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Full Length Research Paper

Effect of the rotor during centrifugal high volume division of oil and water

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Centrifugal separation of oil and water from streams that is concentrated with oil such as the ones from the oil spill disasters is investigated in this study. The existing theories are largely for Stokes settling of oil drops. In this study, two layers, one rich in oil and another rich in water are allowed to spin in a centrifuge. The tangential velocity profile is derived from the equations of continuity and motion. The power drawn at the inner rotor is calculated for a set of parameters for the system and an angular speed ω RPM (revolutions per minute). Each simulation required the solution of four simultaneous equations and simultaneous unknowns. The power draw was found to be linear with angular rotor speed on a log-log plot. The viscosity of the oil was increased five times to study the effect on the power draw. An expression of the interlayer thickness ratio (α) was obtained by use of a component mass balance on oil streams that flow in and out of the continuous centrifuge.

Key words: Centrifugal separation, polar coordinates, equation of motion, layered flow, matrix inversion, computer simulations, power draw, revolutions per minute (RPM).

INTRODUCTION

Oil spills such as the recent one in the Gulf of Mexico called the Deepwater Horizon ("BP leak the world's accidental oil spill" Telegraph, 2010) needs to be cleaned-up. During development of technology and advancement of human mankind, it is not sufficient to discover a new gadget. The technological device has to be used in a safe manner and benignant to the environment. The psyche of the general public would be boosted when appropriate methods for handling these spills are in place. Five oil spills are listed in Table 1. The Deepwater Horizon in 2010 and the Exxon Valdez in 1989 were at a monetary loss of close to $0.5 billion in lost revenue from the crude oil. The largest one was the one in California in 1911. The other two spills were at the Persian Gulf and Mexico. When more than one country is involved when peace is sought after oil spills, may cause friction among otherwise friendly neighbors.

The difference in density between oil and water is used to design separators. Oil and water can be separated by three methods: (i) gravity; (ii) filtration and; (iii) centrifugal separation. The advantages in using centrifugal separation are higher throughput offered, smaller sizes of the separator and lower residence time. One method for cleaning the oil from the sea water is the use of a centrifuge.

A typical CINC centrifugal liquid-liquid separator can be obtained from the CINC processing equipment, Inc. The CINC Liquid-Liquid Centrifugal Separator utilizes the force generated by rotating an object about a central axis. By spinning two fluids of different densities within a rotating container or rotor the heavier fluid is forced to the wall at the inside of the rotor while the lighter fluid is forced toward the center of the rotor. A cut-away view of such a centrifugal separator may be viewed at the internet webpage http:///www.cincmfg.com/How_our_Centrifuges_Work_s/108.htm.

The theory for separation used currently is the Stokes settling of oil droplets. The factors that affect centrifugal separation are throughput capacity, droplet size, temperature, density difference, interfacial tension and debris. Viscosity of the fluids is a salient consideration in design of separators. Laminar flow is assumed in Stokes law, spherical drops and ideal drop size distribution.

Table 1. Some illustrative oil spills.

Oil spill	Date	Amount
Deepwater Horizon, Gulf of Mexico	04-10-10 to 07-15-10	175 million gallons
Lakeview Gusher, Kern County, CA	05-14-10 to 09-1911	378 million gallons
Gulf War Oil Spill (Iraq, Persian Gulf and Kuwait)	01-19-1991 to 01-28-1991	275 million gallons
Ixtoc I, Gulf of Mexico, Mexico	06-1979 to 03-1980	150 million gallons
Exxon Valdez, Alaska	March 24th 1989	30 million gallons

Table 2. Droplet size regimes for different separation technologies.

Separation process	Droplet size regime
Filter	10 – 1000 (μm)
Microfilters	300 A – 10 μm
Ultrafiltration	20 A – 10 μm
Reverse Osmosis	4 – 500 A
Electrodialysis	4 – 1000 A
Ultracentrifuge	40 A – 1 μm
Centrifuge	400 A – 500 μm

When high volume of oil and water mixture are separated using a centrifuge oil rich and water rich layers are formed. The fluids are in a state of transition flow. Skimmers have been suggested for oil recovery from marine spills. Some discussions are provided in Bitting et al. (1993). Emulsion breakers can be used in order to enhance the separation process. Fleischer (1984) provided the range of droplet size regimes for different separators such as microfilters, filter, ultrafiltration, reverse osmosis, electrodialysis, ultracentrifuge and centrifuge. This is shown in Table 2.

Murdoch (1993), provided a summary of performance data for selected separators tested by using oil and emulsion combinations. The separators mentioned were alfa-laval, surge tank, vortoil and intr-septor. Nordvik et. al. (1997) discusses changes in spilled oil properties over time and how these changes affect differential density separation. The oil or water can form the dispersed phase depending on the phase volume of the oil and water present in the mixture. Electrostatic demulsification (Eow and Ghadiri, 2002) can be used to separate water that forms the dispersed phase from a continuous oil phase. Other methods used for this purpose are chemical demulsification, gravity or centrifugal settling, pH adjustment, filtration, heat treatment, membrane separation etc. Use of chemical demulsifiers can affect water/oil interfacial properties leading to coalescence of water drops into larger ones. pH effect is not effective in water-in-oil emulsions. Centrifugation methods are more expensive in general and the operating costs in particular. Heat treatment leads to high fuel consumption.

Electric treatment for oil and water separation was introduced by Cottrell and Speed (1911).

For high volume separation such as the oil that can be recovered from the oil spills, a centrifuge such as the one described in this study may be used. Here, layers form with one layer that is oil rich and another layer that is water rich. The peripheral layer is water rich and may be collected from a port at the outer centrifugal bowl (Figure 1) and the oil rich layer may be collected from the inner rotor wall that is rotating. There is not much discussion in the literature for the theory of centrifugal separation of layered flow. In this study, the velocity profiles of the oil rich layer and water rich layer are derived from the equations of continuity and motion. The thickness of the interface of the oil and water is calculated from a component mass balance of the oil in the inlet and outlet streams of the continuous centrifuge. Numerical simulations are run on a desktop computer for a given angular speed of rotor, ω (RPM) and density ratio of the fluids and viscosities of the fluids. A set of four simultaneous equations and simultaneous unknowns are solved for using the MINVERSE command in Microsoft Excel for Windows 2007. These constants are used to obtain the power draw at the rotor from the torque required. A log-log plot is developed form the simulations for the power draw at the rotor that may be used in the design of such systems.

THEORY

Consider a centrifuge with an outer bowl radius of R (m) and an inner rotor radius of κR (m). The inner rotor is allowed to rotate at an angular velocity of ω RPM. The feed has high concentration of

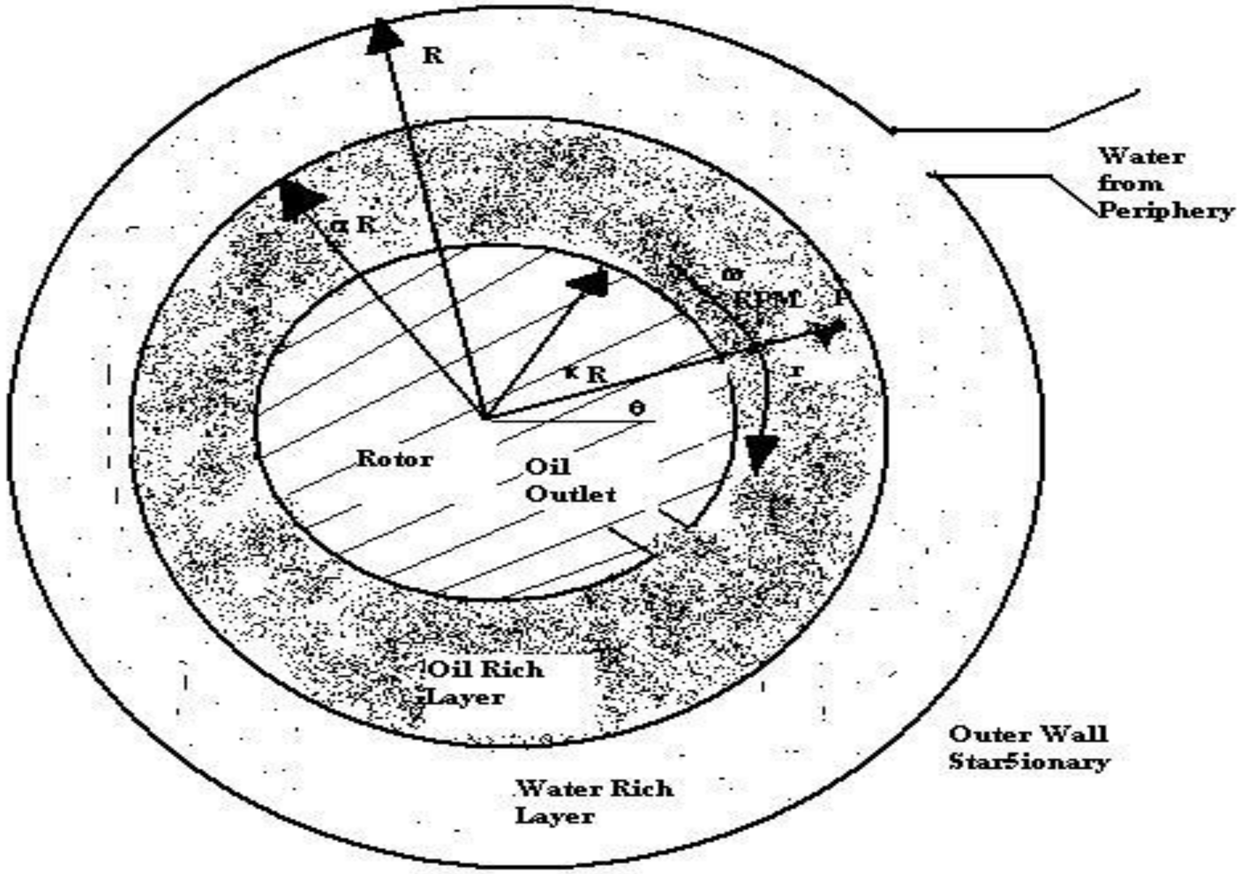

Figure 1. Cross-sectional view of centrifugal separator of oil and water.

oil about 33% mass fraction oil (x_F). It is desired to achieve a separation efficiency of 97.9%. The outlet oil stream is from the inner rotor and the outlet water stream is from the periphery of the bowl. The density ratio of the oil and water is γ. Viscous flows are considered at steady state.

Consider a thin shell of fluid with thickness Δr and at a distance r from the center of the centrifuge as shown in Figure 1. It is assumed that the momentum transfer is predominantly in the radial direction. The tangential velocity assumes a profile that varies with the distance r from the center of the centrifuge. It is assumed that for high volume oil and water feeds such as the one that can be expected from the clean-up of the recent oil spill of BP Americas (http://en.wikepedia.org) two layers are formed, that is, one rich in oil and the second layer rich in water. As the tangential force from the rotor is increased the species with the higher specific gravity will gain more momentum and move to the periphery of the centrifuge.

The species with the lower specific gravity will remain in the inner layer close to the rotor. The density of the crude oil was assumed to be "heavy" and was taken as 900 kg/m^3 and the density of the water were taken as 1000 kg/m^3. For such a pair, the peripheral layer would be water rich and the inner layer would be oil rich. Earlier discussions in the literature have been largely on droplet formation of oil and layer formation or "slick" formation is not discussed much. Let the radius of the outer centrifugal bowl that is held stationary be R (m) and that of the inner rotor be κR (m). The inner rotor is allowed to rotate at an angular velocity of ω RPM (revolutions per minute). The water is collected by a port at the periphery of the bowl and the oil is collected through the port in the inner rotor. The feed is introduced from the top of the centrifuge. The feed location has not been optimized in the study. The equation of continuity and motion for v_θ and the equation of motion for shear stress, $\tau_{r\theta}$ can be written from the Appendice in Bird et al. (2007) as follows:

$$-\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \tau_{r\theta}\right) = 0 \qquad (1)$$

Integrating Equation 1;

$$\tau_{r\theta} = \frac{C_1}{r^2} \qquad (2)$$

The Newton's law of viscosity for the shear rate is given by Equation 2;

$$\tau_{r\theta} = \tau_{\theta r} = -\mu \left(r \frac{\partial}{\partial r}\left(\frac{v}{r}\right)\right) \qquad (3)$$

For the oil rich inner layer (Figure 1) combining Equations 2 and 3;

$$-\mu_{oil}\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right) = \frac{c_1}{r^3} \tag{4}$$

Integrating Equation 4 twice;

$$\frac{v_\theta}{r} = \frac{c_1}{2\mu_{oil}r^2} + c_2 \tag{5}$$

Equation 5 is valid for, $\kappa R \le r \le \alpha R$.

For the water rich peripheral layer (Figure 1), in a similar manner the tangential velocity of the fluid can be written as follows:

$$\frac{v_\theta}{r} = \frac{c_3}{2\mu_{water}r^2} + c_4 \tag{6}$$

Equation 6 is valid for, $\alpha R \le r \le \kappa R$.

The boundary conditions can be seen to be; at the outer stationary wall

$$r = R,\ v_\theta = 0 \tag{7}$$

Substituting Equation 7 in Equation 5;

$$0 = \frac{c_1}{2\mu_{oil}R^2} + c_2 \tag{8}$$

at the inner rotor wall,

$$r = \kappa R,\ v_\theta = \omega\kappa R \tag{9}$$

Substituting Equation 9 in Equation 5;

$$\frac{v_\theta}{\kappa R} = \frac{c_1}{2\mu_{oil}\kappa^2 R^2} + c_2 \tag{10}$$

at the interface of oil rich and water rich layer,
Interface is assumed to be without any accumulation of forces;

$$\tau_{r\theta}(oil) = \tau_{r\theta}(water)$$

$$\frac{c_1}{\alpha^2 R^2} = \frac{c_2}{\alpha^2 R^2} \tag{11}$$

The velocity across the interface of oil rich and water rich layer is assumed to be continuous;

$$\frac{v_\theta}{\alpha R} = \frac{c_1}{2\mu_{oil}\alpha^2 R^2} + c_2 = \frac{c_3}{2\mu_{water}\alpha^2 R^2} + c_4 \tag{12}$$

In this study, Equations 8, 10, 11 and 12 were used to solve for the integration constants, c_1, c_2, c_3 and c_4 using the MINVERSE function in Microsoft Excel for Windows 2007. The set of equations (Equations 8, 10, 11 and 12) that are needed to obtain the integration constants are given in the matrix form as follows:

$$\begin{pmatrix} 0 & 0 & \frac{1}{2\mu_{water}R^2} & 1 \\ \frac{1}{2\mu_{oil}\kappa^2 R^2} & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ \frac{1}{2\mu_{oil}\alpha^2 R^2} & 1 & -\frac{1}{2\mu_{water}\alpha^2 R^2} & -1 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} = \begin{pmatrix} 0 \\ \omega \\ 0 \\ 0 \end{pmatrix} \tag{13}$$

Equation 13 is a set of four simultaneous equations and four unknowns. The vector of constants can be obtained as follows:

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \frac{1}{2\mu_{water}R^2} & 1 \\ \frac{1}{2\mu_{oil}\kappa^2 R^2} & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ \frac{1}{2\mu_{oil}\alpha^2 R^2} & 1 & -\frac{1}{2\mu_{water}\alpha^2 R^2} & -1 \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ \omega \\ 0 \\ 0 \end{pmatrix} \tag{14}$$

The layer thickness ratio α can be estimated as follows. A component balance on the oil in the feed stream, peripheral water stream and inner rotor oil stream would yield;

$$x_F v = (v - v_{rot})x_{per} + v_{rot}x_{rot} \tag{15}$$

or, $$\frac{v_{rot}}{v} = \frac{(x_F - x_{per})}{(x_{rot} - x_{per})} \tag{16}$$

Let the residence time of the fluid in the continuous centrifuge be θ (h). Then;

$$v_{rot}\theta = \pi R^2(\alpha^2 - \kappa^2)H \tag{17}$$

and, $$v\theta = \pi R^2(1 - \kappa^2)H \tag{18}$$

Dividing Equation 17 by Equation 18 and equating with Equation 16;

$$\alpha = \sqrt{(1-\kappa^2)\left(\frac{x_F - x_{per}}{x_{rot} - x_{per}}\right) + \kappa^2} \tag{19}$$

RESULTS

Simulations were run on the desktop computer using Microsoft Excel for Windows, 2007. An example calculation is shown in Table 3.

The calculations were performed for a rotor speed of 1000 RPM. The separation efficiency is about 97.9%.

Table 3. Calculations for a given set of oil and water viscosities and ω = 10 RPM.

Oil water separation by centrifugation				**Feed**	**Outlet (oil)**	**Outlet (water)**	
			x_{oil}	0.33	0.99	0.01	
μ_w	0.001	Pa.S	x_w	0.67	0.01	0.99	
μ_{oil}	1000	Pa.S	v_{rotor}	13.3877551			
κ	0.74		v_{per}	27.6122449			
[redacted]^2	0.4524		Separation	0.979591837	0.326531	Ratio	
α	0.83386		Efficiency				
R	5	10000	gallons	V			
ρ_{oil}	900	kg.m^3	ft	H	0.522028	m	
ρ_{water}	1000	kg.m^3					
θ_{res}	1	hr					
v	41	$m^3.h^{-1}$					
γ	0.9		0	0	0.00002	1	
α	0.83386		3.6523E-05	1	0	0	
			1	0	-1	0	
			2.87636E-05	1	-28.7636	-1	
c1	34.76614		-0.034766137	0.034766137	1	-0.034766137	0
c2	999.9987		1.26976E-06	0.99999873	-3.7E-05	1.26976E-06	1000
c3	34.76614		-0.034766137	0.034766137	-2.7E-07	-0.034766137	0
c4	-0.0007		1.000000695	-6.9532E-07	5.4E-12	6.95323E-07	0
	RPM						
T	ω	α	Torque				
199	1000	0.83386	42.32546536				

The values in bold face are obtained by using the MINVERSE command in Microsoft Excel for Windows 2007. The results are the inverse of the matrix as described in Equation 14. Simulations were repeated for 29 different values of angular speeds of rotor. Each of the torque values were recorded in another column in the spreadsheet. The torque is calculated from the shear stress the rotor wall multiplied with the surface area of the rotor and the moment arm distance, κR, and multiplied with the angular speed ω in RPM. The results of these simulations are shown in Figure 2 on a log-log plot. The relationship is found to be linear in the log-log plot. For the example run as shown in Table 1, the separation efficiency is about 37%. In order to achieve more separation more stages need be considered. The set of simulations were repeated for a higher viscosity of oil, μ_{oil} (5000 Pa.s). The power draw at the rotor is also shown in Figure 2 in the log plot. The increase in power draw corresponding to an increase in viscosity of oil was not high.

DISCUSSION

It has been reported in the literature that when the angular speed reaches a critical value, ω_{crit} secondary flow will develop. The secondary flow is periodic in axial direction and gets superimposed on the tangential flow. Toroidal vortices named *Taylor vortices* will form. When the angular velocity is increased further travelling waves form and then the turbulent regime is reached. The Rayleigh regime (Taylor, 1923), doubly periodic flow regimes, etc have been developed for a single fluid. The system under consideration has two components, that is, oil and water. The Taylor vortex flow, Rayleigh flow regimes can be avoided during the operation of the centrifuge. By running the centrifuge shallow or deep the velocity can be kept close to the laminar regime.

The requirements for layer formation are not clear. The transition from a drop regime to a layer regime can be expected to depend on the surface tension of the oil and water. The Marangoni instability (Coles, 1965) may also be an issue. The centrifuge may be the solution to high volume oil and water mixtures that needs to be separated.

Conclusion

A computer solution procedure was developed to evaluate centrifugal separation of oil and water. At high volumes, oil rich and water rich layers may be expected to form. Expressions for the interlayer thickness ratio, α

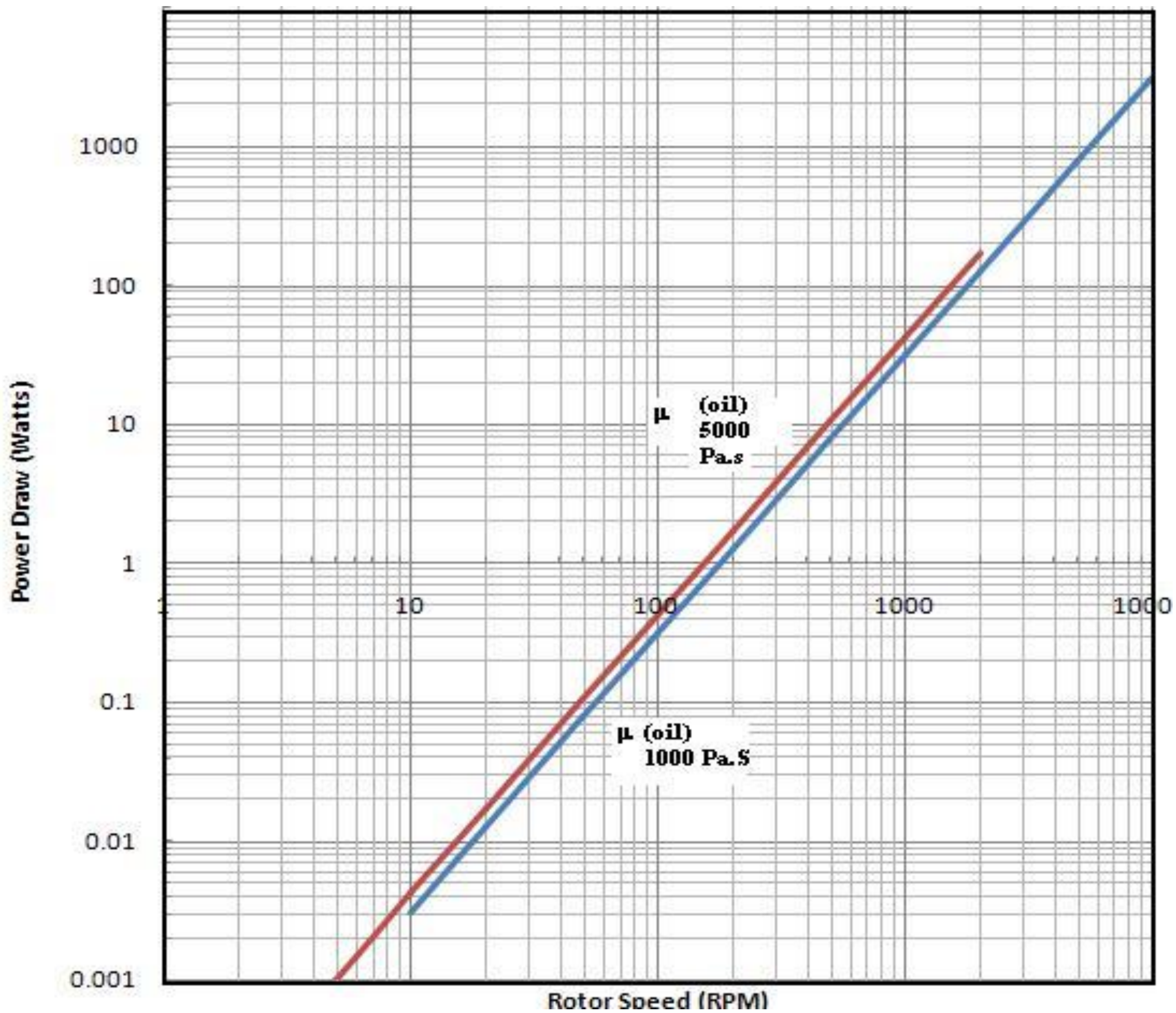

Figure 2. Power draw as a function of rotor speed for $\kappa = 0.74$.

was developed from component material balance on the inlet and outlet streams of the continuous centrifuge. The equations of motion and continuity for the tangential velocity, v_θ were derived for the oil rich and water rich layers. The water is recovered from the outlet at the periphery of the centrifugal bowl that is held stationary and the oil is recovered from the inner rotor that is rotating. The four integration constants in the velocity profile are solved for by use of the MINVERSE operation in Microsoft Excel for Windows 2007. For each RPM and set of parameters the power drawn at the rotor is calculated. The power draw would to be linear with the angular speed of the rotor on a log-log plot. When the density ratios of the two fluid streams, γ approach 1 this method may not be efficient. In a similar manner when the feed contains only small quantity of oil other methods such as molecular sieve adsorption may be considered. Centrifugal separation of high volume oil and water may be designed using the methods shown in this study.

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Nomenclature: α**,** Ratio of the interface radius with the centrifugal bowl radius; α**R,** radius of the interface of oil and water; **c_1, c_2, c_3, c_4,** integration constants in tangential velocity profile; **density ratio,** $\gamma = \frac{\rho_{oil}}{\rho_{water}}$;

H, height of centrifuge (m); κ**,** ratio of inner rotor radius with the centrifugal bowl radius; κ**R,** radius of the inner rotor (m); μ_{oil}**,** viscosity of oil (Pa.S); μ_{water}**,** viscosity of water (Pa.s); **P,** power draw at rotor (watts); **r,** radial distance; **R,** radius of the centrifugal bowl (m); ρ_{oil}**,** density of oil (kg.m^{-3}); ρ_{water}**,** density of water (kg.m^{-3}); $\tau_{r\theta}$**,** tangential shear stress (N.m^{-2}); **T,** torque (N.m.s^{-1}); θ**,** residence time of fluid in centrifuge (h); v_{θ}**,** tangential velocity of fluid (m/s); v_{rot}**,** volumetric flow rate of fluid out through the rotor (m^{3}.h^{-1}); v_{per}**,** volumetric flow rate of fluid through the periphery (m^{3}.h^{-1}); v_{1} volumetric flow rate of fluid into the centrifuge (m^{3}.h^{-1}); **V,** volume of centrifuge (m^{3}) ω**,** angular speed of rotor (rad.s^{-1}); x_{F}**,** weight fraction of oil in feed; x_{per}**,** weight fraction of oil in outlet stream through periphery; x_{rot}**,** weight fraction of oil in outlet stream through inner rotor.

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