THE INVESTIGATION OF INDUCED GAS FLOTATION (IGF) PERFORMANCE AT ELEVATED TEMPERATURES AND HIGH TOTAL DISSOLVED SOLIDS (TDS) PRODUCED WATER

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ABSTRACT

Produced water is a major source of oily wastewater in oilfield sites. The volume and characteristics of this formation water differs in different parts of the world regarding the various geological specifications of the earth. However the crude oil desalting process and unit operation also impact the quality and quantity of the produced water. In the present study, the possibility of application of an innovative rotor/stator mechanical induced gas flotation(IGF) system was investigated for a somehow abnormal produced water in the Persian Gulf region with the temperature of about 100 ^{o}C and total dissolved solid content (TDS) of about 300 g/l. The results showed that at the temperature of 100 ^{o}C and TDS of 300g/l, oil removal efficiency was 80% achieved when the impeller speed was set at 900rpm. In this case, without adding any chemicals such as flotation aids, the outlet oil content from a single flotation cell could not support the regional environmental discharge regulation of 15 mg/l and required the addition of at least one more flotation cell.

Key Words: Induced Gas Flotation (IGF); Oily Wastewater; Produced Water; Wastewater temperature.

INTRODUCTION

Extraction and desalination of oil and gas is usually accompanied by co-produced water (referred as produced water), well-water or formation water. The quantity of the produced water versus the produced oil or gas usually differs from one site to another site as well as its quality. Geological specifications of the reservoirs, the age of extracting period and different extraction/desalting processes may cause various oil/gas-water ratio values and characteristics. In crude oil wells, the percentage of water increases over time and the percentage of product declines. Lee al. (2002) (1) reported that U.S. wells produce an average of more than 7 bbl of water for each barrel of oil. For crude oil wells nearing the end of their productive lives, water can comprise as much as 98% of the material brought to the surface. Wells elsewhere in the world average 3 bbl of water for each barrel of oil (2). Coal bed methane (CBM) wells, in contrast, produce a large volume of water early in their life, and the water volume declines over time.

After Saudi Arabia, Iran is OPEC's second largest oil producer and holds 10 percent of the world's proven oil reserves. It has the world's second largest natural gas reserves_ after Russia_ (3). Meanwhile, 90 percent of Iran's crude oil export is carried out via Kharg Island oil terminal located in the Persian Gulf, 25 km off the coast of Iran's mainland. Three oil refineries are located in Kharg Island named Aboozar, Doroud and Foroozan which totally produce an average amount of 350,000 BOPD desalinated crude oil. As a result, an average volume of about 70,000 BWPD is separated in the desalters/separators and drained and discharged to the Persian Gulf after passing a skimmer tank and storage pit. The temperature and total dissolved solids (TDS) of this stream is about 100^{o}C and 300 g/l respectively. The average oil content of the skimmer tank effluent is measured as 150 mg/l. In order to make a correct treatment decision, it was investigated whether the mechanical induced gas flotation (IGF) system would be able to treat the aforementioned produced water and reduce the oil content up to 15 mg/l which is the regulated oil content for the discharge to the Persian Gulf marine environment according to the Article VI (Pollution from Land-Based Source) of the Kuwait Convention (4). The general characteristics of produced water and its accompanying oil at the outlet of skimmer tank are presented in Table 1 and Table 2 respectively. In this paper, the results of the performance of an innovative IGF pilot plant for the treatment of synthetic produced water resembling Kharg Island oil refinery produced water which contains an average oil content of 150 mg/l and Total Dissolved Solids (TDS) of 200-300 g/l at different temperatures and varying impeller speeds (N) are presented.

Induced Gas Flotation (IGF)

IGF unit is an accelerated gravitational separation technique in which gas bubbles are induced into a water phase stream either by the use of an eductor device or by a vortex set up by mechanical rotor (impeller). The liquid phase (oily wastewater) usually contains immiscible liquid droplets (oil) or oily solid particles and that the gas bubbles attach themselves to the droplets. The oil appears lighter because the density difference between the oil agglomerate and water is increased. Consequently, the oil rises faster enabling a more rapid and effective separation from the aqueous phase. The oil droplets and oil-coated solids rise to the surface where they are trapped in the resulting foam/scum, and removed from the flotation chamber when the foam/scum is skimmed off (5, 6, 7, 8, 9). The nozzles, rotors, baffles and foam/scum skimmers for these units are patented designs (8).

EXPERIMENTAL

IGF pilot plant

Fig. 1, shows a schematic diagram for IGF pilot plant. A transparent Plexiglas cylindrical column, 280 mm in height and 260 mm in diameter with the total volume of 14.8 l was used as the flotation cell. Top of the cell could be fully dismantled from the body of the cell, allowing complete cleanup of the cells after each test. Different parts of the whole body were designed in such a way that would expand together in thermal shocks. The flotation cell was equipped with a variable speed motor (Bosch Drill, GSB 13, 600Watt, coupled with a dimmer). The motor speed varied from 0 to 2000 rpm. The stirrer/rotor speed could be measured by a hand held digital laser tachometer (DT 2236B). A stainless steel flat blade rotor (blade diameter / tank diameter =1/3) with a proper height was used for agitation. A new stator was used to disperse the stream and gas bubbles. The novel combination of this rotor and stator in the flotation cell _so called Mastour flotation cell_ performed a very good bubble generation and dispersion in the flotation cell. Gorain et al.(1995) (10) applied four different types of impellers _Pipsa, Chile-X, Dorr-Oliver and OutoKumpo_ and showed that in spite of small differences in trends, the general performance of impellers in flotation process was independent of impeller type. Therefore, it is believed that the performance of Mastour flotation cell in different testing conditions is not limited to its type. Hydraulic retention time (HRT) for the IGF pilot was set at 1min as suggested by Movafaghian et al.(2003) (9), Arnold and Stewart (1998) (8) and Sylvester and Byeseda (1980) (11) and it was controlled and calibrated by the emulsion preparation tank outlet valve. Although in the oil-water separation devices, it is a rule that: “the longer the residence time, the greater the separation”(11, 12, 13),but it should be noted that IGF system is dominated for its small footprint in oil-fields and specially offshore platforms and if this trait is waned by long HRTs for the purpose of higher oil removal efficiency, as it is observed in the study of El-Kayar et al.(1993) (14), Fench and Aldrich(2000) (15), Melo et al.(2003) (16) and Ramaswamy et al.(2007) (17), Oliveira de Lima et al.(2008) (18), it is only worthful for laboratory pilot studies and it is not practical for IGF design in its commercial uses.

Crude Oil

Crude oil from Doroud oil field, Kharg Island was used for oil in water emulsion preparation. The properties of the crude oil are specified in Table 2.

Produced water

Tap water and table salt were used to prepare the saline water resembling the produced water.

Feed Gas

Pure nitrogen gas (N_2) from a N_2 capsule equipped with a regulator and flow indicator (FI) and pressure indicator (PI) was considered for supplying nitrogen as feed gas with the rate of 10 lit/min as suggested by Sylvester and Byeseda (1980) (11). A pressure indicator on the top of the cell was installed to control the positive pressure in the vapor space in the cell. The feed gas nitrogen capsule is shown in right side of Fig. 1.

Procedure

Oil-water emulsion preparation

A polyethylene (PE) mixing tank with the capacity of 85 liters was used to store the O-W emulsion. It was gauged in different levels/capacities for further volumetric determinations. A 2000 Watt electric heater was used to heat the water and a temperature indicator (TI) instrument ranging from 0-120^{o}C was applied to monitor the temperature. One variable speed mixer equipped with a glass stirrer was used to emulsify oil and salt in water. When the water in the preparation tank reached the intended temperature, the mixer started to work with the speed of 2000 rpm so that the oil droplets would completely be dispersed in water (19). Specified amount of the previously weighted salt was added to the heated water. After about 5 minutes, crude oil was gradually added to the tank and was allowed to mix for 30 minutes so that the oil droplets would completely disperse in water. The mixer speed was then reduced to 400 rpm. Although not measured but according to similar procedure, the mean diameter of oil droplets in this method would be about 20 µm and the maximum diameter of oil droplets would hardly exceed 100 µm (19, 20). The outlet valve was opened and the O-W emulsion was transferred to the flotation cell with constant flow rate of 14 lit/min. In the oil-fields, rarely the produced water is transferred to the IGF system directly and is usually pretreated with simple gravity separators such as API or parallel plate separators. The oil-water emulsions leaving these separators normally have oil droplets less than 30 µm in diameter and oil concentrations below 200 mg/l (11). Therefore the inlet oil content concentration for all the tests were fixed at 150 ± 5 mg/l. For reaching to the constant oil in water content of 150 ± 5 mg/l in all the tests, several samples were taken at the inlet of flotation cell for calibration. In order to determine the performance of IGF system in oil removal, samples were taken at the inlet and outlet of the flotation unit in each running process. The oil & grease measurements were made due to the methods presented in Standard Methods for the Examination of water and wastewater, 1992. It should be noted that the preparation of stable/similar emulsions is a very sensitive step as was experienced by the authors and other researchers (21).

Results and Discussion

Oil removal efficiency

The oil removal efficiency (%E) was obtained using Eq. (1):

$$\%E = \left(\frac{C_o - C_f}{C_o}\right) * 100 \qquad (1)$$

where C_o is the initial concentration of oil present in the produced water and C_f is its concentration after the flotation process.

The results of all the oil removal efficiencies and power consumption measurements are presented in Figs. 2 to 4. Each figure illustrates at a particular impeller speed, constant TDS, constant inlet oil content and feed gas, the oil removal efficiency of IGF and both gassed and ungassed conditions power consumption versus the effect of temperature variations.

Effect of temperature on oil removal efficiency

Figures 2a-2c show that with the test set ups, the IGF oil removal efficiency improves with increasing temperature from ambient temperature _ 20 ^oC_ up to a specific temperature and then the oil removal efficiency falls down. At the TDS of 200 g/l and temperature of 20-100 ^oC and the impeller speed of 450-2000 rpm (Fig. 2a), the best efficiencies are obtained at 70 ^oC which are equivalent to 76%, 76.67%, 85.33% and 83.33% for N= 450, 900, 1450 and 2000 rpm respectively. At the TDS of 200 g/l, after the optimum temperature of 70 ^oC, at tested impeller speeds _N=450 to N=2000 rpm_ there is a small decrease in oil removal efficiency when the temperature exceeds 70 ^oC and reaches 100 ^oC. The maximum oil removal efficiency decrease in this case is observed in N=2000 rpm with the amount of 12.79%. At the TDS of 200 g/l, there is an exception in IGF performance at temperature of 80 ^oC at N=900 rpm in which the oil removal efficiency is similar to the conditions of T=70 ^oC and is equal to 76.67%. At TDS of 250 g/l, temperature of 20-100 ^oC,and the impeller speed of 450-2000 rpm, as it is depicted in Fig. 2b, the best results are again performed at the temperature of 70 ^oC in which the oil removal efficiencies equal to 78%, 80%, 86.67% and 85.33% for N=450, 900, 1450 and 2000 rpm respectively. At TDS level of 250 g/l, IGF oil removal efficiency is reduced when the temperature increases from 70 ^oC to 100 ^oC. The maximum reduction in IGF oil removal efficiency in this case equals to 13.46%. At the TDS level of 300 g/l (Fig. 2c.), the best IGF performances are obtained at 80 ^oC which are equivalent to 87.33%, 90%, 81.33% and 78.67% for N= 450, 900, 1450 and 2000 rpm respectively. For TDS of 300 g/l, after reaching the optimum oil removal efficiency at the 80 ^oC, there is a small decrease when the temperature goes up to 100 ^oC. The maximum decrease in oil removal efficiency in this case is observed at 11.47% when N=1450 rpm. The results correspond with observations of Strickland (1980) (5) and Arnold and Stewart (2008) (22) which indicated that the operation of IGF systems increases when the brine temperature increases up to 60 ^oC. The temperature directly affects the density, viscosity and surface tension of both oil and water. Raising the temperature also increases the enhancement of bubble coalescence (23). According to the authors review, this is the first time that the oil removal performance of flotation cells in a wide range of temperatures, specially at elevated temperatures (higher than 60°C) is investigated. It was visually observed that at temperatures higher than 70 °C, water vapor appeared in the gas space above the produced water and during the induction of impeller, water vapor and moisture were drawn into the liquid instead of nitrogen gas. This phenomenon may also affect the gas bubble size, bubble formation and oil-bubble coalescence.

Effect of TDS and impeller speed on oil removal efficiency

Fig. 3a-d shows the effect of TDS _200-300 g/l_ on the IGF oil removal efficiency at constant impeller speed _450-2000 rpm_ at constant temperatures. Fig. 3a indicates that at the constant impeller speed of 450 rpm, at the test set ups, the effect of TDS is not considerable when the temperature changes from 20 to 70 °C. At temperatures above 70 °C, and constant impeller speed of 450 rpm, the TDS increase from 200 to 250 rpm did not change the oil removal efficiency significantly. But, at the stated conditions, when the TDS increases from 250 to 300 rpm, the IGF oil removal efficiency increases in the constant temperatures of 80, 90 and 100 °C by the amount of 13.9%, 12.61% and 11.43% respectively.

Fig. 3b demonstrates that at the constant impeller speed of 900 rpm, at the test set ups, the effect of TDS is not considerable when the temperature changes from 20 to 70 °C. At temperatures above 70 °C, and constant impeller speed of 900 rpm, the TDS increase from 200 to 250 rpm did not change the oil removal efficiency significantly. But, at the stated conditions, when the TDS increases from 250 to 300 rpm, the IGF oil removal efficiency increases in the constant temperatures of 80, 90 and 100 °C by 15.38%, 9.40% and 11.11% respectively. When the temperature changes from 20 to 100 °C, at the TDS of 200 to 300 g/l and N=900 rpm, there are two exceptions in which the IGF efficiency is reduced due to TDS increase, which takes place at the temperature of 20 °C and 70 °C by the amount of 3.32% and 5% respectively when the TDS increases from 250 to 300 g/l.

The IGF oil removal efficiency at constant impeller speed of 1450 rpm and temperatures between 20-100 °C versus TDS (200-300 g/l) is depicted in Fig. 3c. As it is observed in Fig 3c., at the stated conditions, there is not any significant change in the performance of the IGF system when the TDS changes from 200 to 300 g/l in different conditions. The noticeable change in the performance of IGF system in this case is related to the reduction of efficiency when the TDS increases from 250 to 300 g/l at all testing temperature ranges. In this case, the maximum decrease takes place at the temperature of 20 °C and the minimum decrease is related to 50 °C, which is equal to 15.37% and 1.34% respectively.

Fig. 3d shows the effect of TDS on the IGF efficiency at constant temperatures at constant impeller speed of 2000 rpm and varying TDS levels (200-300 g/l). Similar to the results of N=1450 rpm in Fig. 3c and neglecting some discrepancies, there is no significant change in IGF efficiency while the TDS increases from 200 to 300 g/l at different constant temperatures. Again the noticeable change in the performance of IGF system in this case is related to the reduction of efficiency when the TDS increases from 250 to 300 g/l at all testing temperature ranges. In this case, the maximum decrease takes place at the temperature of 20 ^{o}C and the minimum decrease is related to 100 ^{o}C, which are equal to 15.37% and 1.8% respectively.

Some researchers have shown that the increase of NaCl concentration from about zero to 4% will reduce the bubble size in flotation cells and meanwhile increase the oil removal efficiency. In these researches, only minor increase in oil recovery was observed as the salt concentration increased beyond 4% (21, 24). According to the results of the present research, it could be concluded that at TDSs about 16.5% to 23% _high saline produced waters_ the effect of TDS/NaCl on the mechanically IGF systems could not be studied individually and should be regarded with other parameters as well as temperature and impeller rotational speed.

Agitation can have two opposing effects. On one hand an increase in impeller rotational speed will bring about an increase in energy dissipation, and hence an increase in the number of bubble–bubble or bubble-oil collisions per unit volume per unit time (25, 26). While this may be expected to increase coalescence, the contact time will also be reduced, so the rate of coalescence is not expected to increase at the same rate as the number of collisions. On the other hand, an increase in energy dissipation will increase the rate of bubble break-up (27, 28, 29). As was mentioned above, the increase in TDS also decreases the bubble size in flotation cells. It should be noted that the gas bubble size is an important factor in flotation unit design. If the bubbles are too large, there will be too few bubbles and they will not attach efficiently to the oil droplets as they rise very fast. If the bubbles are too small, they will not rise quickly enough, allowing the oil and gas to be entrained in the outlet water stream. The best performance point will be achieved according to the physical characteristics of produced water and IGF impeller speed specifications.

Environmental regulations and IGF global oil removal efficiency

From environmental perspective, it is important to check whether the selected technology meets the regional environmental regulations or not. According to the inlet oil content of 150 mg/l, the minimum IGF oil removal efficiency at the TDS of 200-300 g/l and impeller speed of 450-2000 rpm with the N_2 fuel gas flowrate of 10 l/m, was at temperature of 20 ^{o}C and impeller speed of 450 and 2000 rpm at TDS of 200 and 250 g/l which led to 96 mg/l outlet oil content and 36% oil removal efficiency. The maximum oil removal efficiency was due to impeller speed of 900 rpm and temperature of 80 ^{o}C which led to 15 mg/l and 90% oil removal efficiency. At the temperature of 100 ^{o}C and the TDS of 300 g/l_ Kharg Island produced water case_ the minimum oil removal efficiency took place at N=1450 rpm which was equivalent to 72% and 42 mg/l oil in outlet stream and the maximum efficiency was achieved at N=900 rpm with 80% oil removal efficiency and 30 mg/l outlet oil content. Therefore if the goal is to use IGF system for the discussed specific produced water at high temperatures (70 ^{o}C or higher) and TDSs (200 g/l or higher) without the use of any chemicals, a single flotation cell could not guarantee the outlet oil content of 15 mg/l which is the regulated oil content for the discharge to the Persian Gulf marine environment according to the Article VI of the Kuwait Convention and should be followed by at least one more flotation cell.

Conclusion

Regarding the conditions of test procedures discussed in this article, at constant TDS levels of 200 and 250 g/l, different impeller speeds_ N=450 to N=2000 rpm_ the IGF oil removal efficiency increases when the temperature increases from 20 ^oC to 70 ^oC. At the constant TDS level of 300 g/l, at different impeller speeds _ N=450 to N=2000 rpm_ the IGF efficiency increase continues from 20 to 80 ^oC. After these points, the oil removal efficiency is usually diminished.

According to the test set ups, at a constant temperature between 20-100 ^oC, at different impeller speeds_ N=450 to N=2000 rpm_ the IGF oil removal efficiency was not so dependent on TDS when the TDS is very high_ 250-300 g/l_, specially at lower temperatures_20-60 ^oC_ and at lower impeller speeds (i.e., <1450 rpm).

At the temperature of 100 ^oC and TDS of 300 g/l, oil removal efficiency would reach 80% when the impeller speed was set at 900 rpm. In this case, without adding any chemicals such as flotation aids, the outlet oil content from a single flotation cell could not support the regional environmental discharge regulation of 15 mg/l according to the Article VI of the Kuwait Convention and should be followed by at least one more flotation cell.

It is recommended to run the tests with different types of crude oil to check whether the results are reproducible in different iol field settings.

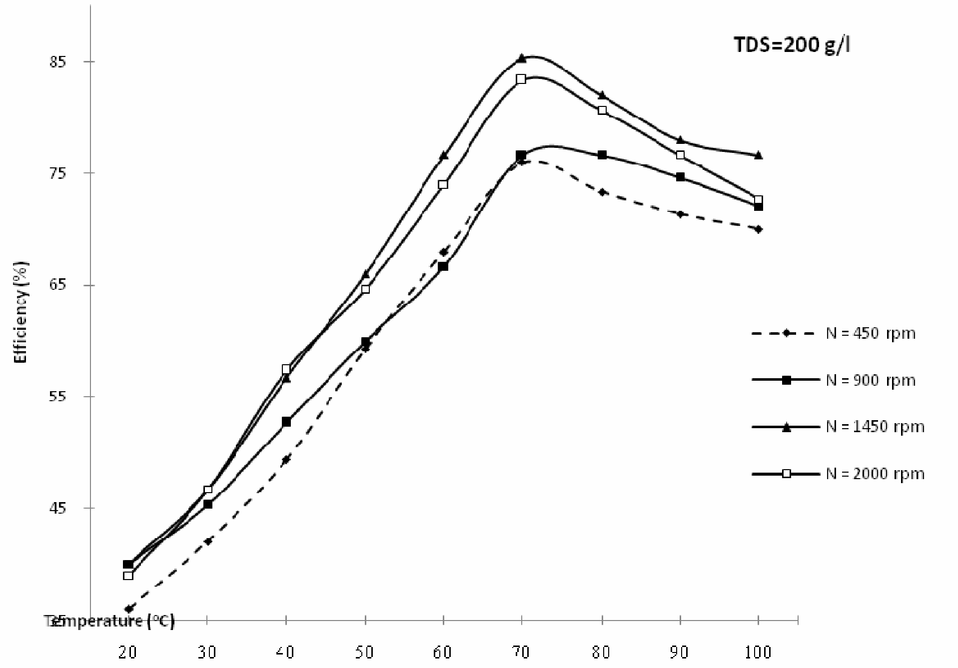
Table 1. Characteristics of Kharg Island produced water at the outlet of skimmer tank

Specifications of Produced Water	Value
Temperature (^{o}C)	90-110
pH	7.02
Suspended Solids (mg/l)	30-60
TDS @ 180 ^{o}C (g/l)	250-310
Oil Content (mg/l)	100-200

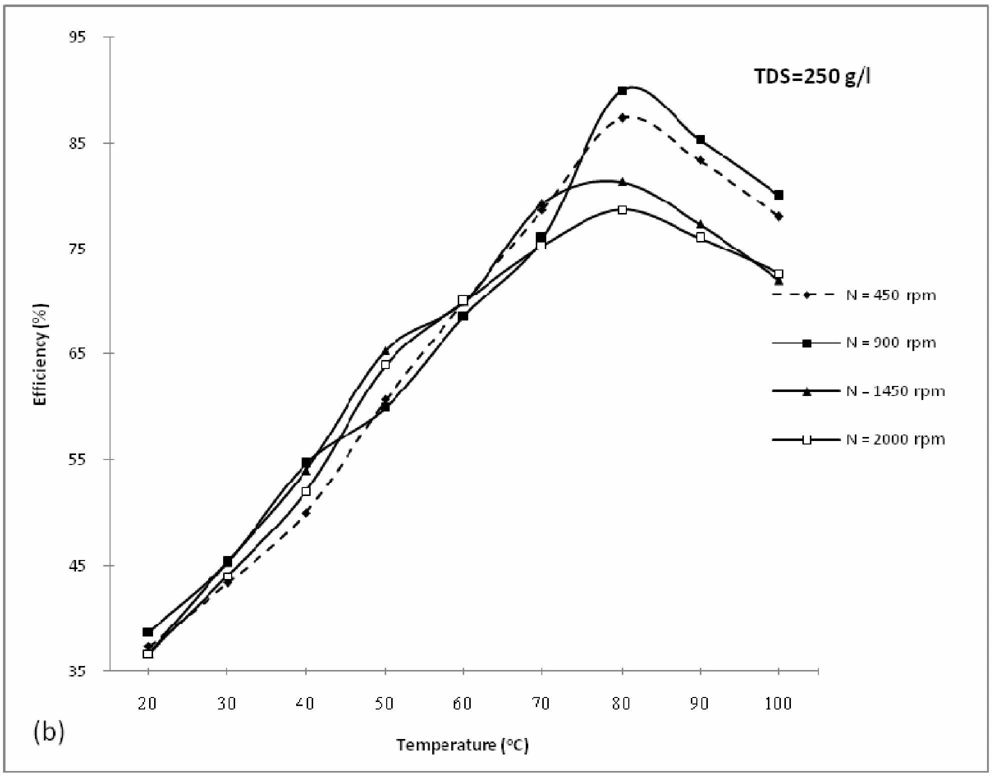
Table 2. Characteristics of Kharg Island crude oil

Specifications of crude oil	Value
SGr @ 60/60 ^{o}F (ASTM D4052)	0.85
API gravity (ASTM D4052)	34
Kinematic Viscosity @ 20 ^{o}C(cSt.)(ASTM D-445)	8.01

Figure 1. IGF pilot set up: IGF flotation cell and the nitrogen capsule Feed Gas


TDS=200 g/l
Efficiency (%)
85
75
65
55
45
35
Temperature (°C)
20
30
40
50
60
70
80
90
100
N = 450 rpm
N = 900 rpm
N = 1450 rpm
N = 2000 rpm

(a)


TDS=250 g/l
Efficiency (%)
95
85
75
65
55
45
35
20
30
40
50
60
70
80
90
100
Temperature (°C)
N = 450 rpm
N = 900 rpm
N = 1450 rpm
N = 2000 rpm
(b)

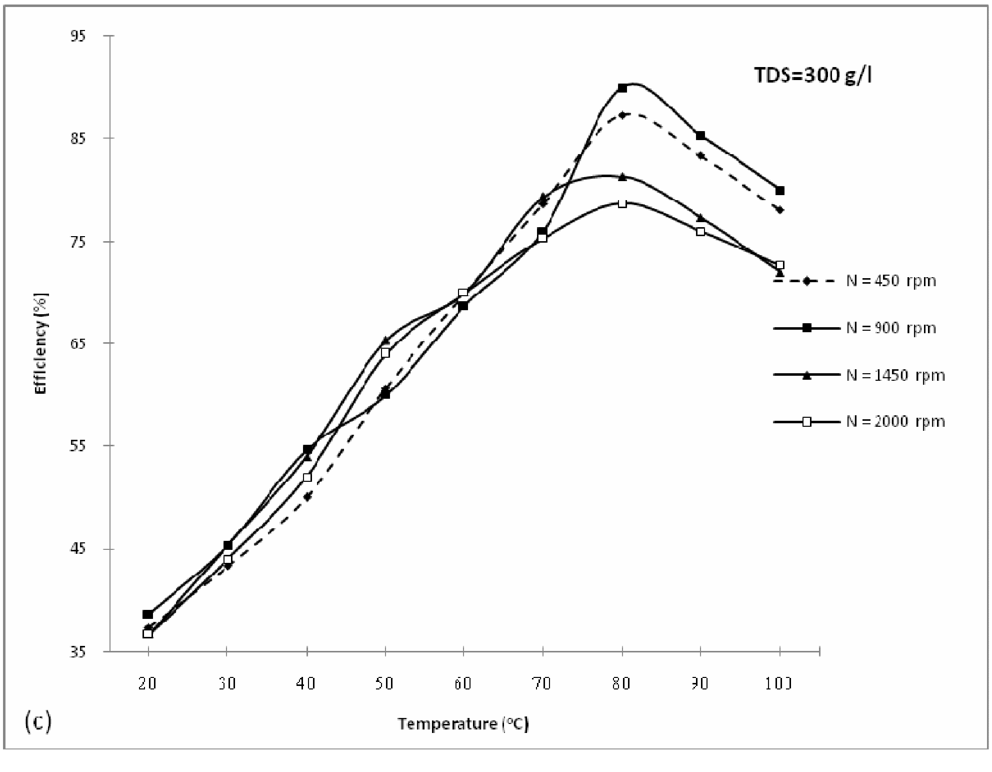
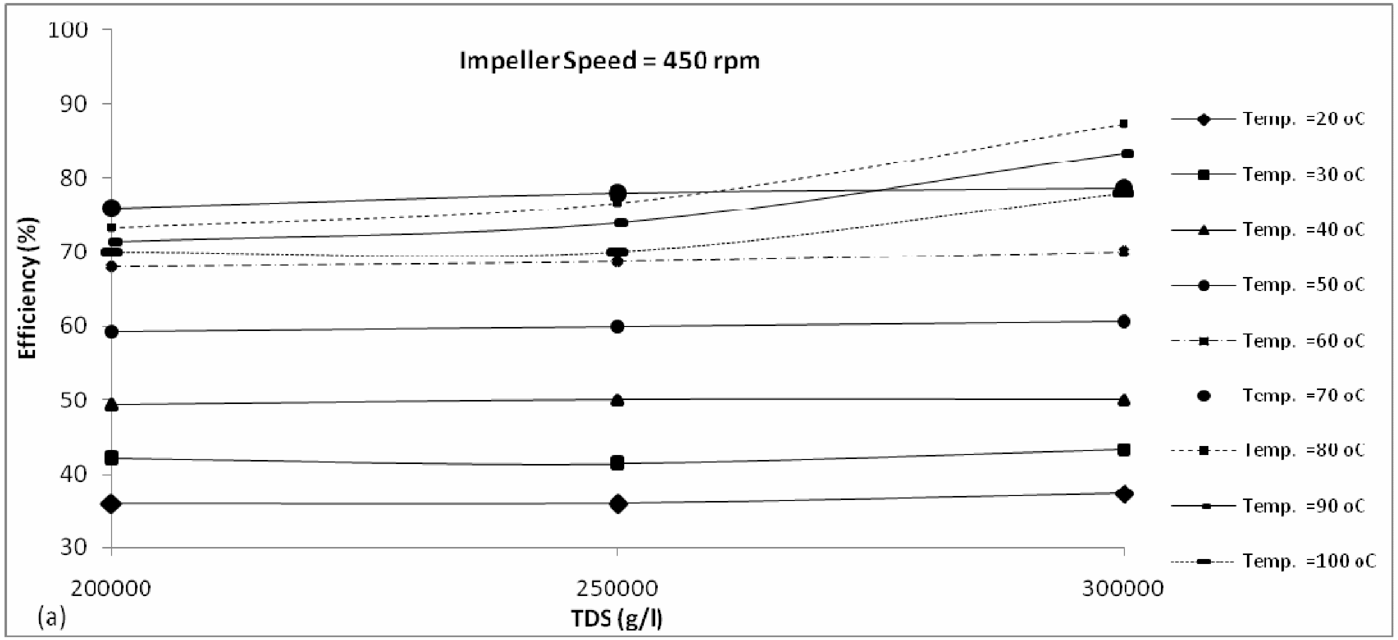
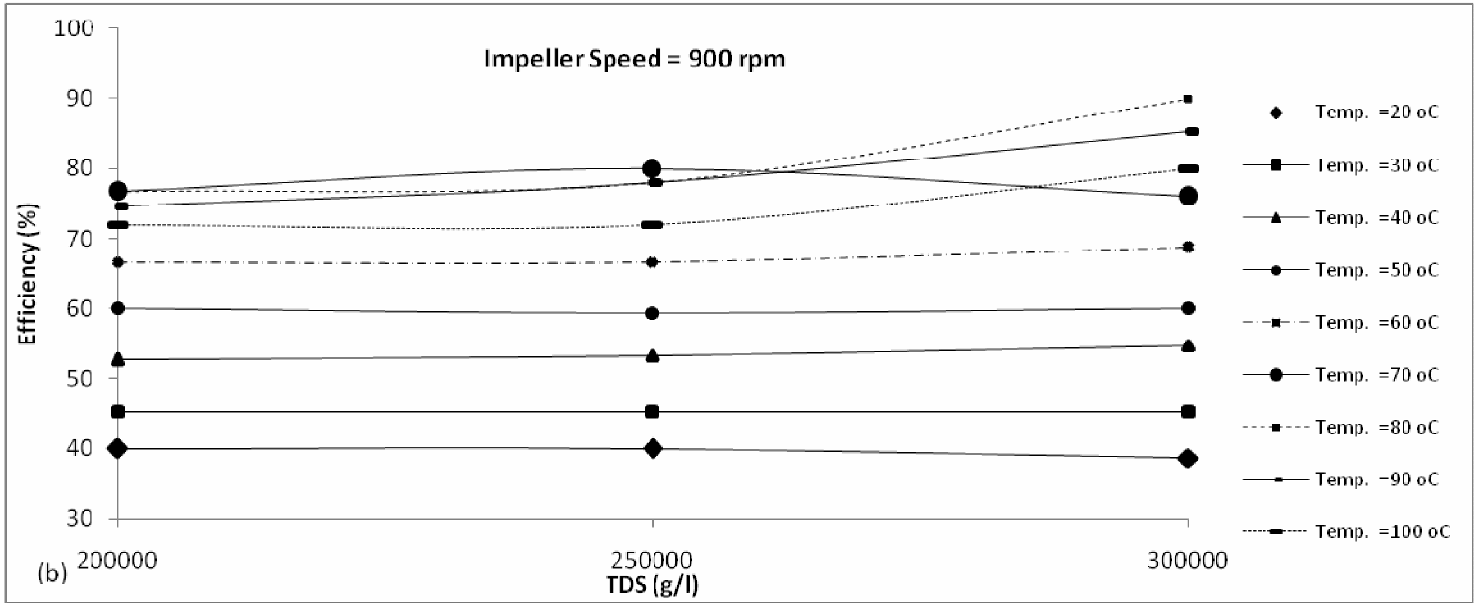
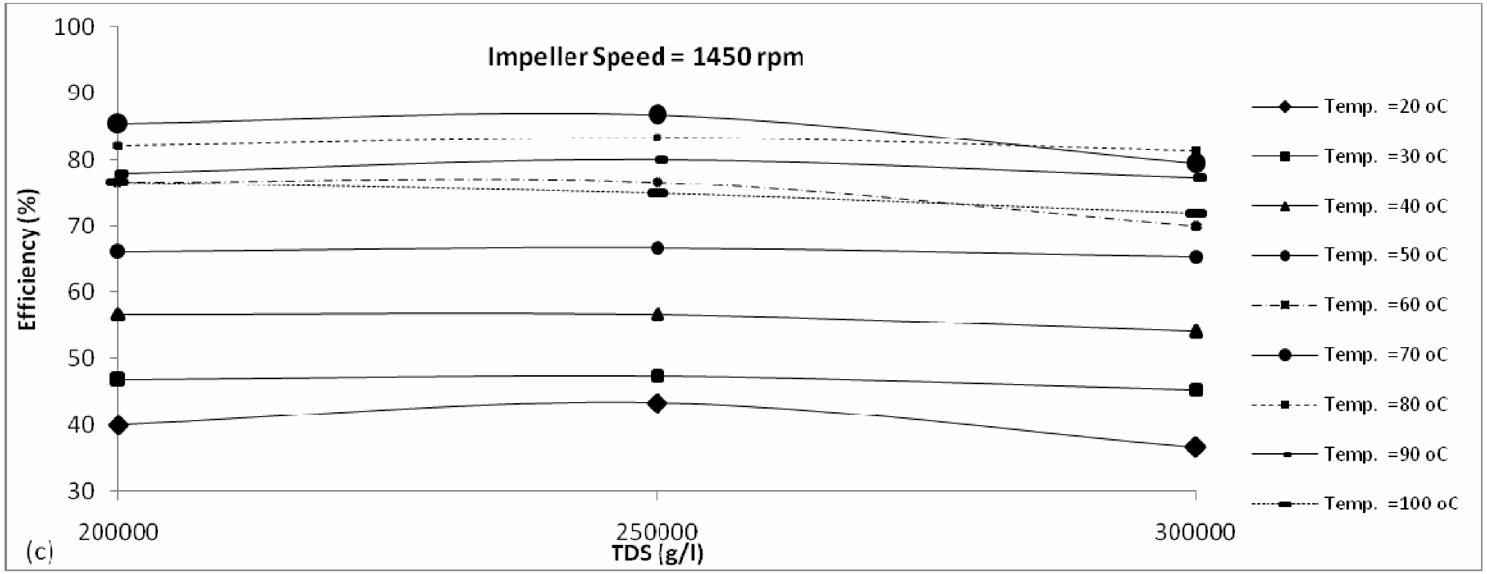

TDS=300 g/l
Efficiency (%)
95
85
75
65
55
45
35
20
30
40
50
60
70
80
90
100
Temperature (°C)
N = 450 rpm
N = 900 rpm
N = 1450 rpm
N = 2000 rpm
(c)

Figure 2. IGF oil removal vs. temperature at different impeller speeds at constant inlet oil content of 150 mg/l and constant N_2 fuel gas(10 l/min) at:
(a)TDS=200 g/l; (b)TDS=250 g/l; (c)TDS=300 g/l


Impeller Speed = 450 rpm
Efficiency (%)
100
90
80
70
60
50
40
30
200000
250000
300000
TDS (g/l)
(a)
Temp. =20 oC
Temp. =30 oC
Temp. =40 oC
Temp. =50 oC
Temp. =60 oC
Temp. =70 oC
Temp. =80 oC
Temp. =90 oC
Temp. =100 oC


Impeller Speed = 900 rpm
Efficiency (%)
100
90
80
70
60
50
40
30
(b)
200000
250000
300000
TDS (g/l)
Temp. =20 oC
Temp. =30 oC
Temp. =40 oC
Temp. =50 oC
Temp. =60 oC
Temp. =70 oC
Temp. =80 oC
Temp. =90 oC
Temp. =100 oC


Impeller Speed = 1450 rpm
Efficiency (%)
100
90
80
70
60
50
40
30
200000
250000
300000
TDS (g/l)
(c)
Temp. =20 oC
Temp. =30 oC
Temp. =40 oC
Temp. =50 oC
Temp. =60 oC
Temp. =70 oC
Temp. =80 oC
Temp. =90 oC
Temp. =100 oC

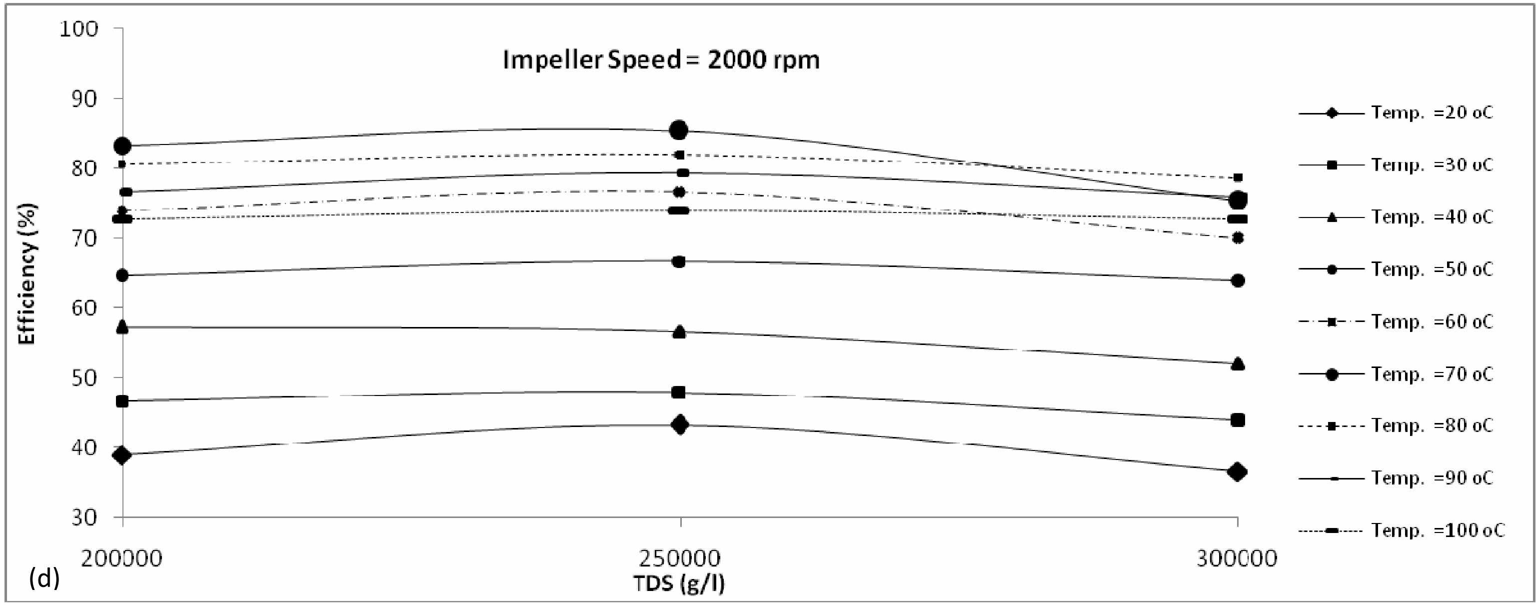


Figure 3. IGF oil removal efficiency vs. TDS at different temperatures at constant inlet oil content of 150 mg/l and constant N_2 fuel gas(10 l/min) at: (a)N=450 rpm; (b)N=900 rpm; (c)N=1450 rpm; (d)N=2000 rpm

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