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Designing and studying operational parameters of hydrocyclone for oil – water separation

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Abstract— This research presents the design procedure for liquid – liquid hydrocyclone to separate kerosene – water emulsion. It studies the effects of varying feed flow rate (6, 8, 10, and 12 l/min), inlet kerosene concentration (250, 500, 750, 1000, and 1250 ppm) , and split ratio (0.1, 0.3, 0.5, 0.7, and 0.9) on the outcomes; separation efficiency and pressure drop ratio . This study used factorial experimental design assisted with Minitab program to obtain the optimum operating conditions. It was shown that inlet concentration of 250 ppm, 12 l/min inlet flow rate, and 0.9 split ratio gave 94.78 % as maximum separation efficiency and 0.895 as minimum pressure drop ratio.

Keywords— hydrocyclone, oil – water separation, design, kerosene – water emulsion.

1. Introduction

Cyclones are simple devices invented in the eighteenth century. They were used for separating solid-liquid, solid-gas, and liquid-liquid. It is called hydrocyclone when liquid is expressed as a primary phase [16] . This usage of hydrocyclone for oil – water separation depends on its simplicity, having no moving parts, low cost, variation in use (as mentioned before), no need to any additives, small space requirement, low space time, and low energy consumption [20]. Cyclones include swirling motion to separate the dispersed phase (oil) from the continuous fluid (water). This motion occurs when the high - pressure feed is injected tangentially into the hydrocyclone body. The centrifugal force produces two spiral flows (vortices) that move in the same circular motion but in opposite directions. The heavier phase is carried by the outer vortex which is close to the cyclone wall directing downward to the underflow stream while the inner vortex carries the lighter phase in the cyclone axis and goes reversely to the overflow stream [11] as shown in Fig.1.

Many researches investigated hydrocyclones design and operation using simulation by CFD . Authors in reference [16] confirmed that the feed flow rate andoil droplet diameter had higher influence on the separation efficiency unlike the inlet oil concentration. Authors in reference [17] concluded that oil concentration did not greatly affect the separation efficiency of oil – water hydrocyclone. Authors in reference [13] concluded that the flow rate and droplet diameter had higher effect on the separation efficiency while oil concentration showed insignificant effect on the separation efficiency. Author in reference [10] concluded that the cyclone had the best efficiency at oil concentration 0.5 % and distribution ratio of 10 % . Under these operation conditions the cyclone could separate 80 % of 15µm oil droplet diameter and 50 % of 9.2 µm droplet diameter of the oil used .

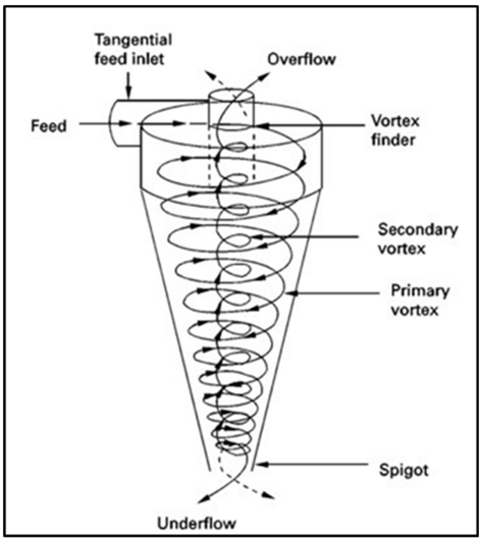

Figure 1: Flow features of the hydrocyclone [7]

Other researchers investigated hydrocyclones performance experimentally. Authors in reference [22] found that the separation efficiency became better at higher feed oil concentration and feed flow rate. Authors in reference [12] in part 1 confirmed that cyclone with inlet oil concentration up to 10 % provided high efficiency, but the performance of the cyclone used was the best at very low concentration (below 1 %). Authors in reference [15] concluded that by increasing flow rate the efficiency increased to obtain the maximum value and then decreased while the pressure drop (-Δp) raised with increasing flow rate . Authors in reference [22] concluded that separation efficiency is more affected by changing flow rate and split ratio , but the pressure drop changed with flow rate and rotating speed . As a result of these conclusions they found the optimal scheme that gave the highest separation efficiency and lowest pressure drop at flow rate 3.5 m3/ h , and split ratio 15 %.

2. Hydrocyclone design

The basic design approaches were presented by Rietema [19] , Bradley [3] , and Thew [6] . In this research Bradley equations [3][2]were used to design the hydrocyclone as his design has greater separation efficiency at the proposed dimensions [5] . The design equations were applied after measuring oil (kerosene) density, viscosity (Table (4)), and oil droplet size. The average droplet size was 20 µm. The equations used in the design are listed below:

$$d_{50} = 4.1 * \left(\frac{(dc^3) * \eta}{Q * (\rho - \sigma)}\right)^{0.5} \quad (1)$$

$$d_i = \frac{dc}{7} \quad (2)$$

$$d_o = \frac{dc}{5} \quad (3)$$

$$L_1 = 2 * d_c \quad (4)$$

$$VFL = \frac{dc}{3} \quad (5)$$

$$\Theta = 9^o$$

The listed equations were adopted from Bradley to obtain the maximum attainable efficiency .

A valve was put on the underflow stream to adjust the flow rate and consequently split ratio **[3]**. These equations were sets for calculating hydrocyclone dimensions.

The material of construction is acrylic which was chosen because of its transparency, optical clearance, resistance to light, rigidity, invariable dimensions, availability, and cheapness. **Fig. 2** shows the dimensions of the designed hydrocyclone

Table 1: The dimensions of designed hydrocyclone

Dimension	Symbol	Equation	Value	Unit
Hydrocyclone diameter	d_c	1	4	cm
Inlet diameter	d_i	2	0.57	cm
Overflow diameter	d_o	3	0.8	cm
Underflow diameter	d_u	----	1	cm
Cylindrical section length	L_1	4	8	cm
Vortex finder length	VFL	5	1.3	cm
Angle of cone	Θ	-----	9°	----
Thickness	h	-----	1	cm

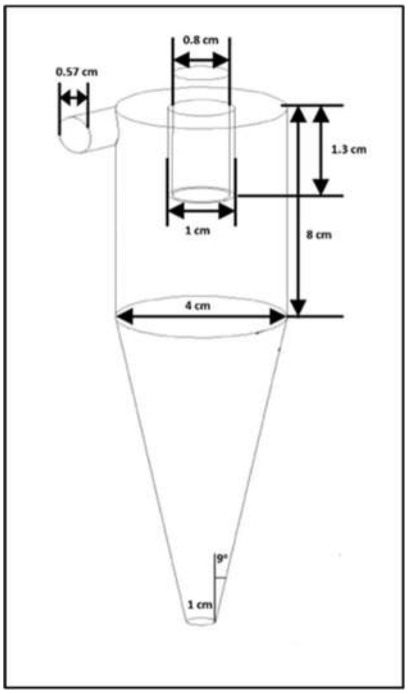

Figure 2: The dimensions of designed hydrocyclone.

3. Separation parameters

The performance of hydrocyclone can be evaluated through the following indicators :

3.1 *Separation efficiency*

Separation efficiency is defined by :

$$Ej = \left(1 - \frac{Cu}{Ci}\right) * 100 \% \quad (6)$$

It ranges from 0 to 100 , when oil concentration in underflow equal to that of inlet so no separation occur inside the cyclone in other words Ej = 0 . Conversely at C_u = 0 that means complete separation Ej = 100 [22]. Experimentally no complete separation occurs but it is used as a maximum limit to compare between different conditions. The separation efficiency depends on geometrical parameters and operational variables. Sometimes there is conflicting between these variables. Therefore seeking maximum efficiency needs optimization of the variables. This optimization can be done by using available software such as Minitab program.

3.2 *pressure drop and pressure drop ratio*

Pressure drop or Δp is the difference between inlet and underflow pressures as follows :

$$\Delta p = p_i - p_u \tag{7}$$

Pressure drop ratio (PDR) is the pressure gradient via inlet and outlet of the hydrocyclone [9], i.e. its equation is as follows :

$$PDR = \frac{\Delta Po}{\Delta Pu} = \frac{pi - po}{Pi - Pu} \tag{8}$$

PDR gives the indication of centrifugal force rejection inside hydrocyclone body and consequently the separation between overflow and underflow streams. As a result this is more representative than Δp to the actual case [8] .

4. Experimental design

The 2^k factorial design of experiments was applied in this work with 3 variables to be investigated . This type of experimental design are most efficient for more than two parameters to decrease number of experiments.

The value 2 stands for number of levels while 3 represents number of variables, 2^k corresponds to 2^3 and that yields 8 runs to study 3 parameters for 2 levels [18] as shown in Table.3 with parameters variation shown in Table. 2.

Table 2: Variation range of parameters

Parameters	Low value (-)	High value (+)
Concentration of oil , ppm	250	1250
Feed flow rate , l/min	6	12
Split ratio , dimensionless	0.1	0.9

Table 2: Design of the experiments

Run	Split ratio , dimension-less	Concentration of kerosene , ppm	Feed flow rate , l/min
1	-	-	-
2	-	-	+
3	-	+	-
4	-	+	+
5	+	-	-
6	+	-	+
7	+	+	-
8	+	+	+

5. Experimental Work

5.1 *Oil properties*

Table. 4 lists kerosene properties at 40°C (the ambient temperature when the experiments were carried out)

Table 4: kerosene properties

Property	Value (measured experimentally)
Viscosity , cp	1.583
Density , g/cm^3	0.78

5.2 *Equipment*

The equipment used in experimental setup are listed in Table. 5

Table 5: The used equipment

Item	Specification	Company	Origin
Pr. gauge	(0 – 8) bar	--------	Purchas-ed locally
Rotameter	(0 – 18) l/min	ZYIA	Purchas-ed locally
Pump2	0.5 hp	TOTAL	China
Pump1	1 hp	SPERONI	Italy
UV spectrophotometer	(0 – 3) absorbance	Thermo	USA

5.3 *Experimental setup*

The experimental setup was assembled by connecting two pumps in series to draw the oil / water emulsion from the feed tank and provid sufficient force to push the feed through the inlet of the hydrocyclone. The feed passes through a valve (1), pressure gauge (1) and a rotameter before entering the hydrocyclone inlet with a high tangential force which is set horizontally for liquid – liquid separation [22]. This tangential force generates a centrifugal force along the hydrocyclone. Then two vortices occurred that separate the two fluids , i.e. the oil – rich fluid appeared from the upper outlet (the overflow) that accumulated in oil tank and the water – rich fluid from the underflow outlet accumulated in water tank as shown in Fig. 3 .

6. Experimental steps

Experimental steps consists of emulsion preparation and running the system to study the changing in operational properties .

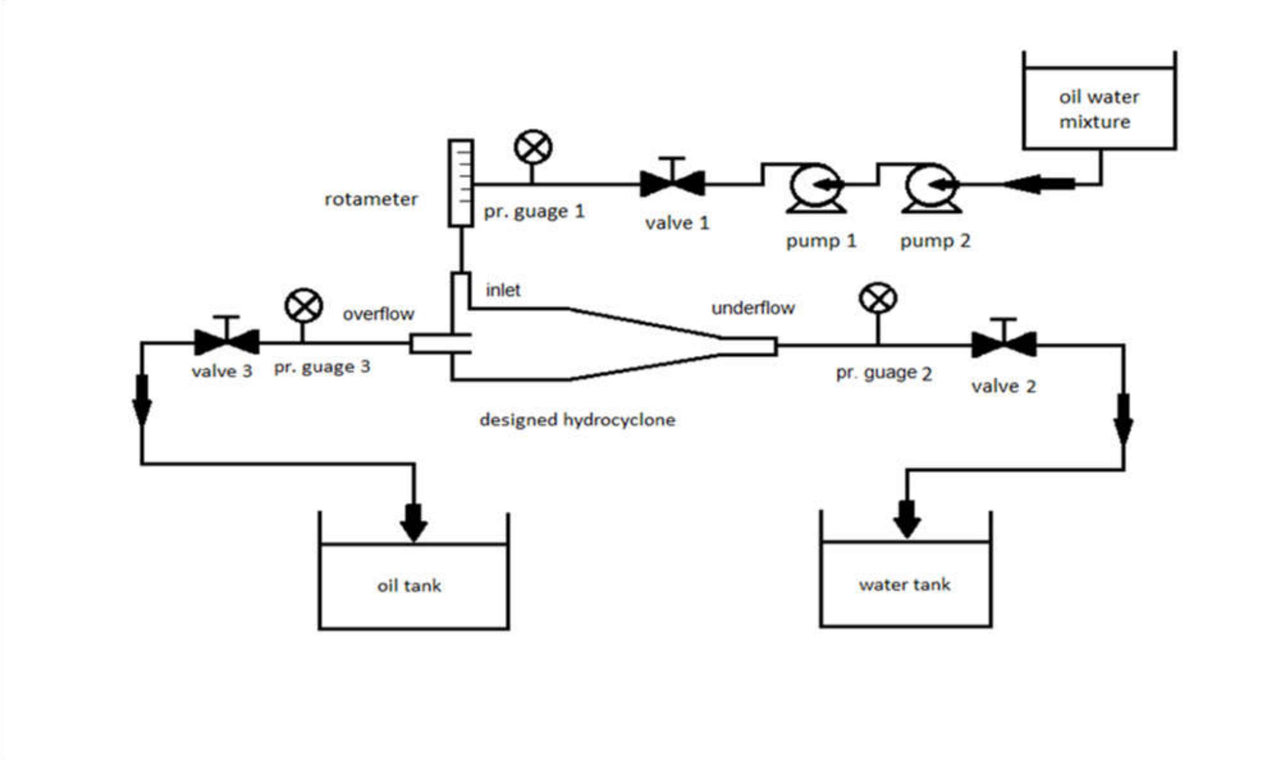

Figure 3: Schematic diagram of the experimental setup.

6.1 *preparation of emulsion*

Emulsion was prepared by mixing specified volume of oil used with certain volume of water in an ULTRA TURRAX homonginizer (1000 rpm , Germany) for 20 min to get stable emulsion (one misty phase without recognition of two clear layers) during the experiments period . Emulsion staibility depends on droplet size, the densities of two liquids, viscosity of bulky phase, temperature, pressure, and parameters of mechanical agitation .

6.2 *Performing the experiments*

The experiments begin with filling the feed tank with oil – water emulsion at appointed concentration and turning on the two pumps.Studying the effect of feed oil concentration, feed flow rate, and split ratio for the cyclone at ranges listed below, by adjusting valves 2 and 3 to achieve the desirable split ratio where Split ratio (F) is the flow ratio between under flow and inlet ($F = \frac{Qu}{Qi}$) , and adjusting valve 1 to obtain the desired inlet flow rate . For each inlet concentration (in ppm) 250, 500, 750, 1000, and 1250, the split ratio was changed (0.1, 0.3, 0.5, 0.7, and 0.9) and the flow rate was varied (in l/min) 6, 8, 10, 12 .

For each experiment , after reaching the steady state (within 5 sec) , samples were taken from overflow and underflow streams to measure the oil concentration in each using UV spectrophotometer. The results from experiments were entered to factorial design in Minitab program and analyzed to determine the best conditions that give maximum efficiency and minimum pressure drop ratio .

6.3 *Outputs*

The outputs obtained for every experiment were :

1. Oil concentration of samples from overflow and underflow streams using UV spectrophotometer device.

2. Pressures were recorded at the inlet, overflow, and underflow using pressure gauges .

3. Flow rates of overflow and underflow streams using the bucket and stopwatch method .

7. Results and discussion

7.1 *Effect of inlet flow rate, split ratio, and concentration on separation efficiency*

Fig. 4 shows Ej % as a function of Q_i for various inlet kerosene concentration C_i at 0.1 split ratio . This figure shows that increasing flow rate led to increase the separation efficiency because when the flow rate increased the velocity increased with constant inlet area and that leads to make centrifugal force inside cyclone body stronger which raised the separation efficiency **[9],** these results were in agreement with that of **Jiang et al. (2002)** , **Kharoua et al. (2009)** , **Hosseini et al. (2015)** , and **Fan (2016)**. Similar behavior was recorded with increasing C_i till 1000 ppm in which the separation dropped . This is because some oil droplets can get away with underflow stream while increasing C_i further increases Ej because the coalescence became more easily at high concentration and that led to increase the efficiency .

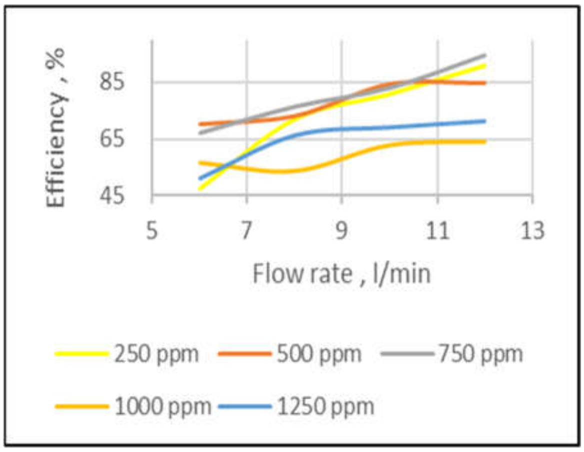

Figure 4: Results of varying flow rates at various feed concentrations and 0.1 split ratio

Fig. 5 also shows increase in efficiency with flow rate and inlet concentration except at C_i = 750 ppm . It was noticed that it has the maximum Ej for 0.1 and 0.3 split ratios. It is thought that there is a matter of optimization between the inlet concentration and the opening available for the droplets to pass, i.e. the split ratio which affects the efficiency .

Fig. 6 shows the effects of concentration and flow rate at 0.5 split ratio. Ej increased with Q_i and C_i increment this is in agreement with reference **[19]** as discussed previously except at 1250 ppm this gives the indication of the availability of sufficient space for the excess amount of oil to pass through.

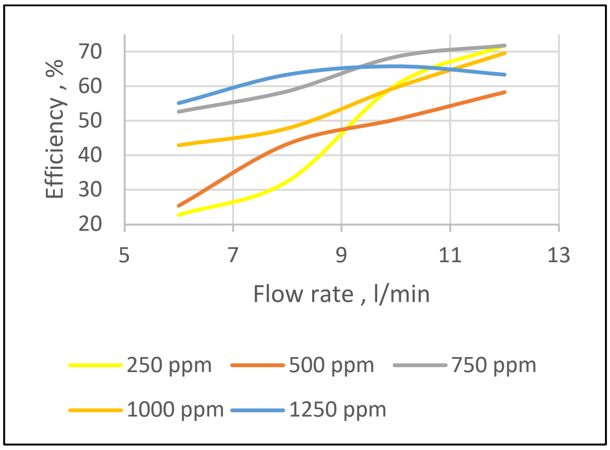

Figure 5: Results of varying flow rates at various feed concentrations and 0.3 split ratio

Peaks of Ej are shown in **Fig. 7** at split ratio 0.7 . This is because increasing Q_i above a certain value may cause decrease in Ej this is in agreement with reference **[23]**. Also increment of C_i cause an increase in separation efficiency at first then it fluctuates between decrease and increase for high C_i which indicates the existence of a maximum efficiency .

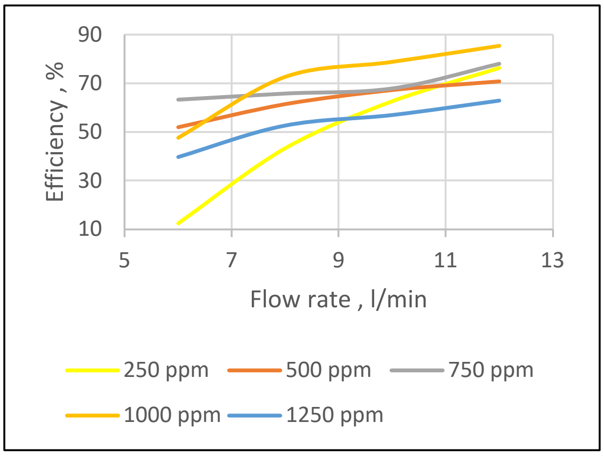

Figure 6: Results of varying flow rates at various feed concentrations and 0.5 split ratio

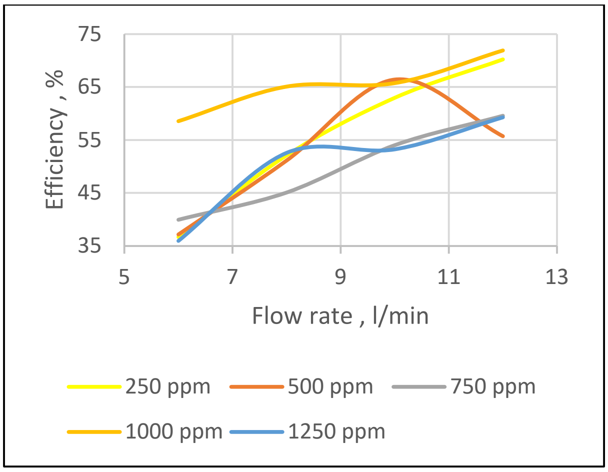

Figure 7: Results of varying flow rates at various feed concentrations and 0.7 split ratio

The same discussion is valid for **Fig. 8** except that the peaks are not clear . The efficiency for this figure are higher than in the previous figures indicating that an optimum exists among them for split ratio 0.9. It can be concluded from the previous figures that at 0.3, 0.5, 0.7 split ratios separation efficiency increased with concentration while at split ratio 0.1 and 0.9 concentration have reversal relation with efficiency . again an optimization is needed to clarify the conflicting situations .

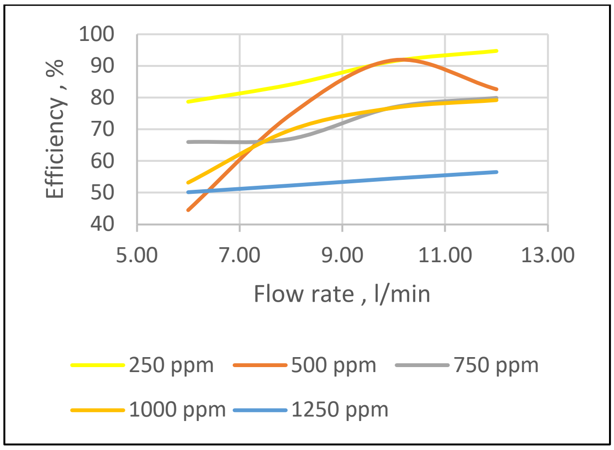

Figure 8: Results of varying flow rates at various feed concentrations at 0.9 split ratio

Fig. 9 represents the effect of changing split ratio with efficiency at various flow rates at 250 ppm feed concentration. As observed from this figure that efficiency has minimum value at 0.5 split ratio and it is increased when drifting away from F = 0.5 . That is because, as reviewed by Bradley **[3]**, cyclones with small d_u and large d_o gives pure water at the underflow stream i.e. C_u equal or close to 0 which gives maximum Ej. The case of split ratio below 0.5, as d_o changed with Q_o and d_u changed with Q_u and vice versa for cyclones with small d_o and large d_u, give most of oil at the overflow stream and that leads to purify water at the underflow giving larger efficiency.

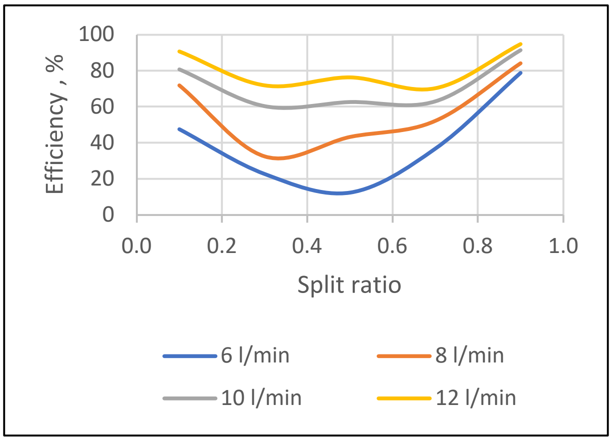

Figure 9: Effect of changing split ratio at various inlet flow rates for 250 ppm feed inlet oil concentration

Minitab program summarizes the effect of operational parameters (Q_i, F, C_i) on separation efficiency at 2^3 factorial experimental design of Table. 2 and Fig. 10

As seen from the figure, the flow rate has the most effect on the separation followed by concentration , and there is an interactions between the three parameters that gave the lowest effect on the separation efficiency . As obvious from Fig. 9 the separation efficiency has its largest value at 0.1 and 0.9 split ratios . These results give an impression that the split ratio has a significant effect on Ej which is not obvious in Fig. 10 . So Fig. 10 does not represent the real order of effect of split ratio on the separation efficiency. Therefore; the analysis of parameters breaks into two parts . Split ratios less than 0.5 and split ratios more than 0.5 .

Fig. 11 shows the effects of operational parameters on the efficiency at split ratios less than 0.5 . It represents that the flow rate have the greatest effect on the efficiency followed by split ratio , while concentration have the lowest effect . Fig. 12 represents the effect of operational variables for split ratios more than 0.5 . The flow rate , followed by the interaction of concentration and split ratio are shown to have the greatest effect on efficiency .

Therefore ; the flow rate have the great effect on separation for all split ratios , but it is more effective at split ratios less than 0.5. So the order of parameters effect on the efficiency is flow rate > split ratio > concentration for all split ratios and this does not appear in Fig. 10 .

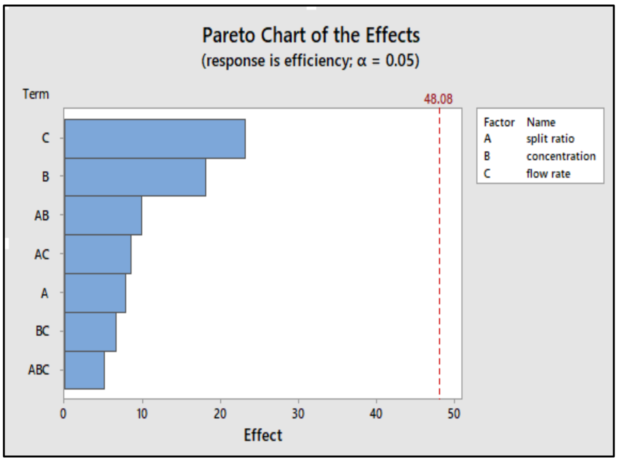

Figure 10: Effect of parameters on separation efficiency

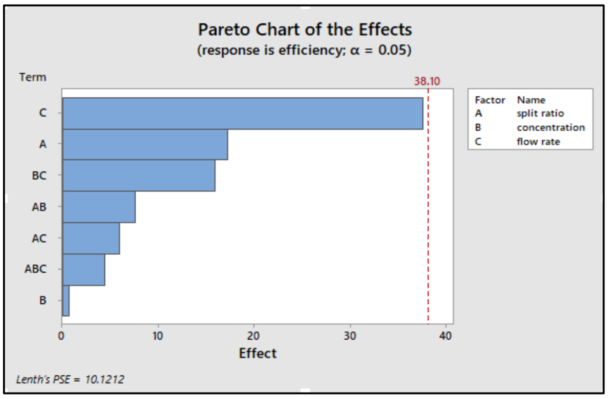

Figure 11: Effect of operating parameters on efficiency at split ratio less than 0.5

The equations that expressed the separation efficiency (Ej) as a function of split ratio , flow rate , and concentration was found using Minitab as follows :

$$Ej = 14.14 - 164.8\,F + 0.01626\,C_i + 7.135\,Q_i + (0.1030\,F * C_i) + (10.38\,F * Q_i) - (0.003139\,C_i * Q_i) - (0.007246\,F * C_i * Q_i) \quad (9)$$

$$Ej = -220.9 + 320.4\,F + 0.1086\,C_i + 21.07\,Q_i - (0.1416\,F * C_i) - (19.99\,F * Q_i) - (0.001939\,C_i * Q_i) + (0.000354\,F * C_i * Q_i) \quad (10)$$

The above equations can be used to calculate the separation efficiency at various split ratios, inlet concentrations, and inlet flow rates. Equation (9) represents the efficiency at split ratios less than 0.5 while equation (10) represents the efficiency at split ratios more than 0.5.

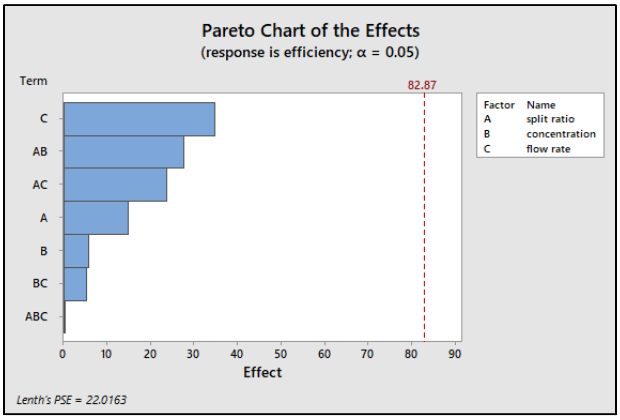

Figure 12: Effect of operating parameters on efficiency at split ratio more than 0.5

7.2 *Effect of operational parameters on pressure drop ratio*

The relationship between inlet flow rate and pressure drop along the hydrocyclone is depicted in Fig. 13 for different split ratios . It is clear that increasing feed flow rate increases the pressure drop . This is because increasing feed flow rate increases centrifugal force and leads to high pressure drop . Fig. 14 represents that PDR is less influenced by increasing flow rate than Δp for different split ratios. The reason behind this behavior is that expressing overflow pressure drop relative to underflow pressure drop limits the range of variation of the pressure drop. That is the values are restricted between 1 (when p_o and $p_u = 0$ therefore p_i - p_o equals to p_i - p_u) and some other value that does not exceed Δp . PDR is also influenced by the split ratio but reversely especially for split ratio 0.1 which shows extensive variation of PDR with the flow rate . That is because when the split ratio is smaller than 0.5 i.e. for large d_o and small d_u, a small portion of the feed discharges from the underflow which is substantially pure water leaving the larger portion at the overflow [3] .

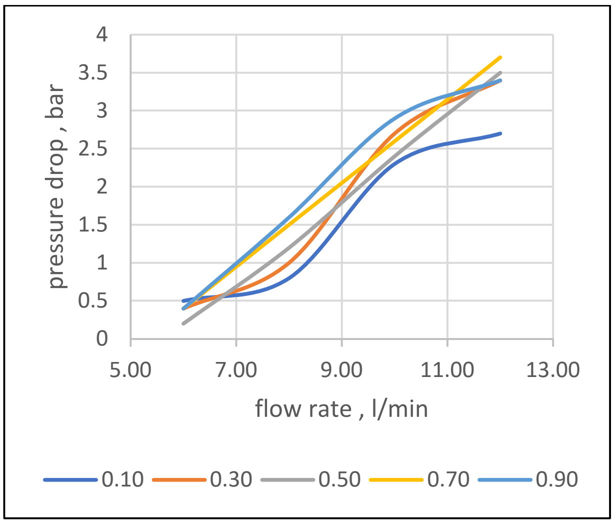

Figure 13: Effect of flow rate on pressure drop

Fig. 15 represents the relationship between PDR and the split ratio for different flow rates. It can be noticed from the figure that no significant effect is there at low flow rates but when the flow rate increases to high values, PDR decreases noticeably with the split ratio. This can be explained by the high centrifugal force and high pressure difference accompanied with high flow rates and low split ratio which leads to direct most of the entering liquid to the forced vortex. Therefore; Δp_o grows up on account of Δp_u causing high values of PDR [9]. When the split ratio increases, most of the entering liquid goes through underflow by the free – like vortex causing weak forced vortex that lowers Δp_o and PDR. It is worthy to notice that PDR equals 1 at split ratios 0.3 , 0.5 , and 0.7 indicating equal pressure drops Δp_o and Δp_u at these values . The dependence of pressure drop on the split ratio can be discussed through Fig. 16 It is evident that split ratio does not greatly influence the pressure drop at different flow rates .

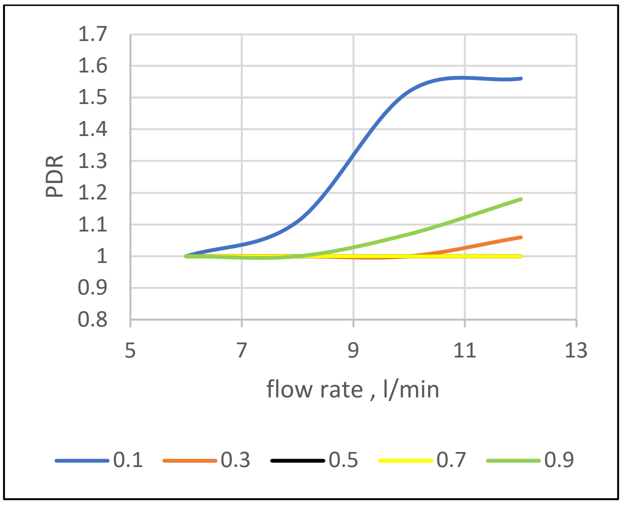

Figure 14: Effect of flow rate on PDR

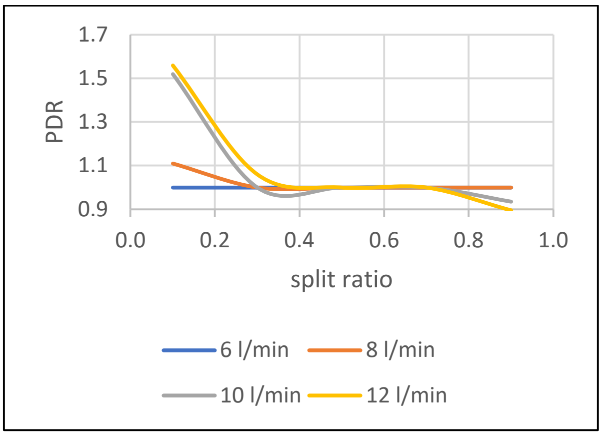

Figure 15: Effect of changing split ratio on PDR for various flow rates

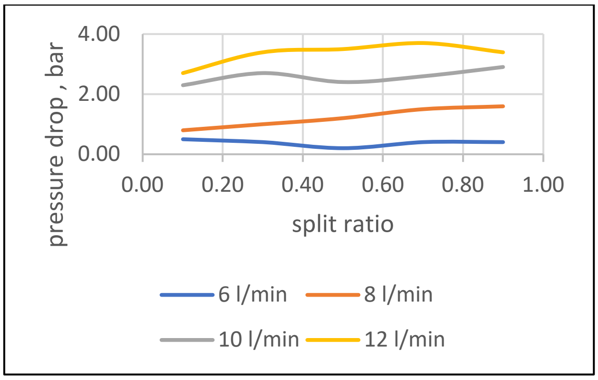

Figure 16: Influence of changing split ratio on Δp at various flow rates

Fig. 17 shows the effects of parameters on pressure drop ratio in Minitab program. Split ratio , flow rate , and interaction between them only effects PDR whereas concentration have no effect on it . Minitab program shows the equation that defined PDR as a function of split ratio and flow rate as follows :

$$\mathbf{PDR = 0.3569 + 0.8312\,F + 0.1072\,Q_i - (0.1385\,F * Q_i)} \quad \mathbf{(11)}$$

Where Eq (11) used to find PDR at different values of split ratio and flow rate .

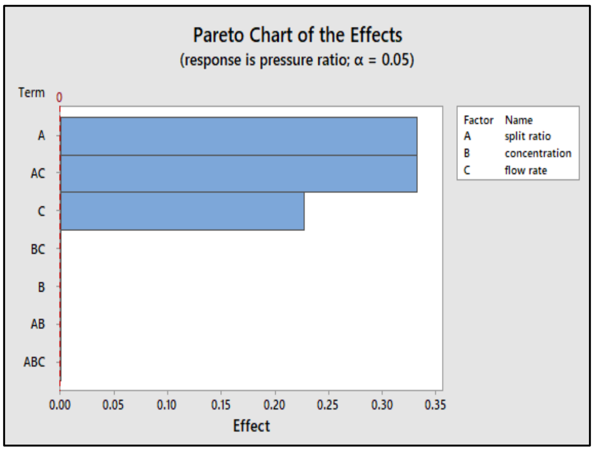

Figure 17: Effect of parameters on pressure drop ratio

7.3 *Optimization*

Optimization has to be done for obtaining the optimum conditions that achieved maximum separation efficiency and minimum pressure drop ratio at appointed value of split ratio , flow rate , and feed oil concentration . Optimization of 2^3 design of experiments in Minitab program is shown in Fig. 18 . It shows that the optimum point occurs at 250 ppm feed oil concentration, 0.9 split ratio, and 12 l/min feed flow rate to gain maximum efficiency (94.78 %) and minimum pressure drop ratio (0.895) .

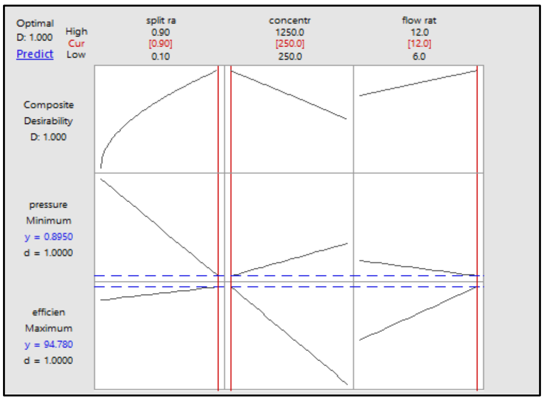

Figure 18: Optimization plot

The obtained results support the previous studies in the aspect that high separation efficiency occurred at high feed flow rate i.e. high centrifugal force .

8. Conclusions :

Some important conclusions can be obtained experimentally from this study as follows:

Efficiency is influenced by feed flow rate , feed oil concentration , split ratio , and interaction between them, and in the order : flow rate > split ratio > concentration , in which flow rate and split ratio have significant influence on separation efficiency when compared with concentration .

The real order of effects was obtained after splitting the analysis using Minitab program . This gives the impression that performing computational analysis without conducting experiments may give incorrect representation of the system .

Separation efficiency varied monotonically with inlet flow rate while it is increased when split ratio drifting away from 0.5 . C_i have varying effect on separation efficiency as it is interacted with other operational variables .

Split ratio and flow rate affected the pressure drop ratio while changing concentration did not influence PDR.

The optimized scheme gave maximum separation efficiency (94.78 %) and minimum PDR (0.895) at 12 l/min feed flow rate , 250 ppm feed oil concentration , and 0.9 split ratio by using 2^3 factorial experimental work in Minitab program , for kerosene – water separation in a hydrocyclone designed according to Bradley equations .

Applying Minitab program is successful in assigning the optimum operating conditions and expressing the influential effect in graphs and equations that can be generalized.

Nomenclature

C	Oil concentration (ppm)
d_{50}	Droplet size (μm)
d	Diameter (cm)
Ej	Separation efficiency
F	Split ratio
L1	Cylinder length (cm)
ΔP	Pressure drop (bar)
P	Pressure (bar)
Q	Flow rate (l/min)

Greek symbols

Ƞ	Viscosity of the oil (cp)
ϴ	Angle of conical section
ρ	Density of water (g/cm3)
σ	Density of oil (g/cm3)

Subscripts

c	Cyclone
i	Inlet
o	Overflow
u	Underflow

Abbreviations

PDR	**Pressure drop ratio**
VFL	**Vortex finder length**

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تصميم و دراسة ظروف التشغيل لجهاز الهايدروسايكلون لفصل الزيت عن الماء

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الخلاصة – هذا البحث يقدم خطوات تصميم جهاز هايدروسايكلون (سائل – سائل) لفصل مستحلب الكيروسين (النفط الابيض) مع الماء و دراسة تأثير تغير معدل جريان اللقيم (12,10,8,6) لتر/دقيقة و تركيز الزيت في اللقيم (1250,1000,750,500,250) ملغم/لتر و نسبة الانشقاق (0.9,0.7,0.5,0.3,0.1) على المخرجات مثل كفاءة الفصل و نسبة هبوط الضغط . هذه الدراسة استخدمت تصميم للتجارب بواسطة برنامج Minitab لايجاد ظروف التشغيل المثلى . تبين ان تركيز الزيت الداخل 250 ملغم/لتر و معدل جريان السائل الداخل 12 لتر/دقيقة و نسبة الانشقاق 0.9 تعطي اكثر كفاءة فصل عند 94.78% و اقل نسبة هبوط للضغط 0.895

الكلمات الرئيسية – هايدروسايكلون , فصل الزيت عن الماء , تصميم , مستحلب الكيروسين مع الماء.