THE EFFECT OF OIL-IN-WATER EMULSION ON HEAT EXCHANGER PERFORMANCE

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ABSTRACT

Oil spills throughout the world where there is an oil production or any oil use activities have raised concern that oil-in-water emulsion may become entrained in sea water used for cooling purposes of heat transfer equipment which work in sea or near by the coast. This paper reviews the findings of an investigation on the effects of fresh oil-in-water emulsion as well as weathered oil-in-water emulsion on water cooled heat exchanger performance. The overall heat transfer coefficient, fouling resistance, percent of oil deposits, oil particulate thickness through the heat exchanger tubes were measured and were shown to be strongly dependent on cooling water velocity, properties of oil and oil concentration in the oil-in-water emulsion. Oil particulate which already has established on the tubes surfaces acts as a bridge and so promote the growth of the deposits on the tubes surfaces as the working time increases. Also it is interesting to note that the fouling initiation period for the tubes surfaces to be fouled occurs in order of minute or even seconds. The effects of fresh oil-in-water emulsion on heat exchanger performance is likely to be serious, however, weathered oil-in-water emulsion effects could be much more severe. If the effect of oil-in-water emulsion on the heat exchanger performance is to be minimized, high cooling water velocities should be maintained, however, still a small oil film thickness can considerably affect the overall heat transfer coefficient.

Keywords: Heat exchanger performance, Oil-in-water emulsion.

INTRODUCTION

Following the input of oil spill into a marine environment, oil spill can undergo a number of compositional changes after a certain period of time such as evaporation, dispersion and emulsification. Clarke [1], studied the transformation that occur after oil is discharged into marine environment. He estimated that some days after an oil spill with an initial volume of 100 units would have lost about 25 units to the atmosphere depending on the weathering conditions, 30 units floating on the sea surface and 40 units dispersed in the water column, in addition the last two percentage transformed finally to an oil-in-

water emulsion. Others have estimated that about 10-30 percent of oil in sea water remains as a tar balls up to a year after discharge [2]. Once the oil spill input to the sea water surface and due to the weathering condition and the contact with the atmosphere oil-in-water emulsion can be presented naturally. Wherever bulk phases of fluid oil and water as a continuos phase are brought into contact in the top of water free surface or subjected to relative motion between the phases, an oil-in water emulsion will result. The degree of dispersion for a particular oil is governed by the intensity and scale of instabilities at the oil-water interface. Local velocity differences

(shear flows) distort the interface and pull the oil out into ligaments. These are unstable and break into segments, which, as a consequence of interfacial tension, adopt a shape with the minimum surface area to form spherical droplets. Further break-up occurs at any point where high turbulence shear flows are experienced. The range of the mean droplet diameter, found in practical situations, span in the order of magnitude from 10 to 1000 μm. Also oil-in-water emulsion can also be released as a results of the presence of bends, valves and pumps work in the presence of oil spill all generate high intensity, small scale turbulence and so bring about oil droplet disintegration. Several workers have examined the break-up of oil in pumps handling seawater contaminated with oil in order to select the least oil dispersive pumps [3]. In general terms, it has been found that positive displacement pumps are the least oil disperse and are preferred to centrifugal pumps in dealing with sea water polluted with oil spill. Cormack *et al.* [4], have reported that, for water polluted with low viscosity oils, a minimum droplet size is reached at even very low shear rate, also droplet size for low viscosity oils to be independent of handling pump type. The formation of oil-in-water emulsion on the cooling water has raised the concern that it may become entrained in the heat transfer equipment which are working either in sea or near by the coast. In these cases, the components which could be highly contaminated and affected by the oil-in-water emulsion are the heat exchangers. This oil-in-water emulsion is expected to interfere with the heat transfer process and can cause a major reduction of the efficiency and the capacity of the heating system. As energy and material costs have increased over the past several years, there has been additional attention devoted to cooling water fouling, its cause and its control. In the past twenty years, fundamental research on cooling water fouling has increased significantly, so that more reliable design criteria may be available to the heat exchanger designer. In their study of

paraffin deposition, Jessen and Howell [5] concluded that in laminar flow, the estimated deposition increased with the flowrate, reaching a maximum prior to transition to turbulent flow and then decreasing with increasing turbulence. The recent work [6,7] reported earlier confirms these observations, namely that as Reynolds number is increased the equilibrium thickness of the deposit is decreased. The deposition removal mechanism will also be a function of the flow rate. Toyama [8] and Tamaki [9] conducted experiments on the process of oil deposit and removal from cooling water contaminated with oil on heat transfer tubes. Under the experimental conditions, they found that the extent of which oil adheres to the heat transfer tubes varies depending upon the material of the tube and the properties of the oil. Jorda [10] concluded that the amount of deposit on the heat transfer surface increased with increased surface roughness. Patton and Casad [11] performed similar studies and concluded that the adhesion bond at a surface should be proportional to the total contact area and therefore related to surface roughness. Taborek *et al.*[12] stated that the tubes material and structure effect will be connected mostly with the initiation of fouling, as once the surface is covered with fouling deposit, the original tubes surface will have diminishing influence after a certain period of time. They also observed that catalytic action of some tubes materials may also promote or delay fouling process, especially the initiation period. It is to be expected that the concentration of the foulant in the flow will influence the foulant deposition thickness. Bott and Gudmundsson [7] demonstrated that as the concentration of the foulant increases the deposit thickness increases for the given flow rate. Thomas and Grigull [13] suggested that the presence of the deposited foulant on the tubes surface could reduce the surface roughness making the surface more hydrodynamically smooth. Under this smooth condition, the laminar sub-layer would be thicker for a given flow rate, and would increase the resistance to the mass

transfer of the foulant towards the surface with an attendant reduction in the particulate deposition rate. Melo and Pinherio [14], concluded that foulant adhesion is the controlling process, and that the adhesion process is more effective in the formation of deposits on the tubes surfaces than foulant concentration. Hopkins and Epstein [15], noted that the foulant deposit decreased as the heat flux was raised. At extremely high heat fluxes little deposit was observed. Their research also suggested that the effect of this high flux could have held the foulant off the surface. Nichols and Parker [16] indicate that oil contamination could reduce power plant output by as much as 15 percent. In their report, no attempt was made to correlate oil concentrations with reduction in power production.

It is of interest to notice that most of the efforts up to date have been devoted to the asymptotic behavior cases, probably that they are more frequent, while very little attention has been given to investigation of the behavior and effect of the cooling water contaminated with oil or oil-in-water emulsion on the heat transfer equipment, despite its wide importance in many specific industrial areas. Unfortunately despite the significant oil spills which have occurred daily around the world, little good quantitative data are available from facilities which have been impacted by these spills. As explained above oil spilt at a water surface can interfere and entrain a significant amounts of water, creating an oil-in-water emulsion. The objective of the present work is to study the adverse effects and impacts on a full scale heat exchanger performance which use cooling water contaminated with oil-in-water emulsion. The effect of varying the cooling water velocity as well as the hot water velocity on the overall heat transfer coefficient, fouling resistance and foulant mass deposition on the tubes surface was investigated. It is intended in the present work to determine the concentration and the properties of oil in the oil-in-water emulsion which would result in problems in vital heat and mass

transfer processes. So, a wide range of fresh oil viscosity and oil concentration are employed. The overall heat transfer coefficient, fouling resistance, and mass deposition through the heat exchanger tube surfaces were measured for oil-in-water emulsion prepared from fresh oil as well as weathered oil. After that the variation of the overall heat transfer coefficient and the fouling resistance with the working time was investigated.

BASIC CONCEPTS AND ANALYSIS

In the light of the preceding remarks, it is obvious that the processes controlling the foulant build-up in heat exchanger tubes can be divided into two distinct groups: foulant deposition rate and foulant removal rate. In addition, the fouling factor value is a function of many factors which belongs to the source of the cooling water and characteristics of the heat exchanger (velocity and temperature of fluids) and the configuration of surfaces of heat transfer. Two things must occur before a foulant in a fluid deposits on a surface to become part of foulant layer. First the foulant has to be transported to the surface by the momentum possessed by the foulant. Having arrived to the surface the foulant must stick if it is to be regarded as part of the foulant layer residing on the surface. In terms of the rate of deposition ϕ_d which can be defined by:

$$\phi_d = k_d\, c_f \qquad (1)$$

where k_d is the deposition coefficient, c_f is the foulant concentration in the flowing fluid. Under these circumstances when some of the foulant that arrive at the surface fail to stick and return to the bulk flow, the term " sticking probability" is sometimes applied, and the deposition rate can be defined by:

$$\phi_d = P\, k_d\, c_f \qquad (2)$$

where P is the sticking probability. The sticking probability will have a value less than unity and its magnitude will depend on

the conditions associated with the flowing fluid, the nature of the foulant and character of the surface [17]. The removal of the deposit from the heat exchanger tubes may or may not begin right after deposition has started. That it does so is an assumption implicit in the removal model originally proposed by Kern and Seaton [18] and further developed by Taborek *et al.*. [12], as given by the general relation :

$$\phi_r = c\, \tau_s\, m\, /\, R_b \tag{3}$$

that is, the removal rate of deposit is directly proportional to both the mass of deposit m and the shear stress τ_s on the heat transfer surface, and inversely proportional to the deposit bond resistance and strength R_b.

The heat transferred is obtained from a heat balance between the two fluids flowing through the heat exchanger. By estimating the temperature driving force between the two fluids, it is possible to estimate the overall fouling resistance as follow:

$$Q_f = U_f\, A\, (\Delta T_m)_f$$

$$\text{or}\quad 1/U_f = A\, (\Delta T_m)_f \quad /Q_f \tag{4}$$

If the initial overall heat transfer obtained from experiments, i.e. when the surfaces area are clean is measured to represent U_c from the following by:

$$1/U_c = A\, (\Delta T_m)_c/Q_c \tag{5}$$

when subtracting (5) from (4), then the total fouling factor, R_f can be determined from the following relation:

$$R_f = 1/U_f - 1/U_c \tag{6}$$

To estimate the amount of foulant deposit that had accumulated on the inside surface of heat exchanger tubes, may be made as follow:

$$V_f = \pi\, d_i\, l\, x_f$$

where d_i and l are the inner diameter and

length of the heat exchanger tube respectively and x_f is the foulant deposit mean thickness, and so :

$$x_f = V_f\, /\, \pi\, d_i\, l \tag{7}$$

and from a knowledge of the thermal conductivity of the foulant λ, it is possible to estimate again and directly the fouling resistance R_f using the following equation:

$$R_f = x_f\, /\, \lambda_f \tag{8}$$

EXPERIMENTAL APPARATUS AND PROCEDURES

A schematic flow diagram of the experimental apparatus with the artificial oil-in-water emulsion contamination cooling water system is shown in Figure 1. The aim of the laboratory technique is to simulate the conditions that are likely to occur in a heat exchanger, particularly in terms of velocity, temperature, foulant type and concentration. The test rig has been built, which was mainly consisted of two circulating water circuits, a pressurized shell and tube heat exchanger capable of simulating the process of heat and mass transport inside the tubes of the heat exchanger. The first water circuit was an open loop in which cooling water is pumped from a storage tank to the heat exchanger. The inlet cooling water velocity to the heat exchanger is controlled using six valves fixed at the side of the storage cooling water tank. In addition a cooling water by-pass is employed between the heat exchanger and the storage cooling water tank to obtain a wider range of the inlet cooling water velocity. Through an opening at the top side of the storage cooling water tank oil with different quantities and viscosities can be supplied as a contaminant. After that the added oil is thoroughly blended with the raw cooling water and as a result of the high turbulence shear flows experienced on both the oil and raw cooling water they were finally converted to an oil-in-water emulsion. The high turbulence shear is applied using a stirrer fixed at the inside

1. Heat exchanger
2. Cooling water sample tap
3. Inlet hot water thermometer
4. Hot water flow orifice meter
5. Temperature controller
6. Hot water circulating tank
7. U-tube manometer
8. Outlet hot water thermometer
9. Electric preheater water tank
10. Inlet cooling water sample tap
11. Inlet cooling water thermometer
12. Outlet cooling water thermometer
13. Outlet cooling water sample tap
14. Hot water circulating pump
15. Cooling water by-pass
16. Cooling water tank opening
17. Cooling water tank
18. Pully, 19. Belt
20. Electric motor
21. Stirrer
22. Cooling water tank drain
23. Cooling water control valve
24. Cooling water drain
25. U-tube manometer
26. Cooling water flow orifice meter
27. Cooling water circulating pump

Figure 1 A schematic flow diagram of the experimental apparatus

side of the cooling water storage tank, the fan is driven by an electric motor through two pulleys and V-belt. Different oil to water concentration ranging from 0.24 % to 0.95 % by volume are employed in the present study. The oil-in-water emulsion is then fed to the heat exchanger inlet port under pressure using a circulating cooling water pump. The kinematic viscosity for each employed oil in centistoke was measured directly using an Ubbelohde viscometer type. The method used is in accordance with ASTM standards. The hot water is prepared in a large capacity preheater water storage tank equipped with four electric heating elements of totally 6 kW heating effect. The water temperature is raised to about 65-75°C in the preheater and then fed to another smaller hot water circulating tank equipped with temperature controller to select the required inlet hot water temperature to the heat exchanger. The hot water with the selected temperature is then passed to the heat exchanger using a hot water circulating pump. The heat exchanger employed for the present work is basically a pressurized shell and tube heat exchanger. It consists of two tube passes with 35 tubes in each pass. The tubes are made of copper with inner and outer diameters of 8 mm and 10 mm respectively. The hot water flowing outside the tubes in the shell is routed back and forth by means of 29 baffles. The shell is fabricated from steel with inner and outer diameter of 15 cm and 17 cm respectively with overall length of 113 cm and is thermally insulated completely. The measurements of the cooling water and hot water velocities are performed by two orifice meters and compared by measuring the flow rate using a standard rotameter, and the temperature measurements at the inlet and outlet of the heat exchanger for each water circuit are measured with four thermometers, especially made for the heat exchanger used. A 100 ml sample from the cooling water contaminated with the oil-in-water emulsion is taken at the inlet and outlet ports of the heat exchanger, so to evaluate the amount of deposit on the heat exchanger tube surface. Each sample is

then fed to the oil separation unit which consists of oil separatory funnel, where the oil is removed from each sample using an oil filter paper located inside the separatory funnel. The filtrated oil with the filter paper is then weighed for each sample using a digital balance and by subtracting both weights, the amount of the foulant deposited inside the heat exchanger tubes can be calculated. This procedure is performed for each set of experiments.

RESULTS AND DISCUSSION

Tests were performed with oil-in-water emulsion artificially prepared from blending fresh oil with the cooling water. The fresh oil was selected with a wide range of viscosity in these early experiments because, to a great extent, it simulates in composition and behavior of the oil likely to be found in the sea water field. The basic way to measure the fouling resistance is to use the so called "clean conditions" to relate the overall heat transfer coefficient when the heat exchanger is fouled to that when it is clean. So, the overall clean heat transfer coefficient U_c is measured firstly and plotted against different inlet cooling water velocity and inlet hot water velocity, Figure 2, to compare it with the fouled value U_f.
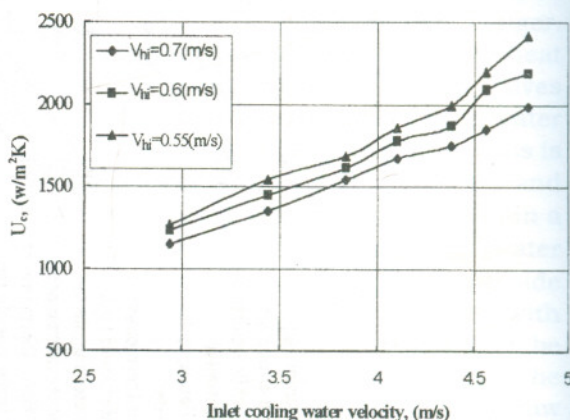

Figure 2 Relationship between clean overall heat transfer coefficient and inlet cooling water velocity.

Figure 3 shows the relationship between the overall fouled heat transfer coefficient versus inlet cooled water velocity when the

cooling water is converted to an oil-in-water emulsion with oil concentration of 0.48%. The working time was kept constant at 3 minutes. It is clear that increasing the inlet cooling water velocity increases the overall heat transfer coefficient U_f. The same figure also shows that the overall fouled heat transfer coefficient U_f increases by decreasing the inlet hot water velocity. The effect of the inlet cooling water velocity on the fouling resistance in the presence of oil-in-water with oil concentration of 0.48% and for different inlet hot water velocity is shown in Figure 4.
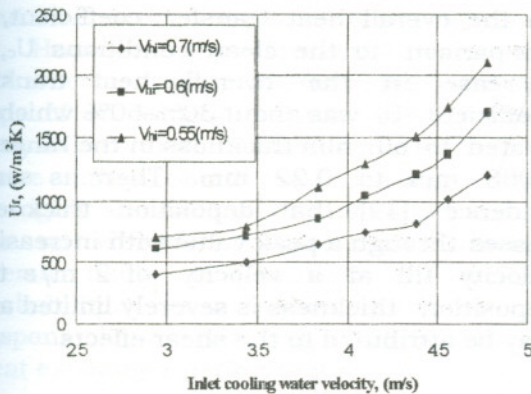
Figure 3 The effect of inlet cooling water velocity on the overall heat transfer coefficient with oil concentration 0.48%.
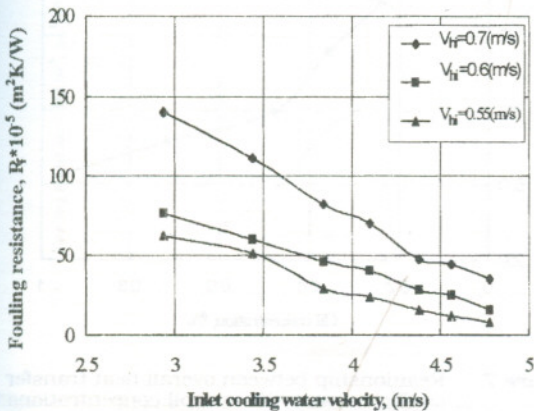
Figure 4 Relationship between fouling resistance and inlet cooling water velocity with oil concentration 0.48%.

Of a particular interest is the decrease of the fouling resistance as the inlet cooling water

velocity increases and also as the inlet hot water velocity decreases. Figure 5 gives the results of the percent of oil deposited in the heat exchanger versus the inlet cooling water velocity for oil concentration of 0.48%. Figure 6 illustrates the variation of the oil film thickness deposited on the inner surface of the heat exchanger tubes for different inlet cooling water and hot water velocities. It can be seen that as the inlet cooling water velocity increases, the percent of oil deposited in the heat exchanger as well as the oil film thickness deposited on the inner surface of the tubes decrease.

It was seen from previous studies that the cooling water velocity has a considerable effect on the fouling rate and behavior for each particular fouling which have been identified as precipitation fouling, particulate fouling and biological fouling. In the present study in the new area of fouling due to the contamination of cooling water with oil-in-water emulsion, experimental results have confirmed this, as shown in Figures 3 to 6. The results indicate that oil deposition rate should be approximately constant under fixed cooling water flow conditions, but that the removal rate increases with increasing the flow velocity leading to falling rate mode of oil deposit as well as oil film thickness as shown in Figures 5 and 6.
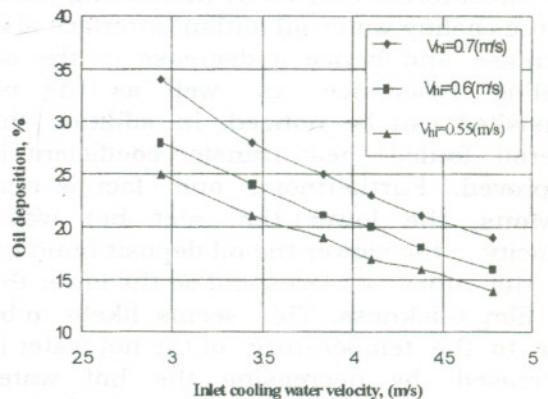

Figure 5 The effect of inlet cooling water velocity on oil deposits at tube surfaces with oil concentration 0.48%.
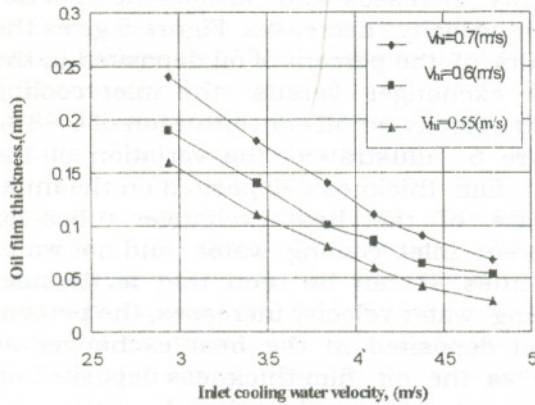
Figure 6 Relationship between oil film thickness and inlet cooling water velocity with oil concentration 0.48%.

The explanation for the effects of cooling water velocity on the oil deposited on the tubes inner surface and consequently on the overall heat transfer, is that at low velocities the resistance to mass transfer of oil to tubes surface is low and so a greater oil film thickness can be sustained on the tubes surfaces. As the velocity is gradually increased, the oil removability rate is increased, especially after the oil deposit has already built up on the surface. As the velocity is further increased, although the greater turbulence will provide increased mass transfer of oil to the tubes surfaces, the shear forces exerted by the cooling water at the cooling water-oil foulant interface also increase and hence a decrease in the oil fouling resistance as well as the oil deposited can be noticed. In addition, the overall fouled heat transfer coefficient is improved. Furthermore, one fact is also obvious, the lower the inlet hot water velocity the slower the oil deposit build up on the tubes surfaces and so the lower the oil film thickness. This seems likely to be due to the temperature of the hot water is increased by decreasing the hot water velocity and as a result of that the foulant viscosity as well as the adhesion forces between the foulant and the tubes surfaces are decreased. This causes the temperature driving potential through the tubes wall to increase and consequently increases the overall heat transfer coefficient. Even though with the oil as foulant, the oil film thickness appears to be small in magnitude, and can considerably affect the overall heat transfer coefficient no matter operating at low or high cooling water velocity and this is due to the very low thermal conductivity of oil unlike other foulants which are relatively high, especially when the oil is converted to an oil-in-water emulsion as the previous studies in the literature proved that once the oil is converted to oil-in-water emulsion its viscosity is highly increased. The results in this section clearly demonstrated the pronounced effect of the oil film thickness on the overall heat transfer coefficient, in comparison to the clean conditions U_c, a decrease in the overall heat transfer coefficient U_f was about 30%-60% which is related to oil film thickness in the range of 0.068 mm to 0.22 mm. There is some evidence [19] that deposition thickness passes through a peak value with increasing velocity till at a velocity of 2 m/s the deposition thickness is severely limited and may be attributed to the shear effects.
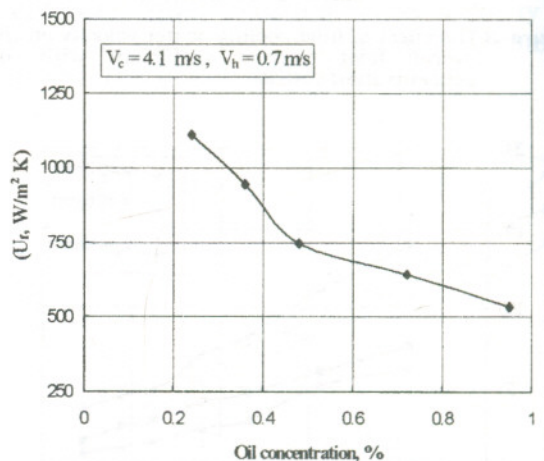

Figure 7 Relationship between overall heat transfer coefficient and different oil concentrations.

Figure 7 illustrates the effect of varying the oil concentration on the oil-in-water emulsion on the overall fouled heat transfer coefficient for cooling and hot water velocities of 4.1 m/s and 0.7 m/s respectively. The overall fouled heat transfer

coefficient markedly decreases by increasing the oil concentration. The overall fouled heat transfer coefficient U_f is decreased by about 50% when the oil concentration is increased from 0.24% to 0.95%. Figure 8 shows that the fouling resistance increases as the oil concentration is increased. The pronounce effect of the oil concentration on the percent of oil deposit and on the oil film thickness respectively is shown in Figures 9 and 10. These curves indicate that the oil deposit as well as the oil film thickness increases by raising the oil concentration. This seems to be due to that the oil deposited on the tubes surfaces is directly proportional to the foulant concentration according to Equation. 1. However, the foulant concentration influence is highly greater in this particular type of oil fouling because the oil sticking probability to the tubes surfaces is high. Since in Equation 2, the sticking probability is highly dependent on the foulant nature, the oil viscosity, cohesion and adhesion seems likely to increase the sticking probability. This seems likely to be responsible of reducing significantly the heat exchanger performance.

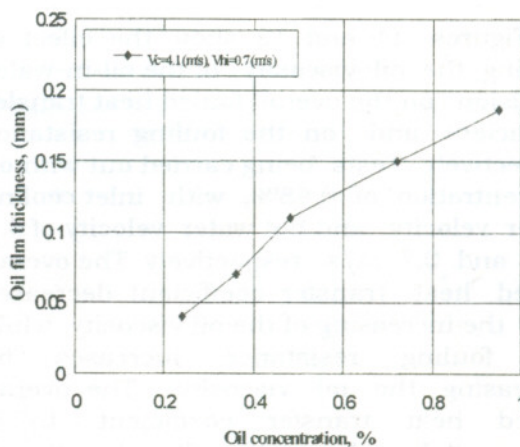**Figure 9** Relationship between oil deposit on the tubes surfaces and different oil concentration.

Figure 10 Relationship between oil film thickness on the tubes surfaces and different oil concentrations.
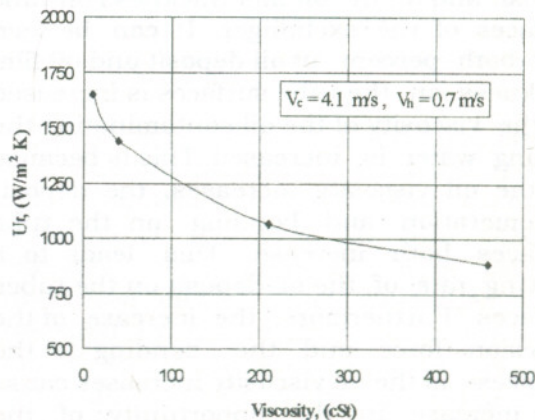

Figure 8 Relationship between fouling resistance and different oil concentration.

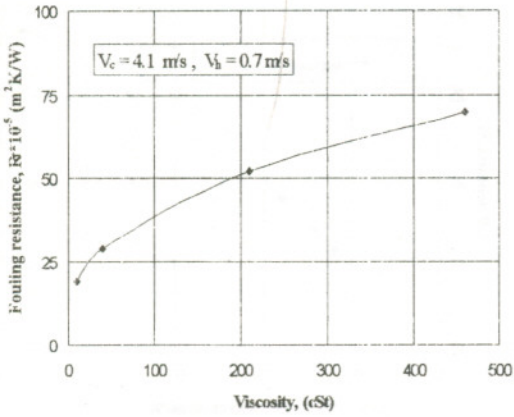**Figure 11** Relationship between overall heat transfer coefficient and oil-in-water emulsion viscosity.

Figure 12 Relationship between fouling resistance and oil-in-water emulsion viscosity.

Figures 11 and 12 show the effect of varying the oil viscosity of the oil-in-water emulsion on the overall fouled heat transfer coefficient and on the fouling resistance respectively. Tests being carried out with oil concentration of 0.48%, with inlet cooling water velocity and hot water velocity of 4.1 m/s and 0.7 m/s respectively. The overall fouled heat transfer coefficient decreases with the increasing of the oil viscosity, while the fouling resistance increases by increasing the oil viscosity. The overall fouled heat transfer coefficient U_f is decreased by about 31%-63% when the oil viscosity increases from 10 cSt to 460 cSt. Figures 13 and 14 illustrate the effect of oil viscosity variation on the percent of oil deposit and on the oil film thickness on tube surfaces of the exchanger. It can be seen that both percent of oil deposit and oil film thickness on the tube surfaces is increased as the viscosity of the oil contaminating the cooling water is increased. This is because as the oil viscosity increases, the deposit agglomeration and bonding on the tube surfaces both increase. This leads to a growing rate of the oil deposit on the tubes surfaces. Furthermore, the increase of the adhesion force and the bonding to the surfaces as the oil viscosity increases cause an increase in the opportunity of the counteract for the tendency of the oil deposited to re-entrainment to the bulk of the cooling water. This is because the drag

force inside the oil deposits increases against the cooling water shear stress imposed on that deposits as the oil viscosity increases.
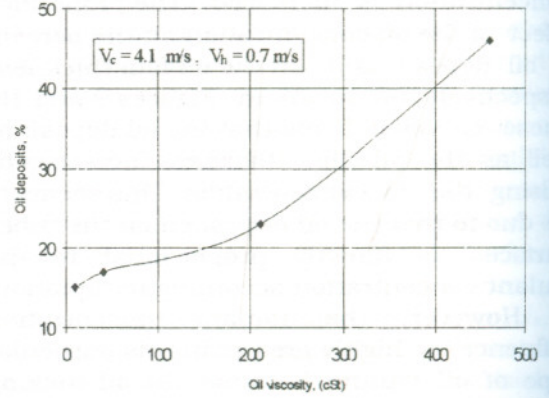

Figure 13 Relationship between percentage of oil deposits on the tube surfaces and oil-in-water emulsion viscosity.
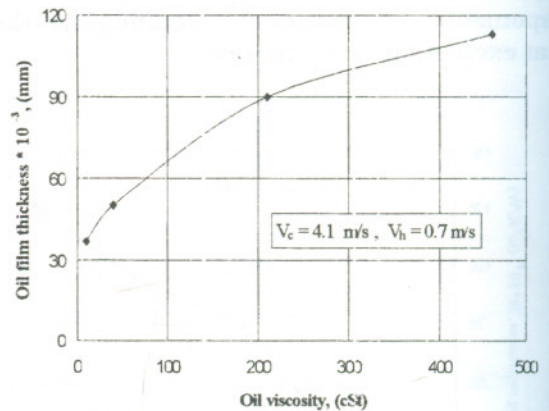

Figure 14 Relationship between oil film thickness deposited in the tubes of H.E. and oil viscosity.

Figures 15 and 16 provide a picture of the variation of the overall fouled heat transfer coefficient and the related fouling resistance with the working time. Attached figures clearly indicate that the overall fouled heat transfer coefficient sharply decreases and the fouling resistance sharply increases as the working time increases. The percent decrease in the overall fouled heat

transfer coefficient is about 50% and the percent increase of fouling resistance is about 80% after about 30 minutes of working time. It is also interesting to notice that with this particular type of fouling, the initiation period for the heat exchangers tubes surfaces to be fouled with the oil deposits is found to be so short and the fouling process begins as soon as the cooling water contaminated with oil-in-water emulsion flows through the heat exchanger tubes. In comparison to most other types of fouling in which initiation periods takes weeks or months to occur [20], the fouling initiation period in the present study occurs in a minute or even seconds. Furthermore, in general terms the phenomenon of fouling represents the interaction between the oil as a foulant and the heat exchanger tube surfaces. In the initiation of the fouling process, the interaction is between the tube surfaces and the foulant. Subsequently, as the working time increases, the oil deposit thickens, the interaction is then between the oil foulant that has already accumulated on the tube surfaces and the fresh oil foulant that arrives with the cooling water. It is important to stress that, as the oil deposition process continues the interfacial forces must change, as the original surfaces become contaminated with the oil deposit. In this situation, tube surfaces roughness is important during the initiation of the fouling process, after that becomes of a minor importance during the building up of substantial oil deposits. The fouling process is then controlled by the accumulated oil deposits on the tube surfaces which work as a bridge which in the particular case of fouling serve to bring and attract the oil deposits and provide the basis for the contact. The oil deposition and the adhesion forces are enhanced due to the availability of oil layer which is already established on the tube surfaces with a large contact area. With regards to Equation 3 since the removal rate of the foulant was classified in terms of cooling water shear stress and the foulant bond resistance which remains constant as the cooling velocity is also constant, so the removal rate remains nearly constant.

However, the continuos flowing of cooling water with the working time increases the oil foulant that arrived to the tube surfaces and so the oil deposits continue to increase with the working time.
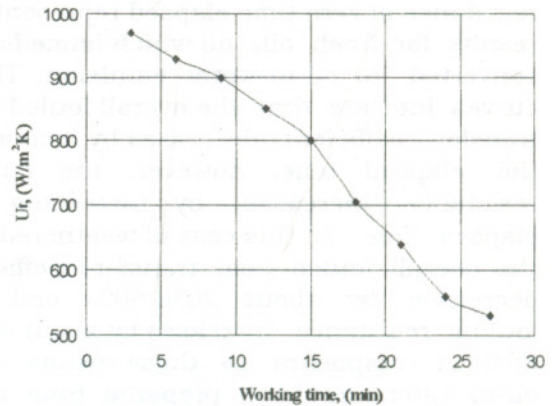

Figure 15 Relationship between overall heat transfer coefficient and working time.
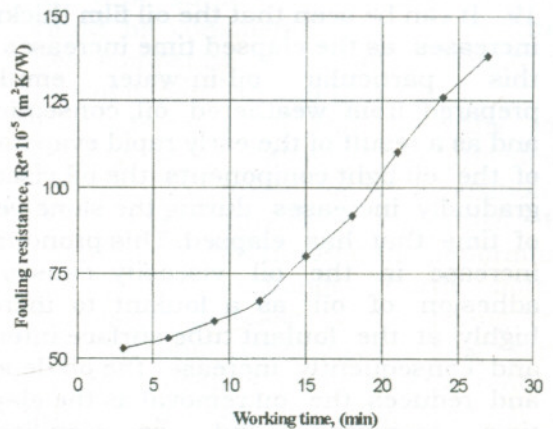

Figure 16 Relationship between fouling resistance and working time.

This section describes and discusses the experimental results of the effect of oil-in-water emulsion on the heat exchanger performance. However, in this case the emulsion was prepared from blending weathered oil with water. Weathered oil was prepared by placing fresh oil layers on the top of water surface for different periods of time up to 672 hours in ambient air temperature to simulate water surface environment when contaminated with oil.

Figures 17 and 18 show the overall fouled heat transfer coefficient and the related fouling resistance versus the elapsed time after the oil being placed on the water surface. In these curves the overall fouled heat transfer coefficient and fouling resistance at zero time elapsed represent the results for fresh oil, oil which immediately converted to oil-in-water emulsion. These curves indicate that the overall fouled heat transfer coefficient decreases by increasing the elapsed time, however, the fouling resistance increases by increasing the elapsed time. In this case of weathered oil , the overall fouled heat transfer coefficient decreases by about 20%-40% and the fouling resistance increases by about 45%-85% in comparison to those results of the oil-in-water emulsion prepared from fresh oil. The effect of the elapsed time on the oil film thickness deposited on the heat exchanger tube surfaces is given in Figure 19. It can be seen that the oil film thickness increases as the elapsed time increases. For this particular oil-in-water emulsion prepared from weathered oil, consequently and as a result of the early rapid evaporation of the oil light components, the oil viscosity gradually increases during the same period of time that has elapsed. This pronounced increase in the oil viscosity causes the adhesion of oil as a foulant to increase highly at the foulant tube surface interface and consequently increase the oil deposits and reduces the oil removal as the elapsed time increases, and so significantly deteriorates the heat exchanger performance.

The experimental results of the overall fouled heat transfer coefficient U_f, the fouling resistance R_f and the percent of oil deposit on the tube surfaces of the heat exchanger D are condensed and summarized by fitting it to three correlations. The three correlations describe U_f, R_f and D as a function of the inlet cooling water velocity V_c, the inlet hot water velocity V_{hi}, the oil concentration C and oil viscosity v. The best correlations which predict U_f, R_f and D take the following forms respectively:

$$U_f=86.1(V_c)^{2.68}\ln\{(V_{hi})^{-1.1}\ (C)^{-0.5}\}(v)^{-0.24} \quad (9)$$

$$R_f = 0.013\ (V_c)^{-2.69}(V_{hi})^{4.67}\ln\{(v)^{3.69}(C)^{9.68}\} \quad (10)$$

$$D=22.18(V_c)^{-1.98}\ (V_{hi})^{0.95}\ln\{(v)^{6.18}\ (C)^{14.86}\} \quad (11)$$

Comparison between the experimental results and the analytically predicted U_f, R_f and D are plotted in Figures 20, 21 and 22. The uncertainty associated with the results using these correlations is of the order of ±8 %.
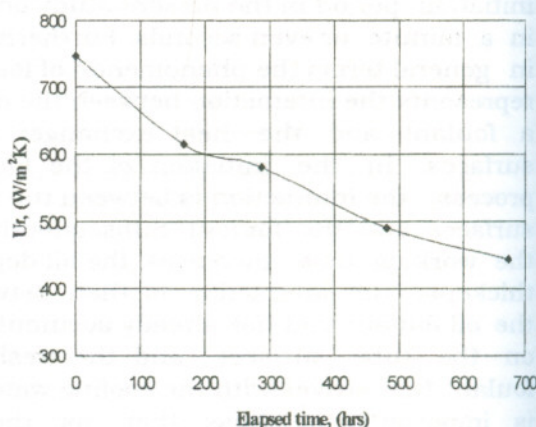

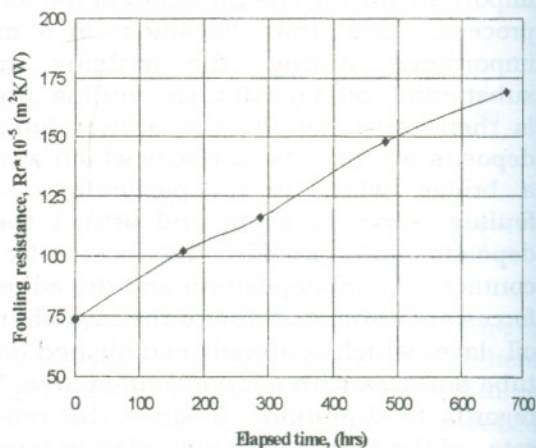Figure 17 Relationship between overall heat transfer coefficient and elapsed time for oil on water surface.

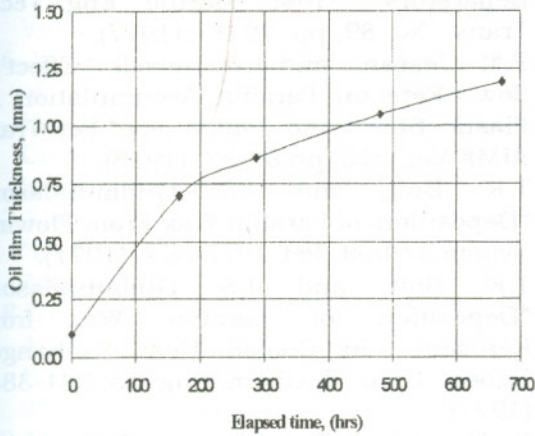Figure 18 Relationship between fouling resistance and elapsed time of oil on the water surface.

Figure 19 The effect of elapsed time for oil on water surface on the oil film thickness on the tube surfaces.
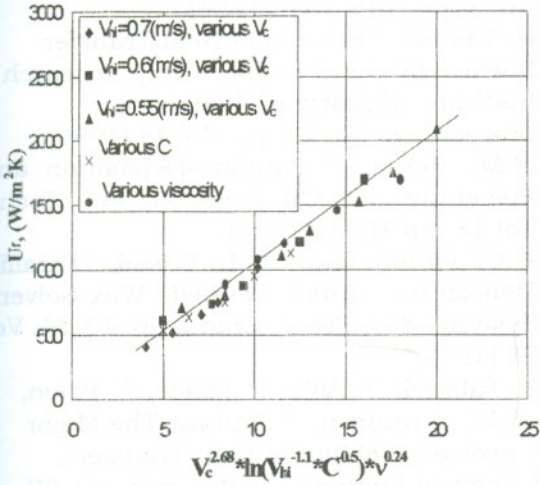

Figure 20 Correlation of overall heat transfer against the various studied parameters.
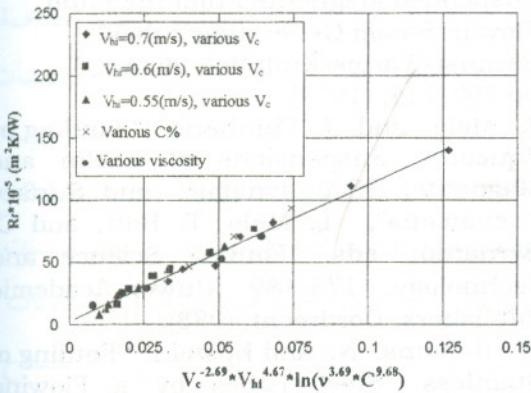

Figure 21 Correlation of fouling resistance against the various studied parameters.
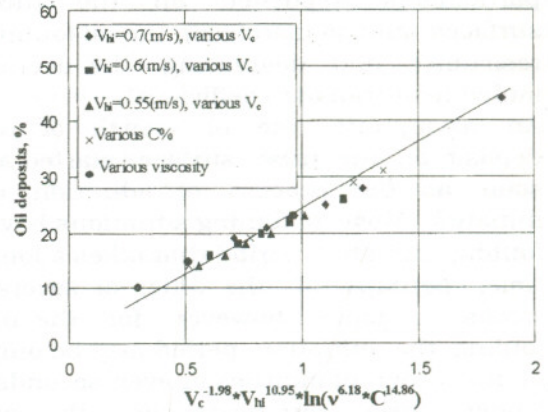

Figure 22 Correlation of percentage of oil deposits at the H.E. tube surfaces against the various studied parameters.

CONCLUSIONS

The following conclusions can be drawn from the previous study:

1. The net accumulation of oil deposit on the tube surfaces of the heat exchanger could be considered to be the results of two competing phenomena, namely the rate of deposition and removal

2. The decrease of the operating inlet cooling water velocity has provided a greater opportunity for oil deposition on the tube surfaces and also has significantly deteriorated the performance of the heat exchanger. Furthermore, a successive increase in the cooling water velocity, and hence viscous drag exerted by the cooling water stream tends to remove the oil deposition which has already established on the tube surfaces and so improving the heat exchanger performance to a certain extent. However, even a small oil film thickness on the tube surfaces, still considerably affect the overall fouled heat transfer coefficient.

3. The combined effect of reduced hot fluid velocity and increased hot fluid temperature resulted in decreases in the fouling resistance and oil film thickness

4. It was concluded that oil particulates generally adhere to heat transfer tubes, the extent of which varies depending upon the oil concentration and properties of oil such as viscosity. Oil viscosity greatly influences the amount of oil

particulates deposited on the tube surfaces and so increasing the oil fouling resistance and decreasing the overall fouled heat transfer coefficient.

5. An asymptotic rate of growth of oil deposit on the tube surfaces started as soon as the process of adhesion is initiated. Most of fouling situations have fouling initiation period that takes a long time, perhaps of the order of several weeks or more, however, for the oil fouling the initiation period may be only of the order of minutes or even seconds. Under these circumstances, the oil fouling found to be a severe fouling problem in deteriorating the heat exchanger performance due to the rapid initiation period. The overall fouled heat transfer coefficient was reduced by 50% of the original clean condition in 30 minutes working time.

6. The effect of the weathered oil-in-water emulsion was significantly higher on the heat exchanger performance with a serious detrimental effects compared to the effect of the fresh oil-in-water emulsion. In this case of weathered oil-in-water emulsion, the overall fouled heat transfer coefficient decreases by about 20%-40% less in comparison to those results of fresh oil-in-water emulsion and particulates deposited on the tubes surfaces of the heat exchanger were observed to be considerably harder to remove.

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تأثير مستحلب الزيوت فى مياة التبريد على اداء المبادلات الحرارية

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ملخص البحث

نتيجة للكم الضخم المتاح من مياه البحار فى معظم انحاء العالم مما دفع باقامة معظم محطات القوى الحرارية ومعامل تكرير البترول وصناعات عديدة اخرى لتكون بجوار الشواطى وذلك لاستخدام مياه البحار فى اغراض التبريد هذا الى جانب الاعداد الضخمة من السفن والمعدات البحرية التى تعمل بطبيعتها داخل المياه البحرية وتستخدم مياه البحار لنفس الغرض. وحيث ان هذه المنشأت تحتاج الى معدلات ضخمة من المياه اثناء عمليات انتقال الحرارة على اسطح المبادلات الحرارية بداخلها. ونتيجة لتسرب الزيوت وبكميات ضخمة الى اسطح البحار مما يؤدى الى تلوث مياه التبريد ومما هو معروف ان هذه الزيوت تتحول بفعل تواجدها فى الماء الى جانب العوامل الجوية الى مستحلبات زيتية خلال فترات زمنية وجيزة. فى هذا البحث تم دراسة وقياس تاثير المستحلبـــات الزيتية فى مياه التبريد على اداء المبادلات الحرارية تم حساب المعامل الكلى لانتقال الحرارة باستخدام مياه التبريد بدون ملوثات للمقارنة بعد ذلك وفى وجود الملوثات (مستحلبات الزيوت) فى مياه التبريد تم قياس معامل انتقال الحرارة ، معامل الاتســـاخ

(fouling factor) ، نسبة الزيوت الملتصقة داخل اسطح انابيب المبادل الحرارى واخيرا تم حساب سمك طبقة الزيت الملتصق على اسطح المبادل الحرارى. وضحت الدراسة ان كل ما سبق يعتمد اعتماد قوى على كل من سرعة سريان مياه التبريد داخل انابيب المبادل، مواصفات ونوع الزيت ونسبة الزيت فى المستحلب الزيتى الملوث لمياه التبريد الداخل للمبادل. وضحت الدراسة ايضا ان اتساخ الانابيب (oil fouling) قد يحدث خلال ثوان او دقائق من بداية التشغيل ويظهر التاثير السلبى فورا بعكس الانواع الاخرى من الاتساخات و الترسبات التى قد يحدث بعد شهور واحيانا اخرى سنوات. وضحت الدراسة ان اضمحلال معامل انتقال الحرارة وصل الى حوالى ٥٠% اذا ما لوثت مياه التبريد بمستحلبات زيتية حديثة. امكن تقليل التأثير السلبى للمستحلبات الزيتية الملوثة لمياه التبريد على اداء المبادل الحرارى بزيادة سرعة تدفق مياه التبريد داخل انابيب المبادل الحرارى ولكن يظل اى سمك من الزيت الملتصق على الانابيب حتى ولو صغير ذو تأثير سلبى واضح.