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Optimization of Refinement Operations of Sugarcane Harvester Hydraulic Oil

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Abstract

The purpose of this study was to model and optimize the offline refinement operations of sugarcane harvester hydraulic oil using RSM. For this purpose, the effects of independent variables of operating hours (250, 500 and 750 hours), Twin Dip Filter Mesh (7, 9 and 11 microns) and hydraulic oil refining times (0, 1 and 2) on variables of water contamination, uncleanness level (NAS), silicon (Si), viscosity (Vis) and oil acid number (TAN) were evaluated. The results indicated that all models were suitable for water contamination, uncleanness level (NAS), silicon (Si), viscosity (Vis) and oil acid number (TAN) for describing experimental data. In addition, the desirability function showed that the optimum conditions for the offline refinement operations of the hydraulic oil of the sugar cane harvester included 728.61 operating hours, the 7-micron filter mesh, and the two refining times of the oil. Under this condition, the amount of water contamination, the uncleanness level (particles 5 to 15 micrometers), Vis, Si, and TAN were equal to 187.63 ppm, 234000, 5.91 ppm, 66.34 centistokes and 0.65 (mg KOH g^{-1}), respectively.

Keywords: Offline Refinement of Hydraulic Oil, Optimization, Response Surface Method, Sugarcane harvester

Introduction

One of the important items in mechanical equipment and in general agricultural machines is the entry of contaminations including water, fuel, silica, chips, soot particles, etc. into hydraulic systems and engine oils. All mechanical equipment that uses oil for lubrication or power transmission, are always affected by the quality of the oil. In fact, Contamination is the enemy of hydraulic systems and other mechanical systems under lubrication which passes through sensitive parts or the environment via lubricant and causes damage to them. Oil contamination in mechanical systems causes major problems such as machine failure, undesired repairs, loss of oil life, etc., which directly affects the efficiency of the equipment and consequently the efficiency of the production and causes unforeseen costs. Using clean oils, removing and controlling contaminants will have many benefits including minimizing equipment failure, reducing operational and repair costs, increasing the operational efficiency of the equipment and increasing the lifespan of the oil. Types of contamination of oils include physical and chemical contaminants. The physical contaminant is the same as solid particles with oil, the most important consequence of which is mechanical erosion. Chemical contaminants generally include water, some metals such as copper and materials produced via oil usage. Therefore, there are two solutions to prevent such problems. First, evacuate all oil from the system and substitute with fresh oil or by filtration, separate particles from contaminated oil (Masoudi, 2011; Ranjbar *et al.*, 2003; Saghafi, 2008). Cargol (2005) identified most of the internal problems of machines by analyzing oil, and mentioned that doing these tests is effective for initial troubleshooting and performance enhancement. Macnian *et al.* (2006) in a study determined the time of detection and the degree of failure using oil analysis on diesel engines and the fuzzy logic.

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This would prevent the car from breaking down, failure and suspension. Macinan *et al.* (2003) stated that if the erosion rate is 100 ppm, an increase of 50% is a significant warning sign to increase erosion of the devices. Qingfei He (2009) reported that the condition monitoring of machines helps prevent the destruction of machines via analyzing oils, corrosive particles, and oil contaminants. Li Jie (2010) considered the use of oil analysis programs for compressors to predict and prevent early failure of the compressors, as well as the optimal use of oil in compressors. Unfortunately, although the use of suitable oils in machinery is very necessary, there is no definite research in this regard and only parts have been mentioned in different books. One of the most important sources of sugar production is sugarcane. Sugar is one of the eight human food sources (wheat, rice, corn, sugar, cattle, sorghum, millet and cassava). Also, sugarcane is mainly used for livestock feed, electricity generation, fiber and fertilizer and in many countries sugarcane is accounted as a renewable source for biofuel (Haroni *et al.,* 2018). Therefore, the present research was conducted with the aim of optimizing the offline refinement operations of hydraulic oil of sugar cane harvester by examining the effects of independent variables of the operating hours (250, 500 and 750 hours), twin spin filter mesh (7, 9 and 11 microns), and the hydraulic oil refining times (0, 1 and 2) on dependent variables of water contamination, uncleanness level, Si, Vis and TAN (Masoudi, 2011).

Materials and Methods

Materials

The main raw materials used in the present study were hydraulic oil samples taken from cane harvesters (Austoft, 7000). The reason for choosing this model was due to its common use in cultivating the sugarcane industry in Khuzestan province).

Equipment and Appliances

For every oil-tested experiment, an example representative of the entire system was needed. Sampling is the easiest stage to run an oil analysis program, but it is very important and if the sampling is not correct, the results of the oil tests will not be valid. The main items in the oil sampling are the selection of tools, determination of sampling frequencies for different components, determination of oil sampling points in different components and oil sampling method. Some equipment was used for sampling such_as 1- Sampling pump (Manual suction pump), 2- Polyethylene tube (hoses with an external diameter of one quarter or five sixteen inches), 3- Sample carrying case (Masoudi, 2003). All of the oil samples, after encoding and labeling, with a fresh and unused oil sample, were sent to the Alborz Tadbir Khuzestan Technical & Engineering Co. Laboratory (Address: 127 Azadi, km 5, Asia Road, Mashhad, IRAN) from the sample of the hydraulic oils tested.

Determination of the Exact Amount of Water in the Oil (water contamination)

The amount of water in the oil was measured by the Karl Fischer test. The result of the test reports the exact amount of water in ppm. This test, known as Crackle Test, used to identify the approximate level of water contamination in the oil. In this way, a few drops of oil are poured on a hot plate (approximately 150 ˚C). If water is present in the oil, it will be bubbled out and removed from the oil. The amount of water in hydraulic oil should not exceed 500 ppm (ISO 760, 1978).

Determination of the Uncleanness Level of Oil

Uncleanness level of oil is one of the important parameters that is mainly studied in the evaluation of hydraulic equipment and systems. The presence of impurities in the environment indicates how the filters and vents operate. Counting the solid particles in hydraulic oil was accomplished using an automatic laser method. In this method, the number of corn oil particles can be counted by the resulted shadow of laser waves. Typical uncleanness levels are usually considered for a hydraulic oil sugarcane harvester; the number of particles from 5 to 15 micrometers in oil should not exceed 256000 (ISO 4406, 1999).

Determination of the Si Amount

Silicon (Si), an anti-foaming agent in oil, if exceeds the standard limit, is considered as an oil contaminant. In order to specify the available amount of Si in hydraulic oil, an elemental analyzer device was used. The amount of Si in hydraulic oil should not exceed 15 ppm (ASTM D6595, 2011).

Viscosity measurement of oil

Viscosity is the most important feature of lubricating oils. The viscosity test shows the internal resistance of the lubricant to the oozing. The viscosity test is normally done at temperature of 40 ˚C and 100 ˚C. Viscosity affected by factors such as the amount of oil function, oil content, contamination, composition, and other abnormalities affecting the service life of the oil. A capillary tube viscometer was used to measure viscosity in the laboratory. In this method, the oil sample is placed into the glassy U-shaped capillary tube and using a suction pump, the sample moves towards the starting point which has been specified on the tube. The suction pump is stopped and then, it is allowed that the sample moves in the opposite direction to the suction due to the gravity. The thin part of the capillary tube controls the velocity of oil flow. The oils with high viscosity take more time than the oils with low viscosity because the flow velocity inside the capillary tube is determined by yielding stress of the oil which is influenced by gravity. In fact, this test measures the kinematic viscosity of the oil. The standard guides for this method are ASTM D445 and ISO 3104. The viscosity of the hydraulic oil should not be changed from ±10% of fresh oil. The viscosity of fresh and used oil is determined in Cst (ASTM D 2270, 2010).

Measurement of the Total Acid Number (TAN)

The total acid number of oil indicates the acidity of the oil. TAN of the oil usually increases gradually with a slight slope. Oils have undergone a qualitative change over time due to various factors such as heat and contamination, where the acid number represents one of the indicators of these changes. The total acid number of hydraulic oil should not be increased by more than 0.2% toward the acid number of the fresh oil. The total acid number of hydraulic oil is measured by the titration method and is determined in (mg KOH g^{-1}) (ISO 6619, 1988).

Experimental Design and Statistical Analysis

The purpose of the present study was to optimize the refinement operations of the hydraulic oil of sugarcane harvester using the RSM method. For this purpose, the effects of independent numerical variables (operating hours, twin suction filter mesh) and categorical (hydraulic oil refinement times) on dependent variables of water contamination, uncleanness level, Vis, Si, and TAN were evaluated. For this purpose, the central composite design used in the Design Expert software included independent variables of work hours (250, 500 and 750 hours), twin suction filter mesh (7, 9 and 11 microns), and the number of hydraulic oil refinements (0, 1 and 2) with 33 treatments and 3 replications at the central point. Table (1) shows the encoded values and different levels of independent variables used for offline hydraulic oil refinement. Table (2) presents the test conditions and the response values obtained for the central composite design used to refine the offline hydraulic oil.

Data analysis was conducted using Design expert 7 software. Experimental data were also tested using the quadratic polynomial equation (Singh *et al.*, 2010).

$$Y = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + b_{13}AC + b_{23}BC \quad (1)$$

Where b_n: Regression coefficients for constant factor coefficients (b_o), Linear effect coefficient (b_1, b_2 and b_3), second-degree effect coefficients (b_{11}, b_{22} and b_{33}) and interaction effect coefficient (b_{12}, b_{13} and b_{23}). Y: The dependent variables or the desired responses include water contamination, uncleanness level, Vis, Si, and TAN. In analysis of a process, one qualitative factor is not considered, but multipurpose optimization is sought. The purposes are in contradiction with each other and have an inverse relationship. One of the problems solving methods of multipurpose issues is combining the response surfaces or the mentioned graphical solution.

Table 1- The encoded different levels of independent variables of offline hydraulic oil refinement

Independent variables	**Encoded independent variables and their different levels**		
Code	-1	0	+1
Operating hours	250	500	750
Filter mesh	7	9	11
Times of oil refinement	0	1	2

Table 2- Experimental design levels and measured values

Independent variable (input)				**Dependent variables (responses)**				
No.	**Operating (hour)**	**Filter mesh (micron)**	**Times of oil refinement**	**Water contamination (ppm)**	**(NAS*1000)**	**Si (ppm)**	**Vis (centistokes)**	**TAN (mg KOH g^{-1})**
1	250	11	2	100	109	4.2	59	0.51
2	500	9	0	100	102	4.4	67	0.52
3	750	11	0	178	282	5.8	61	0.63
4	500	7	1	97	106	3.9	72	0.51
5	500	9	0	103	112	4.5	69	0.53
6	250	9	1	75	77	3.1	63	0.48
7	500	9	2	126	122	5.2	64	0.55
8	750	7	0	153	192	4.3	68	0.54
9	250	7	1	71	70	2.5	67	0.46
10	250	11	0	80	90	3.1	61	0.48
11	250	9	0	69	74	2.3	64	0.47
12	500	11	1	131	141	5.6	62	0.59
13	500	9	0	105	122	4.7	71	0.53
14	500	9	1	108	109	4.8	66	0.54
15	500	9	1	112	122	4.9	68	0.55
16	500	7	0	90	99	3.1	73	0.5
17	250	9	2	86	93	3.5	62	0.5
18	500	9	2	130	141	5.5	66	0.56
19	500	11	0	122	125	4.8	63	0.57
20	250	11	1	88	96	3.7	60	0.49
21	750	9	0	160	218	5.1	63	0.58
22	250	7	0	66	64	2.1	68	0.45
23	250	7	2	80	83	3.2	65	0.48
24	750	7	1	172	205	5.5	67	0.61
25	500	9	1	115	154	5.1	70	0.54
26	750	9	2	210	333	6.4	61	0.72
27	750	9	1	183	230	5.8	62	0.65
28	750	11	1	205	384	6.1	60	0.71
29	750	7	2	200	230	6.2	66	0.68
30	750	11	2	241	512	6.9	59	0.77
31	500	9	2	133	166	5.7	68	0.56
32	500	11	2	148	166	6.5	60	0.6
33	500	7	2	110	115	4.8	70	0.52

Many researchers have introduced a multi-response technique and named it Satisfaction. This technique creates the objective function that equation (2) depicts Satisfaction function (D) and it indicates the range of Satisfaction for each response. The range of Satisfaction varies from zero to one among which, one is the maximum Satisfaction.

$$D=(d_1 d_2 \dots d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}} \quad (2)$$

"n" represents the number of responses. If any of the responses or independent variations are placed out of the Satisfaction range, the function equals to zero. In optimization based on Satisfaction function, an objective can be defined for each response and variable. For instance, there are some favorable interventions in which the response of y1 and y2 would be maximum and minimum respectively, provided that X1 would be in the specific range, X2 exactly equal to the specific number and X3 would be maximum (Qasemi *et al.*, 2015).

Results and Discussion

Water contamination modeling

The result of the analysis of variance for water contamination of oil samples is presented after the test of the exact determination of the amount of water in the oil (Table 3). According to the results, the quadratic polynomial equation used to predict oil contamination was statistically significant (P <0.01) and its lack of fit test was not significant (P>0.05), which indicates the suitability of the model used to predict the effect of independent variables on water contamination. In addition, all linear statements of the model used (A, B, C) were significant (P <0.01). Among the second-level expressions, the second-level expressions of operating hours (P <0.01,A^2) and filter mesh (P <0.05,B^2) were significant. Among independent variables, interacting hours of work- filter mesh (P <0.05, AB) and operating hours-number of refinement (P <0.01, AC) were significant. The obtained results for the correlation coefficients of the model (R^2=0.995 and $R^2_{adjusted}$ =0.992) also indicate that the regression model used with the tested points and its high accuracy in predicting the value of the dependent variable of water contamination was very good. Equation (3) indicates a Quadratic polynomial model used to predict the amount of water contamination based on the actual values after eliminating non-significant factors.

$$\text{Water} = +113.82 + 54.83\, time + 14.11\, mesh - 14.21\, filter[1] - 2.30\, filter[2] + 4.00\, time * mesh - 8.83\, time * filter[1] - 0.50\, time * filter[2] + 17.94\, time^2 + 3.77\, mesh^2 \quad (3)$$

Table 3- Analysis of variance of water contamination of oil samples

Source	Sum of squares	df	Mean square	F Value	Prob > F	
Model	67279.44	11	6116.31	351.04	<0.0001	significant
A-time	54120.50	1	54120.5	3106.2	<0.0001	
B-mesh	3584.22	1	3584.22	205.71	<0.0001	
C-filter	5280.42	2	2640.21	151.53	<0.0001	
AB	192.00	1	192.00	11.02	0.0033	
AC	992.33	2	496.17	28.48	<0.0001	
A2	2445.63	1	2445.63	140.36	<0.0001	
B2	108.13	1	108.13	6.21	0.0212	
Residual	365.89	21	17.42			
Lack of Fit	303.89	15	20.26	1.96	0.2084	not significant
Pure Error	62.00	6	10.33			
Cor Total	67645.33	32				

In this case (after eliminating non-significant factors), the possibility of using the new model was also examined and the significance of the model (P <0.01) and non-significance of lack of fit, as well as the significance of the linear effects (A, B, and C), the second degree (A^2 and B^2), and the interactions (AB and AC) was confirmed. In general, the first-degree expressions A, the second-degree expressions A^2, the first-degree C, the first-degree B, as well as the AC interaction effect, had the highest effect on the degree of contamination of water, respectively. The interaction effect AB and the second-degree B^2expression were also important at a later stage.

Fig 1 shows the interaction effects of operating hours and the filter mesh (times of oil refinement at the central point) on the amount of water contamination. As it can be seen, the graph has an upward edge and in every operating hour, by increasing the filter mesh, the water contamination increases nonlinearly (second degree). In this case, the significance of the effect of the second- degree expression of the filter mesh affirms this observation (Table 3). This increase is higher at higher operating hours, which can be attributed to the effect of the operating hours with a higher filter mesh on the amount of water contamination. In each mesh of filtering, with increasing hours, water contamination also increased nonlinearly, and the highest water contamination was at 750 operating hours and the 11 of the filter mesh. Finally, concerning the changes' reasons, it can be concluded that the more operating time, the more depreciation and the parts rust could happen; accordingly leading to contamination of the oil, and also, passing time causes an increase in water influx into the oil.

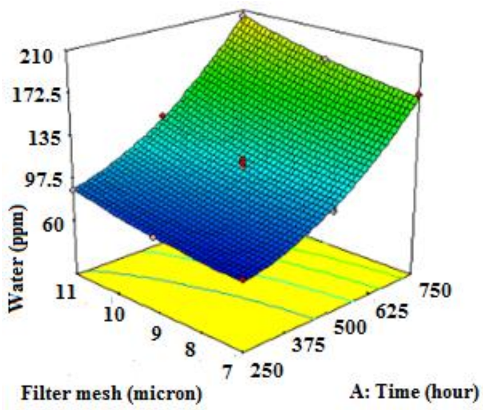

Fig.1. Interaction between the operating hours and filter mesh on the amount of water contamination

Modeling the Level of Oil Uncleanness

The results of the analysis of variance for the level of the uncleanness of oil samples are presented in Table 4. According to the results, the quadratic polynomial equation used to predict the level of oil uncleanness was statistically significant (P<0.01) and lack of fit test was not significant (P>0.05), which indicates the suitability of the model used to predict the effect of independent variables on determining the level of oil uncleanness. In addition, all linear statements of the model used (A and B at P <0.01 and C at P<0.05) were significant.

Table 4- Results of the variance analysis of the uncleanness of oil samples

Source	Sum of squares	df	Mean square	F Value	Prob > F	
Model	2.937E+005	11	26699.93	30.64	<0.0001	significant
A-time	1.860E+005	1	1.860E+005	213.48	<0.0001	
B-mesh	30504.50	1	30504.50	35.00	<0.0001	
C-filter	16220.36	2	8110.18	9.31	0.0013	
AB	18644.08	1	18644.08	21.39	0.0001	
AC	9145.33	2	4572.67	5.25	0.0142	
A2	23878.42	1	23878.42	27.40	<0.0001	
Residual	18301.47	21	871.50			
Lack of Fit	16054.80	15	1070.32	2.86	0.1009	not significant
Pure Error	2246.67	6	374.44			
Cor Total	3.120E+005	32				

Among the second-degree expressions, the only second-degree expression operating hours (A^2 at P <0.01) was significant. Among the independent variables, the interaction of operating hours-filter mesh (AB at P <0.01) and operating hours-frequency of refinement (AC at P <0.05) were significant. The obtained results for the correlation coefficients of the model (R^2=0.941, $R^2_{adjusted}$= 0.911) also indicate a very good correlation between the regression model used with the tested points and its high accuracy in predicting the value of the dependent variable on the level of oil uncleanness. Equation (4) shows a quadratic polynomial model used to predict the level of the uncleanness of oil based on the actual values after eliminating non-significant factors.

$$NAS = +122.58 + 101.67\,\text{time} + 41.17\,\text{mesh} - 24.36\,filter[1] - 4.91\,\text{filter}[2] + 39.42\,time * mesh - 24.33\,time * filter[1] - 5.67\,time * filter[2] + 56.05 time^2 \quad (4)$$

In this case (after eliminating non-significant factors), it was also possible to use the new model and the significance of the model (P<0.01) and non-significance of the lack of fit and also the significance of linear effects (A, B, And C), second degree (A^2) and interactions (AB and AC) was confirmed. Generally, the first-degree expressions A, the second-degree A^2, as well as the AB interaction effect, had the most effect on the level of oil uncleanness. The interaction of AC and the linear effect of C were also important in the next step. Figure 2 indicates the interactions between operating hours and filter meshes (times of oil refinement at the central point) on the level of oil purification.

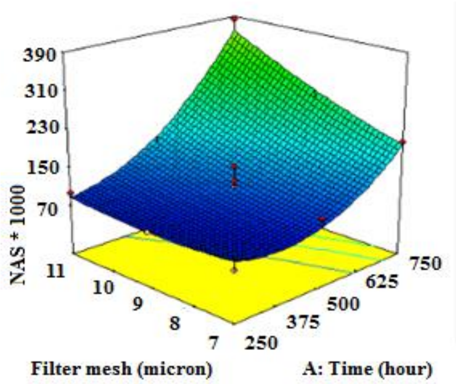

Fig.2. Interaction of the operating hours and filter mesh on the level of oil uncleanness

As can be seen, in any mesh of the filter, with increasing operating time (hours), the level of oil uncleanness increases linearly. The significance of the second-degree operating hour's expression in Table 4 confirms this conclusion. In every operating hour with increasing filter mesh, the level of oil uncleanness increased almost linearly and the highest level of oil uncleanness was 384000 particles (number of particles 5 to 15 micrometers) in 11 filter mesh and 750 hours of the operating hours. The positive coefficients of Equation (4) and the significance of quadratic and linear expressions of Table (4) confirm these trends.

Modeling the Si Rate

The results of the analysis of variance of Si of oil samples are presented in Table (5). According to the results, the second-degree polynomial equation used to predict the amount of Si of oil which was statistically significant (P<0.01) and its lack of fit test was not significant (P>0.05), which indicates the suitability of the model used to predict the effect of independent variables on determining the amount of Si oil. In addition, all linear statements of the model used (A, B, and C) were significant (P<0.01).

Among the second-degree expressions, the only second-degree expression the operating hours (A^2 at P <0.01) was significant. The obtained results for the correlation coefficients of the model (R^2= 0.971, $R^2_{adjusted}$= 0.956) also indicate a very good correlation of the regression model used with the tested points and its high precision in predicting the value of the dependent variable of the amount of Si of oil.

Table 5- Analysis of variance of Si in samples of oil

Source	Sub of squares	df	Mean square	FValue	Prob > F	
Model	50.64	11	4.60	64.47	<0.0001	significant
A-time	33.08	1	33.08	463.21	<0.0001	
B-mesh	6.84	1	6.84	95.86	<0.0001	
C-filter	8.78	2	4.39	61.51	<0.0001	
A2	1.58	1	1.58	22.15	0.0001	
Residual	1.50	21	0.071			
Lack of Fit	1.28	15	0.085	2.33	0.1523	not significant
Pure Error	0.22	6	0.037			
Cor Total	52.14	32				

Equation (5) shows a second-degree polynomial model used to predict the amount of Si of oil based on the actual values after eliminating non-significant factors.

$$Si = +4.92 + 1.36\,time + 0.62\,mesh - 0.63\,filter[1] - 003\,filter[2] - 0.46\,time^2 \quad (5)$$

In this case (after eliminating non-significant factors), the possibility of using the new model was also examined and the significance of the model (P<0.01) and non-significance of the lack of fit and also the significance of linear effects (A, B, and C) and the second degree (A^2) were confirmed. In general, the first-degree expression of the model (A, B and C) and the second-degree A^2expression had the most effect on the amount of Si of oil.

Modeling the Viscosity Rate of Oil

The results of the variance analysis of Vis of oil samples are presented in Table 6. According to the results, the second-degree polynomial equation used to predict the viscosity of oil was statistically significant (P<0.01) and its lack of fit test was not significant (P>0.05), which indicates the suitability of the model used to predict the effect of independent variables on Vis of oil; in addition, linear statements of the model used, B (P<0.01) and C (P<0.05) were significant. Among the second-degree expressions, the only second-degree expression of the operating hours (A^2 at P<0.01) was significant. The results obtained for the correlation coefficients of the model (R^2= 0.913, $R^2_{adjusted}$=0.867) also indicate a very good fit of the regression model used with the tested points and its high accuracy in predicting the value of the dependent variable of the viscosity of the oil. Equation (6), the second-degree polynomial model used to predict the viscosity of oil based on the actual values after eliminating non-significant factors.

$$\text{Vis} = +67.26 - 3.94\,mesh + 1.18\,filter[1] + 0.18\,filter[2] - 4.16\,time^2 \quad (6)$$

In this case (after eliminating non-significant factors), the possibility of using the new model was also examined and the significance of the model (P<0.01) and the non- significance of lack of fit, as well as the significance of the linear effects (B, C) and the second degree (A^2), was confirmed. In general, the second-degree expressions A^2 and first-degree B had the greatest effect on Vis. The first-degree expression C was also important in the next step.

Modeling of the Acid Number (TAN) of Oil

The results of the analysis of variance for the TAN of the oil samples are presented in Table 7. According to the results, the second-degree polynomial equation used to predict oil TAN was statistically significant (p<0.01) and the lack of fit test was not significant (P>0.05), which indicates that the model was used to predict the effect of independent variables on the acid number of oil. In addition, all linear statements of the model used (A, B, and C) were significant (P<0.01).

Table 6- The results of the variance analysis of Vis in oil samples

Source	Sum of squares	df	Mean square	F Value	Prob > F	
Model	458.05	11	41.64	19.90	<0.0001	significant
B-mesh	280.06	1	280.06	133.83	<0.0001	
C-filter	36.18	2	18.09	8.65	0.0018	
A2	131.39	1	131.39	62.79	<0.0001	
Residual	43.95	21	2.09			
Lack of Fit	19.95	15	1.33	0.33	0.9610	not significant
Pure Error	24.00	6	4.00			
Cor Total	502.00	32				

Among the second-degree expressions, only the second-degree of operating hours (A^2 at P<0.05) was significant. Among the independent variables, interacting with operating hours- filter mesh (AB at P<0.05) and operating hours-times of refinement (AC at P<0.01) were significant. The results for the correlation coefficients of the model (R^2= 0.974, $R^2_{adjusted}$= 0.961) also indicate that the regression model used with the tested points is very appropriate and its high accuracy in predicting the value of the dependent variable of the acid number of the oil. Equation (7) shows a second-degree polynomial model used to predict the acid number of oil based on the actual values after eliminating non-significant factors.

$$TAN = +0.54 + 0.087\,time + 0.033\,mesh - 0.030\,filter[1] - 004\,filter[2] + 0.016\,time * mesh - 0.029\,time * filter[1] - 003\,time * filter[2] + 0.022\,time^2 \quad (7)$$

In this case (after eliminating non-significant factors), the use of the new model was also examined and the significance of the model (P<0.01) and the non- significance of lack of fit and also the significance of linear effects (A, B and C), second degree (A^2) and interactions (AB and AC) were confirmed. In general, the first-degree expressions of the model and the interaction effect (AC), respectively, had the most effect on the acid number of the oil. The second-degree expression $A^2$and the interaction effect of AB were also important in the next step.

Table 7- results of variance Analysis for determining the TAN of oil samples

Source	Sum of squares	df	Mean square	F Value	Prob > F	
Model	0.19	11	0.018	71.82	<0.0001	significant
A-time	0.14	1	0.14	561.78	<0.0001	
B-mesh	0.020	1	0.020	82.05	<0.0001	
C-filter	0.019	2	9.603E-003	39.40	<0.0001	
AB	3.008E-003	1	3.008E-003	12.34	0.0021	
AC	9.144E-003	2	4.572E-003	18.76	<0.0001	
A2	3.568E-003	1	3.568E-003	14.64	0.0010	
Residual	5.119E-003	21	2.438E-004			
Lack of Fit	4.919E-003	15	3.279E-004	9.84	0.50	not significant
Pure Error	2.000E-004	6	3.333E-005			
Cor Total	0.20	32				

Figure 3 indicates the interaction effects of the operating hours and the filter mesh (times of oil refinement at the central point) on the acid number of the oil (TAN). As can be seen, the graph has an upward edge, and each hour of the function, with increasing filter mesh, the acid number of the oil increases almost linearly. In each mesh of the oil filter, increasing the operating time of the harvester, the acid number of the hydraulic oil increases non-linearly (second degree). The highest acid number of oil was 0.71 (mg KOH g^{-1}) after 750 hours of operation and the filter was used with a mesh of 11. The positive coefficients of equation (7) and the significance of second-degree and linear expressions of Table (7) confirm these trends. Finally, with regard to the changes' reasons, it can be concluded that influx of suspended particles in the oil is increased as the filter mesh (diameter of filter grids) rises, and also it brings about some increases in the depreciation, rust, and contamination which can change the chemical properties of the oil and the times of filtration of the remaining suspended particles in the oil are increased due to overuse of the oil before the oil change which could bring about more depreciation and the parts rust and consequently, causing an increase in the oil contamination and the chemical changes of the oil. In order to confirm the achieved results, it can be stated that Blouki (2009) in research titled "determination of the best time to change engine oil of transtainer crane (RTG) using oil condition monitoring techniques" analyzed the oil condition monitoring techniques to decrease the cost and environmental damages. Therefore, it was concluded that a precise viewpoint concerning the future status of the machine can be achieved. Reducing the engine oil consumption as a result of rising its operating time can help the national economy by reducing the currency exchange costs arising from the importing inputs of petrochemical industries. This research was focused on the mentioned machines and equipment which are being worked in Imam Khomeini port. In order to test the oil degradation, the specified amount of the oil samples was prepared at regular intervals (110, 130, 150 and 170 hours) during the operating time of the crane. In this research, two operational and predictive criteria were utilized to analyze the oil condition in which the two criteria evaluate the existing rust in the oil so that the normal amount of various rusting elements is up to 100 ppm. A 50% increase in these elements could be a proper warning. It should be noted that for further rusting, this percentage should be declined while this value should be considered more for the slow rusting condition. Therefore, it was observed in the study that engine oil of the studied cranes can work for 170 hours without any problem and the oil change is not economical in 125 hours. The percentage of changes in rusting elements of the oil was less than 50 % for all elements, however, several elements such as Iron and Chromium are in warning threshold. Finally, evaluating five categories of oil index achieved by oil analysis concluded that the engine oil can work for 170 hours and the oil change in 125 hours has brought a decline in efficiency. Furthermore, Masoudi (2001) stated that the maintenance group of the locomotive condition of Iran railways has reported 123 cases of oil change in the first ten months of 2000 which were due to diagnosing unfavorable condition like water contamination, excessive increase or decrease of viscosity and unusual increase of rusting elements. Hence, the damages to 67 cylinders, 58 pistons, 281 rings and 40 sets of bearings have been prevented which can result in saving more than 309,000 dollars. Moreover, by increasing the oil function from 65000 Km to 96000 Km and preventing the unnecessary oil change, this unit has been able to save 734,000,000 rials in oil consumption. Masoudi (2001) stated that during the implementation of a Base-Line aiming to determine the rusting effect of erosive particles for a steam turbine of Arak petrochemical complex with a volume of 18000 liters, the unusual amount (17 ppm) of Silica element was identified. The amount of Tin and Aluminum rose simultaneously which implies an uncommon erosion of the device. The following graph returns to a normal situation after eliminating the contamination, and the device continues to function normally. Thus, identifying and controlling the amplifier erosion elements of expensive petrochemical and power plant equipment, using the maintenance condition of the machines lead to enormous economic savings. It should be mentioned that the financial loss due to the unplanned stoppage of the mentioned turbine was 200 million rials per hour and its major maintenance is estimated hundreds of thousands of dollars.

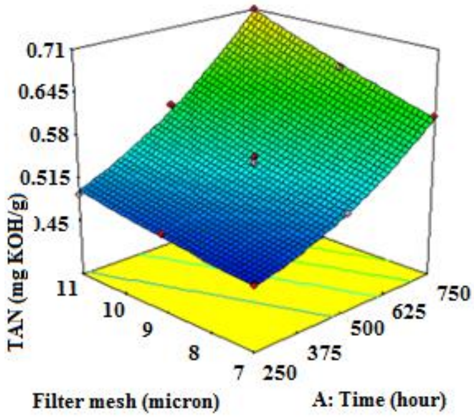

Fig.3. Interaction of the operating hours and filter mesh on the acid number of the oil

Optimization

In order to achieve optimum conditions for the offline hydraulic oil refinement operation, the numerical optimization technique was used. In general, the final decision on the choice of optimal conditions depends on taking into account some economic factors (costs), industrial, etc. However, it should be noted that since regression models are valid only in the area and conditions under consideration, limited economic and qualitative constraints are considered for determining operating conditions. In the present study, operating hours (250, 500 and 750 hours), twin suction filter mesh (7, 9 and 11 microns), and the number of hydraulic oil refinements (0, 1 and 2) were selected in the range. In this study, the aim was to optimize the operation, maximize the operating hours and the frequency of filtering of the oil according to the permitted range of dependent factors. According to the stated contents and results, the permissible range for water contamination was less than 500 ppm; the level of uncleanness or NAS (the number of particles 5 to 15 microns was less than 256 thousand), Si was less than 15 ppm; Vis was between 62.8 and 76.8 Centistokes and TNA was less than 0.65 mg KOH g^{-1}. This goal was chosen to increase the efficiency of offline hydraulic oil refinement operations. Finally, using the desirability function method, the optimal conditions for the offline refinement of hydraulic oil included 728.61 hours, 7-micron filter mesh and oil refinement frequency was two. Under these conditions, the amount of water contamination parameters, the level of uncleanness (NAS), Vis, Si and TAN of hydraulic oil was 187.63 ppm, 234000, 5.91 ppm, 66.34 centistokes and 0.65 mg KOH g^{-1}, respectively. The desirability obtained in optimal conditions for the variables and responses analyzed was 0.957. In sum, the results of this study showed that the offline oil refinement operation of the hydraulic oil could do the trick at high operating hours (728.61) with good performance (water contamination, level of uncleanness, Vis, Si and TAN within the permitted range). In order to confirm the model's prediction, the dependent variables were evaluated in optimal conditions and were determined with a difference of less than 5%, which confirmed the accuracy of the model.

Conclusions

In order to increase the operating hours of sugarcane harvester hydraulic oil, determination of the optimum conditions for performing offline refinement of hydraulic oil can be beneficial and economically feasible. In this research, the effect of independent variables of operating hours, filter mesh and the frequency of hydraulic oil purification were evaluated on the responses studied and optimal operating conditions were also determined. The results of the optimization of the offline hydraulic oil refinement operation indicated that under operating conditions 728.61 hours, 7-micron filter mesh and oil filtration rate of two, water contamination level, uncleanness level (5 to 15 micrometers), Vis, Si and TAN of hydraulic oil was 187.63 ppm, 234000, 5.91 ppm, 66.34 centistokes and 0.65 mg KOH g^{-1}, respectively. The desirability obtained in optimal conditions for the variables and responses analyzed was 0.957. In sum, a second-degree polynomial model was used to predict the extent of the dependent variables concerning the effect of independent variables used. Therefore, the data obtained from the above model can be used to obtain offline refinement hydraulic oil with a degree of water contamination, level of uncleanness, Vis, Si and TAN in the permitted range.

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نشریه ماشین‌های کشاورزی
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بهینه‌سازی عملیات پالایش آفلاین روغن هیدرولیک دروگر نیشکر

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چکیده

روش سطح پاسخ (RSM)، مجموعه‌ای از تکنیک‌های آماری و ریاضی برای طراحی آزمایش‌ها، مدل‌سازی، بهبود دادن و بهینه‌سازی فرآیندها می‌باشد. هدف از مطالعه حاضر مدل‌سازی و بهینه‌سازی عملیات پالایش آفلاین روغن هیدرولیک دروگر نیشکر به روش RSM بود. بدین‌منظور، اثرات متغیرهای مستقل ساعات کارکرد (۲۵۰، ۵۰۰ و ۷۵۰ ساعت)، مش فیلتر مکشی دوقلو (۷، ۹ و ۱۱ میکرون) و دفعات تصفیه روغن هیدرولیک (۰، ۱ و ۲) روی متغیرهای وابسته آلودگی آب، سطح عدم تمیزی (NAS)، سیلیسیوم (Si)، ویسکوزیته (Vis) و عدد اسیدی روغن (TAN) ارزیابی شد. نتایج نشان داد که همه‌ی مدل‌های به‌دست آمده برای آلودگی آب، سطح عدم تمیزی (NAS)، سیلیسیوم (Si)، ویسکوزیته (Vis) و عدد اسیدی روغن (TAN) برای توصیف داده‌های آزمایشی مناسب بودند. علاوه‌بر این تابع مطلوبیت نشان داد که شرایط بهینه عملیات پالایش آفلاین روغن هیدرولیک دروگر نیشکر شامل ساعت کارکرد ۷۲۸/۶۱ ساعت، مش فیلتر ۷ میکرون و دفعات تصفیه روغن ۲ بود. تحت این شرایط، مقدار پارامترهای آلودگی آب، سطح عدم تمیزی (تعداد ذرات ۵ تا ۱۵ میکرومتر)، Si، Vis و TAN به‌ترتیب برابر با ppm ۱۸۷/۶۳، ۲۳۴۰۰۰، ppm ۵/۹۱، ۶۶/۳۴ سانتی استوک و ۰/۶۵ mg KOH/g به‌دست آمد.

واژه‌های کلیدی: بهینه‌سازی، پالایش آفلاین روغن هیدرولیک، دروگر نیشکر، روش سطح پاسخ

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