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Effect of Crude Oil-Water Two-Phase Flow on Pump Performance

Dr. Banipal N. Yaqob* & Ihsan F. Abbas**

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Abstract

An experimental study of pump performance (i.e. head, discharge, power, etc.) was achieved by using a centrifugal pump with crude oil-water two-phase flow. The crude oil used was from Sherao oil field in Kirkuk (Iraq) with a density of 838 kg/m^3, dynamic viscosity of 6.0 cP and surface tension of 0.027 N/m at a temperature of 25^{o}C. A centrifugal pump was used with straight impeller and one suction line and one discharge line. The results show that the pump head and the discharge of two-phase flow decrease as oil volume fraction increased, and the power of the pump increase as oil volume fraction increased.

Keywords: Two-phase flow; Crude oil-water; Centrifugal pump; Volume fraction

تأثير جريان ثنائي-الطور للنفط الخام-الماء على اداء المضخة

الخلاصة

تم اجراء دراسة عملية على اداء المضخة (ارتفاع ضغط، تصريف، قدرة وغيرها) من خلال استخدام مضخة طاردة مركزية لضخ النفط الخام-الماء كجريان ثنائي-الطور. النفط الخام المستخدم هو من حقول شيراوه النفطية من مدينة كركوك (العراق) بكثافة قدرها 838 كغم/م^3 ولزوجة ديناميكية قدرها 6.0 سنتي بويس وشد سطحي مقداره 0.027 نت/م في درجة حرارية قدرها 25 م^o. المضخة المستخدمة كانت من نوع طاردة مركزية وبريش مستقيمة مع انبوب واحد للسحب وانبوب واحد للدفع. النتائج التي تم التوصل اليها تبين ان ارتفاع الضخ والتصريف للجريان ثنائي الطور يقل مع زيادة النسبة الحجمية للنفط، بينما تزداد قدرة المضخة مع زيادة النسبة الحجمية للنفط.

Nomenclature

A	total flow area, *m*
A_g	area occupied by gas phase, *m*
A_f	area occupied by liquid phase, *m*
H_P	pump head, *m*
g	gravitational acceleration, m/s^2
I	electric current input to pump, *A*
P_1	pump inlet pressure (suction side), *Pa*
P_2	pump outlet pressure (delivery side), *Pa*
V	voltage across the pump, *V*
V_g	volume occupied by gas phase, m^3
V_f	volume occupied by liquid phase, m^3
$V_{(oil)}$	oil volume fraction
$V_{(water)}$	water volume fraction
Δz	certain length of pipe, *m*

Greek symbols

α	void fraction
$\bar{r}$	average two-phase flow density, kg/m^3

Subscripts

f	liquid phase
g	gas phase
oil	oil phase
water	water phase
1	pump suction side
2	pump delivery side

*Mechanical Engineering Department ,The Technical college of Erbil\ Erbil-Kurdistan Region
** Mechanical Engineering Department, The Technical college of Kirkuk\ Kirkuk

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2412-0758/University of Technology-Iraq, Baghdad, Iraq
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Introduction

Two-phase flow is encountered in many engineering system of chemical process, power generation, and petroleum industries. Typical examples are oil-gas pipelines, boilers, heat exchanger, refrigeration equipment, evaporators, and nuclear reactor. In a simple way, two-phase flow is an extension of single phase flow and two-phase flow, in reality, is much more complex due to the uncertain in various interfacial parameters.

In lubrication system subject to two phase flow, Wood [1] used the oil pump provided with a capacity such that it can always pump sufficient oil plus the refrigerant and/or excess oil. The excess oil and/or out gassed refrigerant is vented to provide the desired lubricant flow.

An improved model for the calculation of the two-phase pump head was developed by Poullikkas [2]. The model takes into account phase separation and compressibility and condensation effects of the gas phase.

One of the most severe accidents in nuclear power generation is the loss of coolant, where the recirculating coolant of the pressurized water reactor may flash into steam. Under such two–phase flow conditions, the reactor cooling pumps become unable to generate the same head as that of the single phase flow case. Poullikkas [3] were conducted high speed video (HSV) observation on a nuclear reactor cooling pump. The HSV identified the bubbles motion into the impeller passages and assisted in the development of mathematical model based on the control volume method for rotating machines.

A special test–pump with 2D curvature blade geometry in cavitating and non–cavitating conditions was investigated by Hofmann & Stoffel [4] using different experimental techniques and a 3D numerical model of cavitating flows. Experimental and numerical results concerning pump characteristics and performance breakdown were compared at different flow conditions. Appearing types of cavitation and the spatial distribution of vapor structures within the runner were also analyzed.

Stratified oil-water two-phase turbulent flow in a horizontal tube was numerically simulated by Gao *et. al.* [5] using a volume of fluid (VOF) model. A single momentum equation was solved throughout the domain. Results of pressure loss, slip ratio, local phase fraction profile and the axial velocity profile were verified by experimental data in literature.

A new gas-liquid model was presented by Sun & Prado [6] to predict electrical submersible pumps head performance. The newly derived approach based on gas-liquid momentum equations along pump channels has improved. The new two-phase model includes novel approaches for wall frictional losses for each phase using a gas-liquid stratified assumption and existing correlations. The model can predict pressure and void fraction distributions along impellers and diffusers in addition to the pump head performance curve under different fluid properties, pump intake conditions, and rotational speeds.

An experimental study was made by Piela *et. al.* [7] to predict of phase inversion in an oil-water flow through a horizontal pipe loop. The experimental

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started with the flow of a single liquid through the pipe loop; thereafter the second liquid was gradually added (using different injectors and different injection flow rates) until inversion took place.

Yinshan & Jamal [8] presents the successful control of dielectric liquid/vapor flow distribution between two parallel branch lines utilizing an electrohydrodymamic (EHD) conduction pump at select mass flux level under adiabatic condition.

A method of pumping and related arrangement for multi-phase fluid flow wherein a centrifugal pump was used by Zaher [9] for the suction and delivery of the multi-phase fluid which has a fluid communication providing portion to provide a communication of fluid bled from the outlet at a higher pressure to be injected into the inlet conduit of the centrifugal pump in operation.

In all the literatures, there were no study deals with liquid-liquid two-phase flow through a pump except that of Kendoush *et. al.* [10], although there study was not on pump performance, were they measured the local oil volume fraction using a novel technique named the auto-transformer technique for crude oil-water two-phase stratified flow, and compare the results with the capacitance technique. They used a simple and small centrifugal pump to pump the oil-water through the Pyrex glass test section.

In this work, the effect of crude oil-water two phase flow on pump performance was studied, were a centrifugal pump with straight blades was used.

The Oil-Water Flow System

The oil-water system consists of an oil-water mixing tank, a stirrer to mix oil and water thoroughly in the mixing tank, a centrifugal pump with description in Table (1), valves to control the flowrate, and a storage tank. The basic instrumentations used are: Flowmeter, two gauge pressures (one for suction side, P_1, and the other for the delivery side, P_2) and connection plastic tubes. The crude oil used was from Sherao oil fields in Kirkuk (Iraq) with the density of 838 kg/m^3, dynamic viscosity of 6.0 cP and surface tension of 0.027 N/m at a temperature of 25^{o}C. The schematic description of the oil-water flow system is shown in Figure (1).

Experimental Method and Procedure

The performance of the pump under two-phase flow condition depends on the behavior of the gas-liquid interaction in the pump.

Void fraction is the ratio of area occupied by vapor/gaseous phase to the total flow area for a certain pipe length, depends strongly on pressure, mass flux, and quality. It applied to calculate the acceleration pressure drop in steady-state homogeneous code.

$$a = \iiint_{V_g} dV \Big/ \iiint_{V} dV = \frac{V_g}{(V_g + V_f)} \qquad ..(1)$$

Since;

$$V_g = A_g \Delta z \qquad ..(2)$$

Then Eq. (1) becomes,

$$a = \Delta z \iint_{A_g} dA \Big/ \left(\Delta z \iint_{A} dA \right) \qquad ..(3)$$

or

$$a = \frac{A_g}{(A_g + A_f)} = \frac{A_g}{A} \qquad ..(4)$$

and

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$$(1-a)=\frac{A_f}{A} \qquad ..(5)$$

The two-phase flow mixture density is given as;

$$\bar{r}=\frac{\iiint_{V_g V_f} r\,dV}{(V_f+V_g)}=\frac{\iiint_{V_f} r_f\,dV+\iiint_{V_g} r_g\,dV}{(V_f+V_g)} \qquad ..(6)$$

If the density for each phase is constant within the volume for that phase, then using the definition of void fraction as in Eq. (1), then Eq. (6) becomes;

$$\bar{r}=a r_g+(1-a)r_f \qquad ...(7)$$

The different flow regimes present in the flow are accounted for or represented using void fraction, such that the mixture density becomes flow regime dependent.

In present work were liquid-liquid two-phase flow have been used, the term void fraction was replaced by volume fraction or cut ratio, (volume ratio of phase 1 to the total volume of the flow).

Then for oil volume fraction;

$$V_{(Oil)}=\frac{\text{Volume occupied by oil}}{\text{Total volume of flow}} \qquad ..(8)$$

and for water volume fraction;

$$V_{(Water)}=\frac{\text{Volume occupied by water}}{\text{Total volume of flow}} \qquad ..(9)$$

Equation (7) can be modified to represent the oil-water mixture density in the pump lines;

$$\bar{r}=V_{(Oil)}r_{Oil}+V_{(Water)}r_{Water} \qquad ...(10)$$

The two-phase pump head was calculated as the ratio of the static pressure difference across the pump to the two-phase mixture density;

$$H_P=\frac{P_2-P_1}{\bar{r}\cdot g} \qquad ..(11)$$

The electrical input pump power was calculated from the following equation,

$$\text{power}=V\cdot I \qquad ..(12)$$

During the experimental work, the temperature of the laboratory was kept nearly constant which was ranging from 23 to 27^{o}C. For the oil–water flow system and for each test, the following procedure was used:

1. Putting water in the mixing tank and pumping it to the storage tank, during the flow, measuring the suction pressure (P_1), delivery pressure (P_2), and the flow rate. Knowing that the all valves were fully open.
2. Mixing a known percentage volume of oil with that of water (e.g. 10 % oil and 90 % water) in the mixing tank.
3. The operation of the stirrer provides good mixing of oil and water in the mixing tank.
4. While the oil–water mixture flow through the system, the reading of the suction pressure, delivery pressure, and the flow rate was taken by suction pressure gauge, delivery pressure gauge, and the flow meter respectively.
5. Repeating the procedure from 2 to 4 for another percentage of oil–water mixture until reaching 100 % oil pumping flow.
6. From Eq. (10), calculating the average density ($\bar{r}$) of oil-water mixture, from Eq. (11) obtain the pump head (H_P), and from Eq. (12) calculating the pump input power for each reading.

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Results and Discussion

The experimental data were translated into figures showing the performance of the pump used in the present work with crude oil-water two-phase flow.

Figure (2) indicates the relationship between pump head and oil volume fraction. This curve show that the pump head decrease as oil volume fraction increases, and this is because of decreasing the density of the two-phase as oil volume fraction increased. It is known that where free gas is present in a liquid being pumped the head, power and efficiency of the rotodynamic pumps are known to decrease, Zaher [9].

Figure (3) shows the relation between the discharge of the two-phase flow and oil volume fraction. In this figure, the discharge of the two-phase flow decrease as oil volume fraction increased (i.e. decreasing water volume fraction). The cause belong to the increasing in the viscosity of the mixture as oil volume fraction increased, which cause to decrease in the velocity of the two-phase flow. The curve in the figure has a concave up shape at oil volume fraction of about 0.8, and this is because of the phase inversion at this point, Piela *et. al*. [7], as can be seen in the last two figures.

The pump power will increase as oil volume fraction increased because of increasing in viscosity of the two-phase flow causing more torque on pump motor. This clarification can be seen in Figure (4).

The results are given in Figure (5), which shows the relationship between water volume fraction and pressure drop per meter tube length. The profile of the present work and that of Gao *et. al.* [5] is nearly the same. At water volume fraction about 0.8, the two curves show a concave down which is the point of inversion.

The point of inversion can be clearly shown in Figure (6). This figure shows the relationship between scaled pressure drop (ratio of the actual pressure drop and the pressure drop at the start of the experiment with the single-phase flow) and oil volume fraction. In this figure, the agreement between the present work and that of Piela *et. al.* [7] for the point of inversion, where this point for the two works is approximately at 0.8 oil volume fraction.

Conclusions

Experiments were done for measurements of pump head, discharge, power, etc. for oil-water two-phase flow using a centrifugal pump. The following conclusions were abstracted:

1. The discharge of the two-phase flow decreases as oil volume fraction increased, while the discharge increases as water volume fraction increased.
2. Due to increasing the viscosity of oil-water mixture as oil volume fraction increased, therefore the power of the pump to be proportional directly with oil volume fraction.
3. For gas-liquid two-phase flow, the pump head and pump power decrease as void fraction increased, while in oil-water two-phase flow, the pump head decreases and pump power increases as oil volume fraction increased.
4. For water to oil two-phase flow, the point of inversion was at 0.8 of oil volume fraction.

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Table (1) Pump Specifications

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Pump type	Centrifugal Single suction Single discharge
Impeller	Straight type
No. of blades	22-in each side
Impeller dia.	7 *cm*
Max. Head	30 *m*
Max. Flow	30 *l/min*
Max. Power	0.74 *hp*
Motor speed	2850 *rpm*
Max. Current	2.5 *A*
Frequency	50 *Hz*

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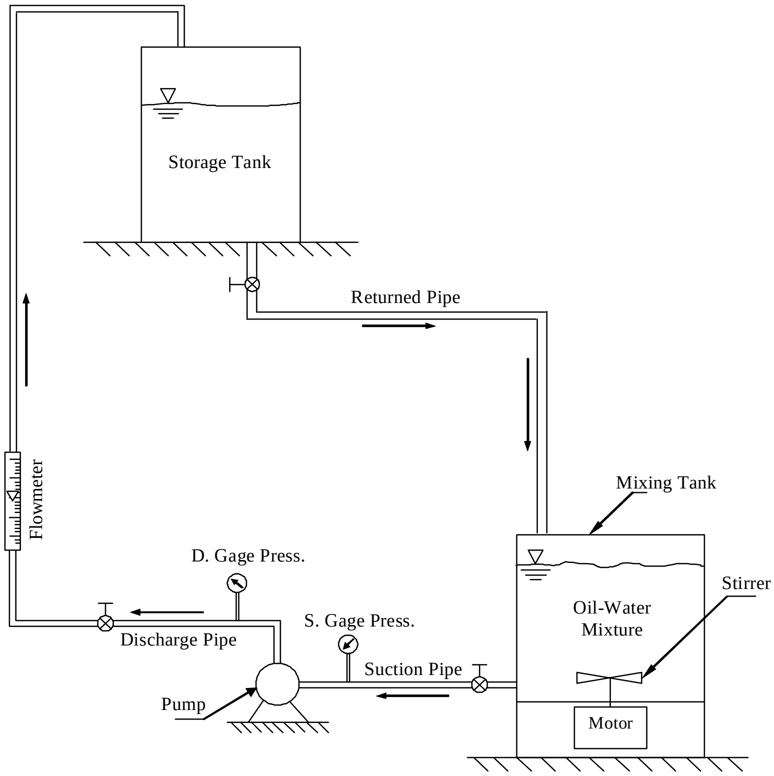

Figure (1) The oil-water flow system.

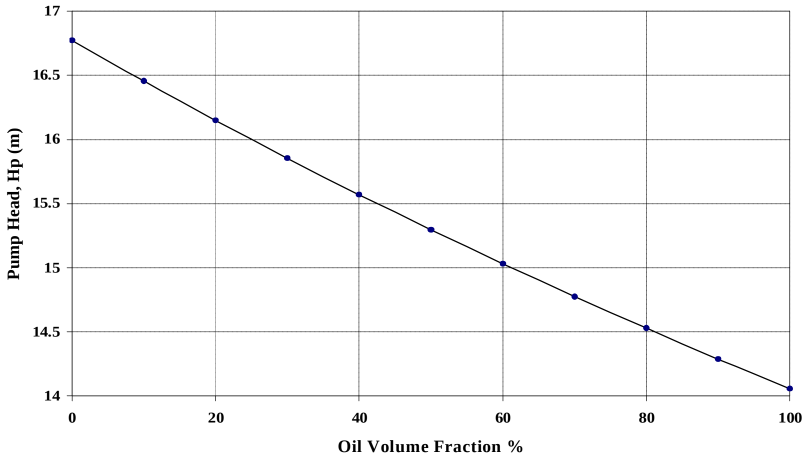

Figure (2) Pump head vs. oil volume fraction.

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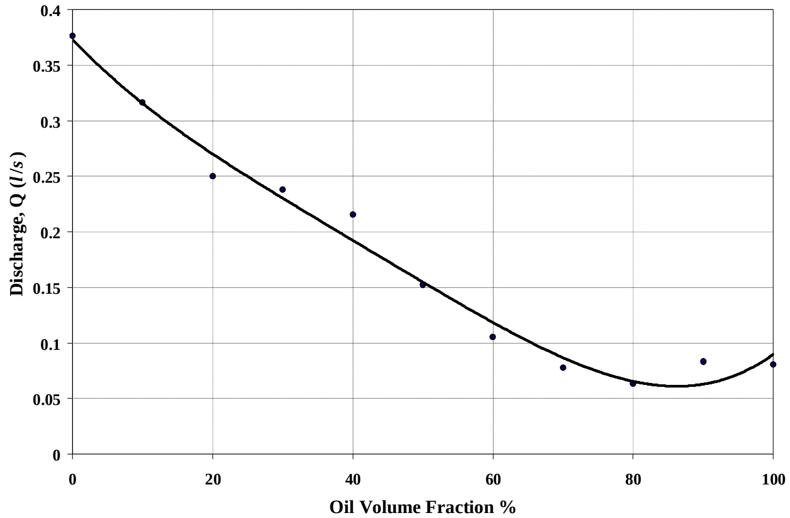

Figure (3) Discharge vs. oil volume fraction.

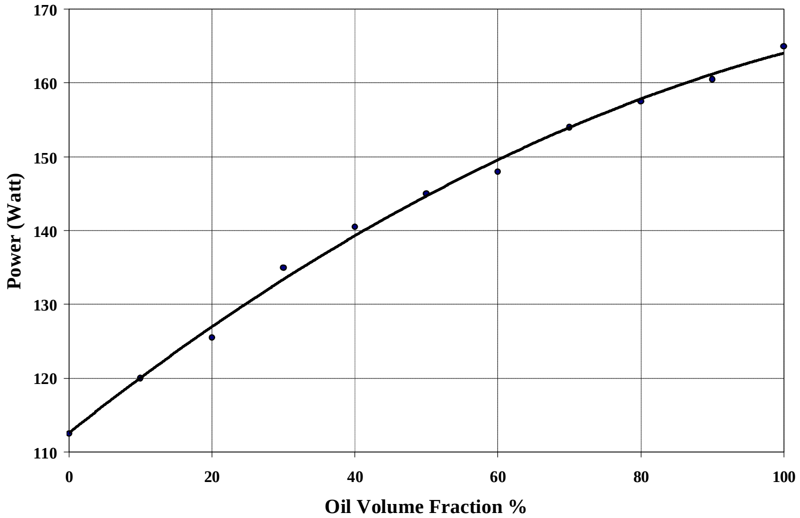

Figure (4) Power vs. oil volume fraction.

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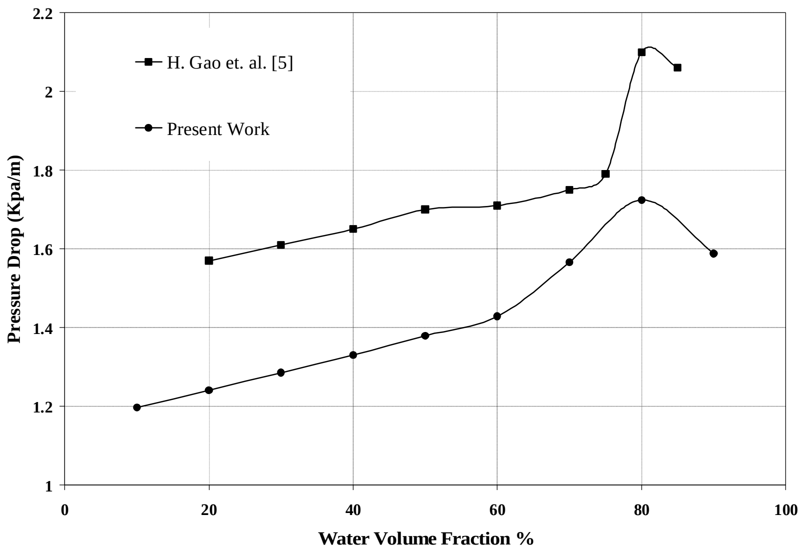

Figure (5). The comparison between present work and H. Gao *et. al.* [5] for pressure drop per meter length vs. water volume fraction.

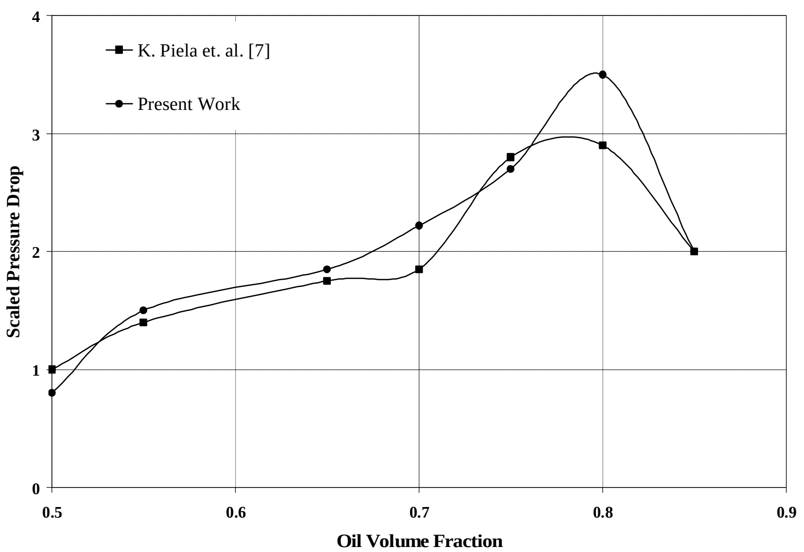

Figure (6). The comparison between present work and K. Piela *et. al.* [7] for scaled pressure drop vs. oil volume fraction.

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