EFFECTS OF CRUDE OIL PROPERTIES ON DEHYDRATION EQUIPMENT SELECTION

Enas Abu Obieda Abd El Gadir Hilal and Taj Alasfia Mubarak Barakat
Chemical Engineering Department, Faculty of Engineering, University of Khartoum

Received Feb. 2014, accepted after revision March 2014

Abstract
The present study addresses all facets of equipment sizing and an efficient, safe and environmentally acceptable crude oil dehydration operation based on three different equipments. The liquid-liquid separator, heater-treater system and electrostatic coalescer equipments will be considered in this work. Case studies present the effect of crude oil properties and operating conditions on the right decision on equipment selected. The selection is based on mathematical equations that characterize the choices of the separation system through the determination of the required size and efficiency. The results of this study show that the liquid-liquid separator is suitable for dehydration of light crude oil density (less than 850 kg/m$^3$) and low water-cut (water content) (less than 40%) crudes since it gives reasonable efficiency. The heater-treater system is found to be giving high efficiency. Furthermore the study concludes that the electrostatic coalescer is most suitably used for dehydration of crude oil with water cut 20% or less because short circuiting occurs above this limit; In this case the electrostatic coalescer gives the highest efficiency with the lowest size requirements.

Keywords: crude dehydration, liquid-liquid, heater-treater, electrostatic coalescer.

1 INTRODUCTION
During the operation life of a petroleum production well, dry oil is produced initially followed by the onset of water, the amount of which will generally increase with time with processing reservoir depletion. This water can cause many problems in the oil processing units such as corrosion and plugging problems and increase the cost of oil processing operations. Furthermore it reduces the selling price of the crude oil. Crude oil needs to be dehydrated to a certain level to meet purchaser’s limits. In general, a dehydration process consists of the initial removal of the (often larger) part
of the produced water which is not emulsified ('free' water) followed by the subsequent further treatment of the emulsified part of the oil/water mixture.

This research aims to study an oil water separation system and the most appropriate separation procedure. This study will focus on the comparative analysis between different dehydration equipments and procedures for an efficient and cost-effective operation.

2 BACKGROUND

Probably the simplest way of separating a (destabilized) crude oil/water mixture is to route it directly to storage tanks and allow the water to settle out whilst the crude is awaiting shipment. As the water cut increases, it becomes more attractive to remove water in a continuous process rather than in a batch dehydration process. The types of continuous dehydration equipment that are commonly being used are the dehydration tanks, coalescers and centrifuges.

These equipments have different operating principles such as: gravity difference, application of heat, application of electric charge and application of centrifugal force (see Table 1). In general, a typical oil field dehydration system will progress through (i) Destabilization of the emulsion by injection of chemicals, (ii) Degassing in a separator and/or degassing boot, (iii) Heating (especially for heavy, viscous crudes), (iv) Coalescence of small water droplets into larger ones and finally (v) Settling of water.

3 MATERIALS AND METHODS

This section focuses on the equipment selection and design/sizing guidelines for oil-water separation processes. Details of the liquid-liquid separator, heater-treater and electrostatic coalescer as described by empirical relations are given next.

### Table 1: Dehydration equipment selection guidelines [1]

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Application</th>
<th>Particulars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free water knockout separator</td>
<td>For high water cut crudes where the bulk of the water separates quickly</td>
<td>Final crude polishing to export quality can be carried out using other methods</td>
</tr>
<tr>
<td>Dehydration type separators</td>
<td>For low water cut crudes where dehydration to about 1-5%water is required</td>
<td>Usually located downstream of FWKO separators in offshore applications</td>
</tr>
<tr>
<td>Heater-treater</td>
<td>Considered for dehydration of difficult emulsions or very viscous crudes</td>
<td>Choice based on economic arguments. can be operated at higher temps than 100C</td>
</tr>
<tr>
<td>Wash tanks</td>
<td>General purpose, particularly useful with higher water cut crudes</td>
<td>Careful design of internals required to avoid channeling</td>
</tr>
<tr>
<td>Settling tanks</td>
<td>General purpose. use especially where plenty of tankage is available</td>
<td>Not a good choice for high water cut crudes</td>
</tr>
<tr>
<td>Electrostatic coalescers</td>
<td>Considered when deep dehydration is required (to about 0.5% water)</td>
<td>More sophisticated, hence more potential problems. short-circuiting problems</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>Suitable for deep dehydration and solid removal compact size potential for offshore application</td>
<td>Field tested. Cost saving. More trials required.</td>
</tr>
</tbody>
</table>

Furthermore efficiency calculations for each equipment will be outlined. These equations are used to evaluate the different separation systems considered to allow for the appropriate decision to be made regarding the best possible choice for a given oil-water mixture.

Empirical relations were established in equation (1) between two of the terms in Stokes' Law, \( Q/A \) (flow /horizontal cross-sectional area) and \( \Delta p/\mu \) (density difference / (oil/water) viscosity of the continuous phase). This empirical relation [1] is in the following form:

\[
(Q/A) = a \times (\Delta p/\mu)^b
\]

The coefficients (a) and (b) depend on the type of liquid and the dehydration performance. The above relationship forms the basis for the sizing methods for dehydration equipments.
In order to arrive at an optimum design and sizing of dehydration equipment, a number of general considerations need to be taken into account:

- Design conditions which include the flow rate and temperature.
- Nature of the feed which include density, viscosity, Emulsion stability, Droplet size distribution and gas fraction.
- Product specification which include oil quality and water quality.

### 3.1 liquid-liquid separators

**Figure 1: liquid-liquid separator [1]**

For sizing of a liquid-liquid separator (figure 1), the following data are required at the minimum operating temperature, Net oil flow \( q_o \) \( m^3/s \), total liquid flow \( q_1 \) \( m^3/s \), oil density \( \rho_o \) \( kg/m^3 \), water density \( \rho_w \) \( kg/m^3 \), oil viscosity \( \mu_o \) \( Pa.s \) and water viscosity \( \mu_w \) \( Pa.s \). The sizing routine is then as follows.

**Step 1**

Calculate the density difference and the ratio of density difference to oil and water viscosity [1].

\[
\Delta \rho = \rho_w - \rho_o
\]

\[
\Delta \rho \div \mu_o \text{ and } \Delta \rho \div \mu_w
\]

**Step 2**

Find the maximum allowable flux rates \( (q_1/A)^* \) and \( (q_o/A)^* \) in term of (m/s).

Liquid flux rate = \( 1.25 \times 10^{-8} \times (\Delta \rho \div \mu_o) \)

Oil flux rate = \( 1.4 \times 10^{-6} \times (\Delta \rho \div \mu_o)^{0.6} \)

**Step 3**

Select the minimum required horizontal cross-sectional area [1] in square meter of the separation compartment from:

\[
A_{h \text{ min}} = q_1 \div (q_1/A)^*
\]

\[
A_{h \text{ min}} = q_o \div (q_o/A)^*
\]

**Step 4**

Select a vessel with suitable dimensions to satisfy \( A_{h \text{ min}} \) requirement. The \( L/D \) ratio should be in the range 3 to 5 [1], where \( L \) is the length of the vessel and \( D \) is the vessel diameter.

**Step 5**

Calculate the efficiency of the separation unit from the following equations (equations 6 to 11).

Calculate the settling velocity of the water droplets

\[
U = d^2 \times g \times (\rho_w - \rho_o) \div 18 \times \mu_o
\]

Calculate the interface area

\[
A_{\text{int}} = W \times L
\]

\[
W = 2 \times (D \times Z - Z^2)^{0.5}
\]

\[
Z = 0.15 \times D
\]

Calculate the amount of water settled in the equipment

\[
q_{ws} = U \times A_{\text{int}}
\]

Calculate the efficiency of the equipment

\[
\text{Efficiency} = \frac{\text{separated water}}{\text{water entering the system}}
\]

\[
E = \frac{q_{ws}}{q_w}
\]

### 3.2 Heater-treater (heat application)

In addition to the data requirements of the liquid-liquid separator (section 3.1), the following data are also required for the heater-treater horizontal vessel sizing. Inlet temperature: \( t_i \) \( ^\circ C \), operating temperature: \( t \) \( ^\circ C \) and specific heat of crude: \( C_p \) \( (kJ/kg \ ^\circ C) \). The sizing routine is then as follows.

**Step 1**

Calculate the density difference and the ratio of density difference to oil and water viscosity [1].

\[
\Delta \rho = \rho_w - \rho_o
\]

\[
\Delta \rho \div \mu_o \text{ and } \Delta \rho \div \mu_w
\]

**Step 2**

Find the maximum allowable flux rates \( (q_1/A)^* \) and \( (q_o/A)^* \) in term of (m/s) and calculate the required horizontal cross-sectional area for the separation compartment as described in Section 3.1 for
a liquid-liquid separator in dehydration service.

**Step 3**
Select a vessel size which satisfies the $A_{h \text{ min}}$ requirement. The L/D ratio should be in the range 3 to 5 [1].

**Step 4**
Calculate the required heat input [1]
\[ H = q_o \rho_o C_p (t - t_i) \text{ kJ/s} \]  
(14)

**Step 5**
Calculate the efficiency of the separation unit as stated in equations (6) to (11).

### 3.3 Electrostatic coalesce

Feed inlet water cut is usually restricted to 20% for AC and AC-DC units, and 10% for bi-electric units [2]. Otherwise short circuiting of the grids may occur. It is not usual to consider water flux rates since these are nearly always satisfied.

Similar data requirements of the liquid-liquid separator (section 3.1) are required. The sizing routine is then as follows:

**Step 1**
Calculate the density difference and the ratio of density difference to oil viscosity [1]
\[ \Delta \rho = \rho_w - \rho_o \]  
\[ \Delta \rho / \mu_o \]  
(21)

**Step 2**
Find the maximum allowable oil flux rate ($q_o / A$) in terms of (m/s).
\[ \text{Oil flux rate} = 2.3 \times 10^{-6} \times (\Delta \rho / \mu_o)^{0.6} \]  
(23)

**Step 3**
Calculate the minimum required horizontal cross-sectional area in terms of square meter of the separation compartment:
\[ A_{h \text{ min}} = q_o / (q_o / A) \]  
(24)

**Step 4**
Select a suitable electrostatic coalescer to satisfy $A_{h \text{ min}}$. Suitable standard sizes are available in Petronas Tech. Standards [1].

**Step 5**
Calculate the efficiency of the separation unit as stated in equations (6) to (11).

### 4 RESULTS AND DISCUSSION

From the sizing routines mentioned in chapter three it is clear that the selection of appropriate dehydration equipment for a particular case depends on three principal factors, namely density, viscosity and the water cut.

To study the effect of these factors on the selection of the appropriate equipment it is necessary to make the above sizing routines for the three types of the separation equipments in different ranges of oil density, oil viscosity and water cut.

The oil density ranges (700-850) kg/m$^3$ for light crudes, (850-900) kg/m$^3$ for medium crudes and (900-970) kg/m$^3$ for heavy crudes [1].

The oil viscosity range selected for the purpose of this study (0.009-0.05) Pa.s for low viscosity, (0.05-0.1) Pa.s for medium viscosity and (0.1-0.5) Pa.s for high viscosity.

The water range selected for the purpose of this study (5%-20%) for low water cut crudes, (20%-40%) for medium water cut crudes and (40%-60%) for high water cut crudes.

Using MATLAB to solve the set of equations from (2) to (30) in order to calculate the area and the efficiency of each equipment in the different ranges of oil density, oil viscosity and water-cut for the various case studies presented next.

| Table 2: Oil-water properties at minimum operating temperature 50°C [6], [7] |
|-----------------------------|-------------------------------|
| **Oil-water Properties**    | **Value**                     |
| Total liquid flow $q_l$     | 20 m$^3$/hr $\times$0.00556 m$^3$/s |
| Net oil flow $q_o$          | 0.00445 m$^3$/s               |
| Oil density $\rho_o$        | 832.01 kg/m$^3$               |
| Water density $\rho_w$      | 988.0 kg/m$^3$                |
| Oil viscosity $\mu_o$       | 0.018836 Pa.s                 |
| Water viscosity $\mu_w$     | 0.000547 Pa.s                 |
| Water droplet diameter      | 200 µm                       |
| Water droplet diameter after the effect of electric charge (in the electrostatic coalescer) | 320 µm                        |
### Table 3: Oil-water properties at heating temperature 70°C [6], [7]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil density ρ&lt;sub&gt;o&lt;/sub&gt;</td>
<td>812.19 kg/m³</td>
</tr>
<tr>
<td>Water density ρ&lt;sub&gt;w&lt;/sub&gt;</td>
<td>978.0 kg/m³</td>
</tr>
<tr>
<td>Oil viscosity µ&lt;sub&gt;o&lt;/sub&gt;</td>
<td>0.009503 Pa.s</td>
</tr>
<tr>
<td>Water viscosity µ&lt;sub&gt;w&lt;/sub&gt;</td>
<td>0.000404 Pa.s</td>
</tr>
<tr>
<td>Specific heat of crude C&lt;sub&gt;p&lt;/sub&gt;</td>
<td>2.125 kJ/kg °C</td>
</tr>
<tr>
<td>Water droplet diameter</td>
<td>210 μm</td>
</tr>
</tbody>
</table>

#### 4.1 The oil density effects

In the range of oil density (700-850) kg/m³ for light crude oil and from figures 4, it is found that the liquid-liquid separator has the highest area and the less efficiency. Furthermore, the heater-treater has a lower area and higher efficiency than the liquid-liquid separator. While the electrostatic coalescer has the least area and the highest efficiency. In the range of oil density (850-900) kg/m³ for medium crude oil, it is found that the liquid-liquid separator has the highest area and the separator efficiency becomes low. The heater-treater and electrostatic coalescer, however have lower areas and higher efficiencies than the liquid-liquid separator.

In this case of high oil density range (900-970) kg/m³, it is found that the gravity difference between the oil and the water is small and this slows the separation process and thus decreases the efficiency. Here the

#### 4.2 The oil viscosity effects

For low viscosity crude oil and range (0.009-0.05) Pa.s, it is found that the liquid-liquid separator require the highest area (figure 3) and the least efficiency. The electrostatic coalescer and the heater-treater are the better choice because they give high efficiencies. Similar results are found for the case for viscosity range (0.05-0.1) Pa.s. In the range (0.1-0.5) Pa.s the results showed that the three separation systems give low efficiencies with increasing sizes. It is recommended that some modifications in the operating conditions are made to further increase the separation efficiency.
4.3 The water cut effects
In the range of water cut (5%-20%) it is found that the liquid-liquid separator requires the highest area (figure 4) and the least efficiency. The heater-treater indicated a lower area and higher efficiency than the separator while the electrostatic coalescer showed the least area and the highest efficiency. In the range of (20%-40%) and (40%-60%) water cut, the electrostatic coalescer is not included because of the occurrence of electrical short circuiting. The results for both ranges showed the merit of heater-treater system over the liquid-liquid separator.

Figure 4: the area at water cut range (5% - 20%)

5 CONCLUSION
The study concludes that the separator is suitable for low density, low viscosity and low and medium water cut crudes.

The heater-treater considered suitable for dehydration of heavy or viscous crudes and can also be used for the dehydration of the different types of crude oil considered. This choice however will depend on the cost consideration of heat provision.

The electrostatic coalescer is considered suitable when high level of dehydration is required as it showed high efficiency. This is restricted however to maximum water cut of 20% since short circuiting occurs above this limit.

REFERENCES

NOMENCLATURE
Q: flowrate m³/s
q₁: design total liquid flow m³/s
q₂: design net oil flow m³/s
q₃: water flow m³/s
µₒ: oil viscosity Pa.s
µₜ: water viscosity Pa.s
ρₒ: oil density kg/m³
ρₜ: water density kg/m³
A: Area m²
Aₕ: horizontal cross-sectional area m²
D: vessel diameter m
L: length of the vessel m
Cₜ: specific heat kJ/kg°C
H: enthalpy kJ/s
t: heating temperature °C
tᵢ: minimum operating temperature °C
U: settling velocity of the water droplets m/s
d: droplet diameter µm
g: gravitational acceleration m/s²
Z: height of the interface from the base of the vessel m
W: width of the interface m
Aₘᵢ: interface area m²
qₚ: water settled in the separator m³/s
E: equipment efficiency