity. Also, the highest velocity noticed to be in the nozzle zone at 64 m/s for 1.45 GPM motive flow rate and 46 m/s for 1 GPM.

4.8 Emulsified Acid System (EAS) Experimental Results:

4.8.1 Emulsion 1 (EM.1):

After mixing both motive and suction streams using the ejector at 2.05 GPM motive and 3 GPM suction flow rates, the TDS for water were set to 1000 PPM. The experiment took 20 seconds and resulted in an unstable O/W (water as an external phase) emulsion which separated after 20 minutes as it shown in **Table 7** which illustrate the emulsion stability status, both pictures were taken immediately and after 20 minutes of mixing.

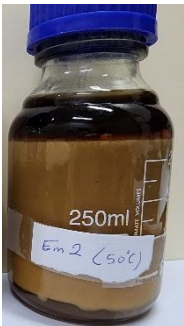
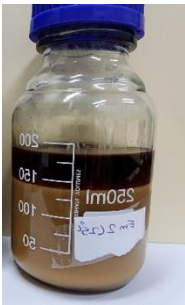
Table 7 EM.1 experiment, EAS with 1000 PPM of total water salinity.

	
immediate	After 1 hr

4.8.2 Emulsion 2 (EM.2):

The second trial were conducted at the same ARAMCO's recipe as in (EM.1), but the water salinity was set to 15000 PPM. Then after mixing, a drop test was performed, and it resulted in the water as an external phase (O/W). Moreover, the stability of the resulted emulsion was checked at both temperatures (25°C) and (50°C) after 1 hour and 13 days, the results with timings are presented in **Table 8**.

Table 8 Em.2 experiment, 15000 PPM of total water salinity

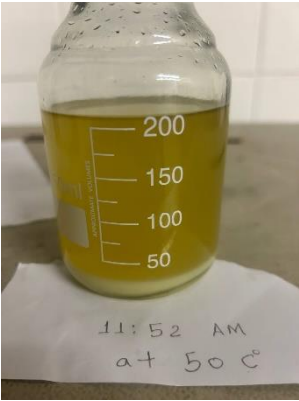
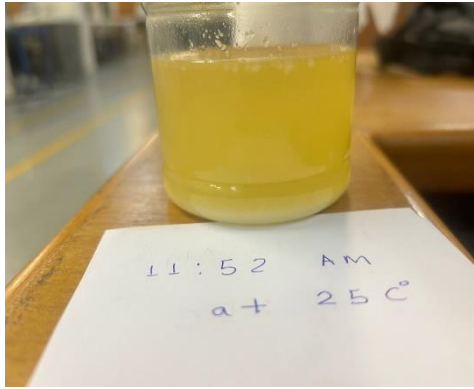
		
Immediate	1 Hour After October 24, 2023 12:21 PM 50°C	1 Hour After October 24, 2023 12:21 PM 25°C
		
	13 Days After November 6, 2023 5:36 PM 50°C	13 Days After November 6, 2023 5:36 PM 25°C

4.8.3 Emulsion 3 (EM.3):

The third trial involved the utilization of Halliburton's recipe, where diesel served as the motive flow, and the aqueous phase functioned as the suction. The water fraction introduced into the aqueous salinity was maintained at 15000 PPM. The outcome revealed an unstable emulsion characterized by segregation started from above between the diesel

and aqueous phases. Additionally, the external phase was diesel (W/O emulsion). This separation was evident both immediately after emulsion generation and one hour afterward, as depicted in **Table 9**.

Table 9 EM.3 experiment, EAS with 15000 PPM of total water salinity with Halliburton recipe.

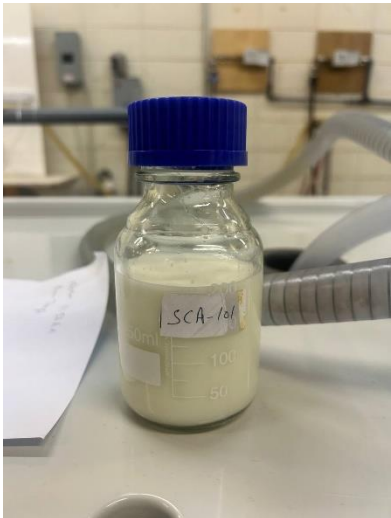
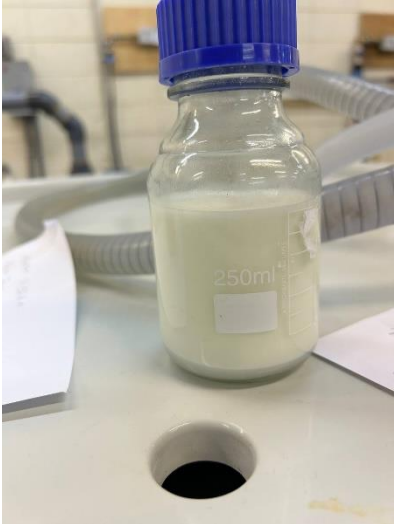
		
Immediate	1 Hour After 12:21 PM 50°C	1 Hour After 12:21 PM 25°C

4.8.4 Emulsion 4 (EM.4):

During this experiment, Halliburton's recipe was employed, using tap water as the aqueous phase without added salt to distinguish it from the acidic phase where diesel served as the motive flow. The resulting emulsion exhibited increased stability compared to previous trials, with separation occurring predominantly in a smaller fraction beneath the entire volume after 1 hour, as depicted in the figures in **Table 10**. The external phase was water,

indicating an oil-in-water (O/W) emulsion. Additionally, the suction to motive percentage was 60/40 as in the pervious trials.

Table 10 EM.4 experiment, 0 PPM of total water salinity with Halliburton recipe without Acid.

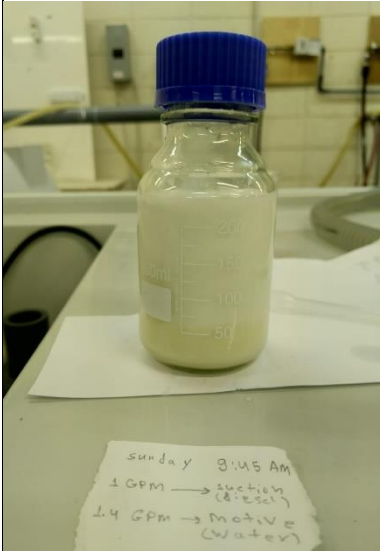
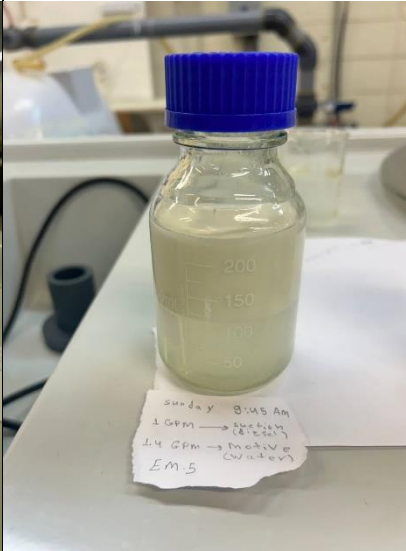
	
Immediate	1 Hour After 25°C

4.8.5 Emulsion 5 (EM.5):

During this experiment, the roles of motive and suction flows were reversed, with the aqueous phase (tap water without added salt) serving as the motive flow, and diesel as the suction flow. The ratio of suction to motive flow was set at 58/41.6. Halliburton's recipe was applied in this trial, resulting in a relatively stable emulsion that maintained its stability even after the initial hour, which was completely separated after 3 days. It's worth noting

that the external phase was water in this trial. Immediately, after 1 hour and 3 days figures are shown in **Table 11**.

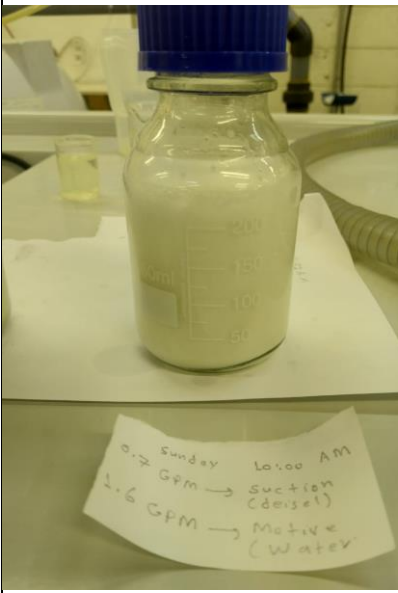
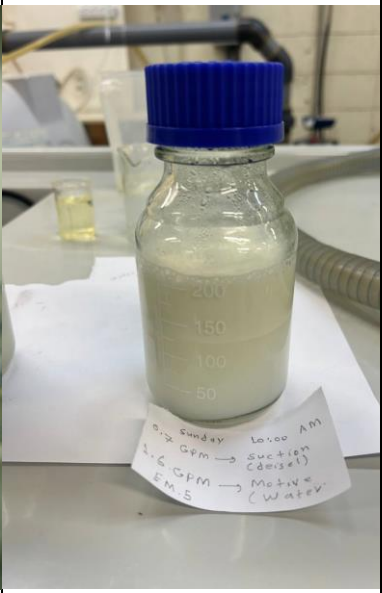
Table 11 EM.5 experiment, 0 PPM of total water salinity with Halliburton recipe without Acid, water as the motive and diesel as the suction with 41.6 /58 suction to motive percentage.

		
Immediate	1 Hour After 25°C	3 Days After 25°C

4.8.6 Emulsion 6 (EM.6):

The same conditions and parameters used in EM.5 trial were used here except for the suction to motive percentage, which was set to 70/30. The result was more stable compared to EM.5 trial, the emulsion did not separate after 1 hour, furthermore, after 3 days, the emulsion did not separate completely which was the case in EM.5 trial. However, the external phase was water. The figures are shown in **Table 12**.

Table 12 EM.6 experiment, 0 PPM of total water salinity with Halliburton recipe without Acid, water as the motive and diesel as the suction with 30/70 suction to motive percentage.

		
Immediate	1 Hour After 25°C	3 Days After 25°C

4.8.7 Emulsion 7 (EM.7):

During this experiment, the formulation from ARAMCO was employed, with the aqueous phase containing acid serving as the motive flow and diesel as the suction flow. The suction to motive flow ratio was established at 70/30, and the total dissolved solids (TDS) of the aqueous phase was set at 15000 ppm. This formulation led to an unstable emulsion that separated within 5 minutes. Notably, the external phase in this trial was water. As indicated in **Table 13**, after 1 hour, the emulsion demonstrated clear separation, with the aqueous phase settling in the upper fraction and the diesel in the lower fraction.

Table 13 EM.7 experiment, 15000 PPM of total water salinity with ARAMCO recipe with acid, acid as the motive and diesel as the suction with 70/30 suction to motive percentage.

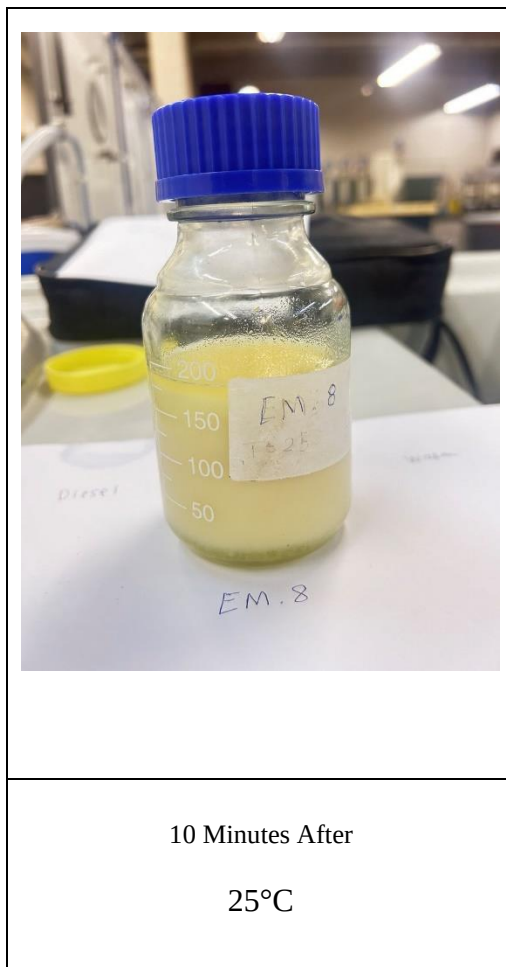


4.8.8 Emulsion 8 (EM.8):

In this experiment, Schlumberger's emulsifier was introduced into the oil phase (diesel). The diesel functioned as the motive flow rate, while the aqueous phase was employed as the suction flow. The total dissolved solids (TDS) of the aqueous phase salinity were set at 25000 ppm, with a suction to motive flow ratio of 53/46. The resulting emulsion proved to be unstable, separating after 10 minutes at room temperature (25°C). Notably, the external phase in this trial was oil. This suggests that the TDS plays a vital role in phase inversion during emulsion generation, and further efforts are underway to address the need for

increased turbulence to stabilize the emulsion. **Table 14** provides a snapshot of the emulsion after 10 minutes of its creation.

Table 14 EM.8 experiment, 25000 PPM of total water salinity with Schlumberger's recipe with acid, acid as the motive and diesel as the suction with 53/46 suction to motive percentage.



4.8.9 Emulsion 9 (EM.9):

In this experiment, ARAMCO's emulsifier was introduced into the oil phase (diesel). The diesel functioned as the motive flow rate, while the aqueous phase was employed as the suction flow, moreover, the acid grade was changed to a laboratory grade. The total dissolved solids (TDS) of the aqueous phase salinity were set at 20000 ppm, with a suction to motive flow ratio of 60/40. The resulting emulsion proved to be unstable, separating

after 30 minutes at room temperature (25°C). Notably, the external phase in this trial was water. **Table 15** provides a snapshot of the emulsion after 10 minutes of its creation.

Table 15 EM.9 experiment, 20000 PPM of total water salinity with ARAMCO's recipe with acid, acid as the motive and diesel as the suction with 60/40 suction to motive percentage.



4.8.10 Emulsion 10 (EM.10):

The centrifugal pump supplying the motive stream was replaced with a gear pump to alleviate the back pressure resulting from the reduction in nozzle area. ARAMCO's emulsifier was introduced into the oil phase (diesel), with diesel serving as the motive flow rate and the aqueous phase acting as the suction flow. The aqueous phase salinity was adjusted to a total dissolved solids (TDS) level of 20000 ppm, with a suction to

motive flow ratio of 62/38. However, the resulting emulsion proved unstable, exhibiting separation after 30 minutes at room temperature (25°C) from above. Notably, water served as the external phase in this trial.

Furthermore, to assess mixing integrity, a V-Pump, employing the same ejector concept but with a different design, was utilized to create an emulsion using the same recipe and gear pump as the motive stream. The resulting emulsion demonstrated similar characteristics to the ejector-produced emulsion but exhibited relatively higher stability after 20 minutes and exhibited a separation from below. Notably, water served as the external phase in this trial as the as the ejector's. Additionally, a high shear homogenizer was employed to mix the mixture at 9000 RPM for 5 minutes, resulting in a stable emulsion even after 1 day of mixing with an oil as the external phase. Table 16 presents snapshots of the emulsions.

Table 16 EM.10 experiment, 20000 PPM of total water salinity with ARAMCO's recipe with acid, acid as the motive and diesel as the suction with 60/40 suction to motive percentage.

		
30 Minutes After	20 Minutes After	20 Minutes After
25°C	25°C	25°C
		
1 day After	1 day After	1 day After
25°C	25°C	25°C

4.8.11 Emulsion 11 (EM.11):

Similar to the EM.10 experiment, the same recipe and flow ratios were utilized, with the exception of increasing the emulsifier quantity from 15000 PPM to 20000 PPM, and TDS value of 1000 PPM. However, the resulting emulsion exhibited stability, with oil serving as the external phase. Separation occurred after 30 minutes under the same conditions as

described above. Moreover, a sample was taken from the resulted emulsion and mixed using the high shear homogenizer for 2 minutes, and the resulting emulsion was stable for more than 1 hour.

Table 17 EM.11 experiment, 20000 PPM of total water salinity with ARAMCO's recipe with acid, acid as the motive and diesel as the suction with 60/40 suction to motive percentage.

	
Using the ejector	Using the homogenizer
Immediate 25°C	1 Hour After 25°C

4.8.12 Emulsion 12 (EM.12):

In the EM.12 experiment, the recipe and ratios remained consistent with those of EM.11, with the exception of omitting the corrosion inhibitor. Additionally, a small submersible pump was introduced into the discharge tank for two minutes following the completion of the experiment. As a result, a stable emulsion was observed for 5 hours, with minor separation occurring from below. It is noteworthy that the external phase of the emulsion

was oil as it is shown in **Table 18**. Additionally, Table 19 and Figure 32 summarize the whole Emulsified Acid System experiments.

Table 18 EM.12 experiment, 20000 PPM of total water salinity with ARAMCO's recipe with acid, acid as the motive and diesel as the suction with 60/40 suction to motive percentage with submersible pump.



30 Minutes After

25°C

Table 19 Summary of the EAS trials.

Trial	Motive Flow Rate (GPM)	Suction Flow Rate (GPM)	Motive/Suction Fluids	Flow Percentage (Suction/Motive)	TDS (PPM)	External Phase	Stability At 25°C (after 1 Hour)
EM.1* ¹	2.05	3	Diesel/Acid	60/40	1000	Water	Not Stable
EM.2* ¹	2.05	3	Diesel/Acid	60/40	15000	Water	Not Stable
EM.3* ¹	2.05	3	Diesel/Acid	60/40	15000	Oil	Not Stable
EM.4* ¹	2.05	3	Diesel/Water	60/40	0	Water	Stable
EM.5* ¹	1.45	1	Water/Diesel	42/59	0	Water	Stable
EM.6* ¹	1.45	0.65	Water/Diesel	30/70	0	Water	Stable
EM.7* ¹	1.45	0.65	Acid/Diesel	30/70	15000	Water	Not Stable
EM.8* ¹	2.05	2.4	Diesel/Acid	53/46	25000	Oil	Not Stable
EM.9* ¹ *A	2.05	3	Diesel/Acid	60/40	20000	Water	Not Stable
EM.10* ² *A	3.1	5	Diesel/Acid	62/38	20000	Water	Not Stable
EM.11* ² *A*B	3.1	5	Diesel/Acid	62/38	1000	Oil	Not Stable
EM.12* ² *A*C	3.1	5	Diesel/Acid	62/38	20000	Oil	Stable

*1 Centrifugal pump used for the motive stream.

*2 Gear pump used for the motive stream.

*A Laboratory acid and water grade used for the trial.

*B Higher emulsifier quantity added.

*C Small submersible pump placed in the discharge tank for 2 minutes.

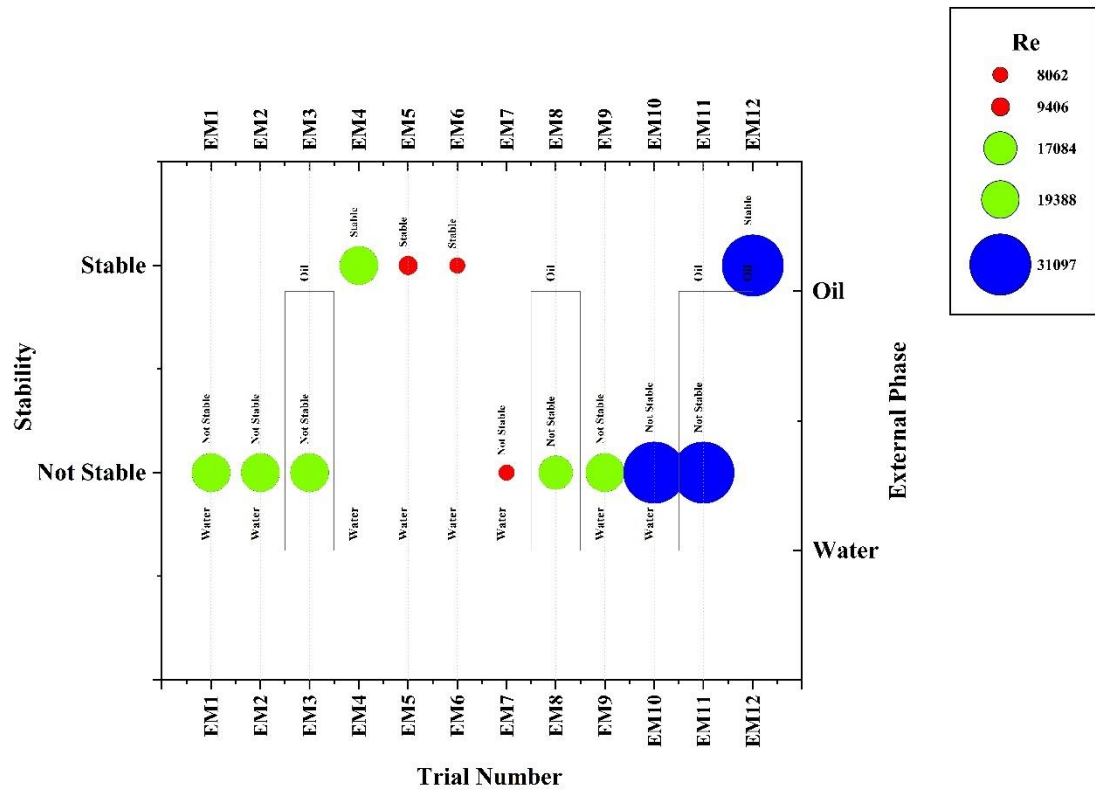


Figure 32 Comprehensive EAS trials stability and external phase.

4.9 Conclusion:

To enhance the performance and efficiency of the liquid ejector, a series of Water-Water experiments were conducted without modifying the ejector's design specifications. The experiments involved the addition of drag reducing polymers (DRPs) at varying concentrations, specifically 50 and 100 ppm. Furthermore, the impact of controlling the valves on the ejector's performance was investigated across different motive flow rates (1 and 1.45) gallons per minute (GPM). To evaluate the performance of the ejector, several efficiency models from the available literature were examined to assess the performance of our specific liquid ejector system. The most favorable performance was observed when the motive flow rate was set to 1 GPM, with the addition of DRPs to the suction stream at

a concentration of 100 ppm. Additionally, at a motive flow rate of 1.45 GPM, it was found that controlling the suction valve by partially opening it to 70% resulted in higher efficiency compared to having the valve fully opened using the experimental efficiency model (η_{EX}) (case 1), while in the other efficiency models, controlling the suction flow rate control valve did not enhance the efficiency. Moreover, a notable inverse relationship was found between the entrainment ratio and pressure ratio at high efficiency. Specifically, as the motive flow rate increased, the pressure ratio also increased while the entrainment ratio decreased. Overall, these findings demonstrate the effectiveness of incorporating DRPs and optimizing valve control in improving the performance and efficiency of the liquid ejector. The results contribute valuable insights for future research and practical applications in enhancing the operation of liquid ejectors for various fluid systems.

Furthermore, a series of experiments were conducted utilizing the same configuration to produce emulsified acid systems (EAS). The ejector demonstrated satisfactory performance and yielded stable emulsions when water was mixed with diesel as the external phase. However, when acid was substituted for water in the diesel mixture, the ejector failed to achieve adequate mixing, resulting in a majority of emulsions with water as the external phase. To address this issue, the introduction of Total Dissolved Solids (TDS) into the mixing process was attempted, often resulting in oil as the external phase. Despite this improvement, maintaining stability in the EAS proved challenging due to the shear forces required for emulsion mixing. Consequently, the primary motive stream pump was replaced from a centrifugal pump to a gear pump, which led to enhanced stability primarily in the mixing ratio.

In the conclusive of the experiment EM.12, a small submersible pump was introduced into the discharge tank for a duration of two minutes, significantly increasing stability from 30 to 40 minutes to 6 hours, with minimal separation observed in the oil phase. Importantly, the ratio of TDS played a critical role in determining the external phase, notably by accelerating the inversion point of the emulsion from water to oil phase. We recommend implementing a multi-stage procedure involving either multiple ejectors or inline homogenizers following the ejector to improve mixing integrity and consequently enhance emulsion stability.

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