

## THE INFLUENCE OF CRUDE OIL ON WELL TUBING CORROSION RATES

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### Abstract

A model is proposed to describe the corrosion caused by CO<sub>2</sub> dissolved in a fluid containing crude oil and water. To this end three types of phase behaviour of water/oil mixtures has been taken as a starting point to describe the effect of the presence of oil on the resulting corrosion rate of carbon steel. An equation is postulated expressing the likelihood of each of these suggested modes of phase behaviour occurring, which relates directly to their influence upon the corrosivity of the oil/water mixture.

An extrapolation of this model to heavier types of crude oil is proposed, which links the API gravity to the water-in-oil-emulsion stability, which, in turn, is linked to the effect of oil wetting of the metal.

For very light oil the model defaults to a model derived for an oil field studied previously. The resulting formula, combining the watercut, fluid velocity, angle of deviation of the tubing and API gravity of the oil is also shown to reproduce the typical behaviour for the corrosion of steel in oil/water emulsions observed by others.

### Keywords

oil-in-water, model, tubing, API gravity, fluid velocity, angle of deviation

## 1 Introduction

It has long been recognised that the presence of oil has a beneficial effect in reducing corrosion rates in oil production tubing. Early general statements suggested the ability of oils to carry water up to 20%, if flowing at  $>1\text{m/s}$ <sup>1</sup>, resulting in no water wetting and hence no corrosion. Refinements by later studies showed oils of different gravity having different water carrying capacity<sup>2</sup>. 'Light' oils were generally not regarded as capable of carrying water<sup>1</sup> but recent work has shown that even they do offer some protective capacity<sup>3</sup>.

This paper discusses the general basis of water-wetting in oil systems and attempts to establish a general approach, taking into account different types of oils, water-cuts, flow rates and angle of deviation of tubing.

## 2 Proposed modes of water entrainment

In a study of oil field corrosion<sup>3</sup> data it was found that the tubing corrosion could be satisfactorily explained by means of a semi-empirical equation for the CO<sub>2</sub> corrosion rate<sup>4</sup>, when this was combined

with a multiplier accounting for the influence of the presence of crude oil. This multiplier could be written as:

$$F_{oil} = 4.3WU_{liq} + 0.545 \frac{\dot{a}}{90} + 4.3WU_{liq} \frac{\alpha}{90} \quad (F_{oil} \leq 1) \quad (1)$$

where  $\alpha$  is the tubing angle of deviation with the vertical,  $W$  is the waterfraction of the oil, and  $U_{liq}$  is the liquid velocity (m/s).

The validity of this "oil factor" is restricted to a field producing a very light oil.. Since equation 1 consists of three terms, this equation suggests that the influence of this oil on corrosion rates in near liquid full systems consists of three contributions. In the following, it will be tried to link each of these contributions to a specific "mode" of water entrainment (*Figure 1*).

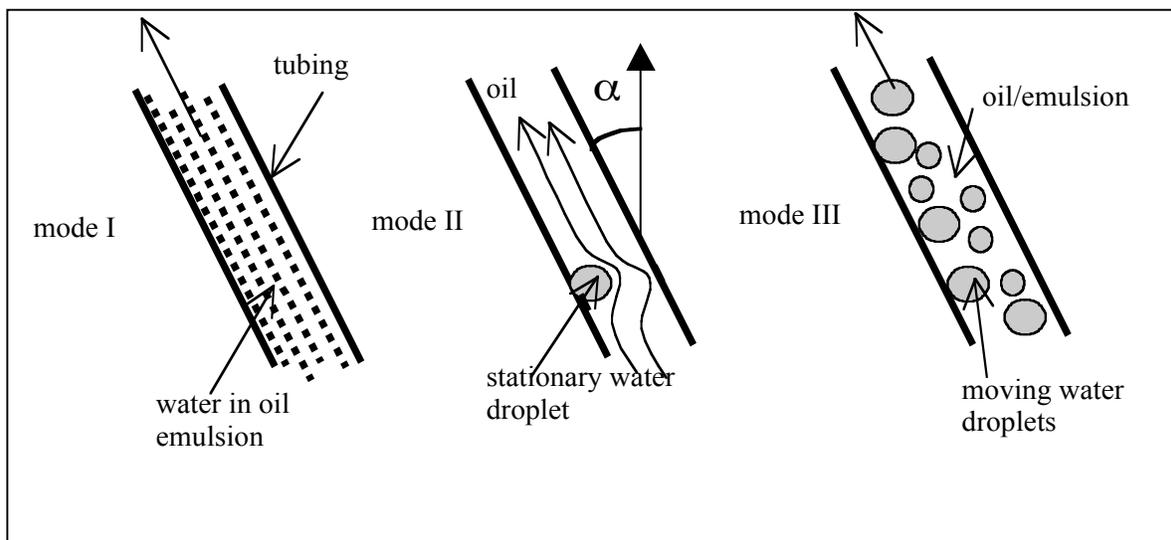


Figure 1. Modes of water entrainment in wet oil in production tubing at an angle of deviation,  $\alpha$ .

Depending on conditions of watercut, deviation angle and velocity, the corrosive fluid can consist of:

1. a water in oil emulsion (mode I water entrainment) or,
2. a water phase separated from the oil phase (mode II and III water entrainment)

Each of these cases can influence the base corrosion rate  $V_{base}$  in a different way. (Note that the extreme case of a water phase containing oil as an emulsion or droplets is not covered here as this results in full water wetting of the surface and is not a mode of 'water entrainment').

The likelihood of the tubing wall being exposed to these modes of water entrainment should be expected to correlate with parameters conducive to the stability of these fluids.

Water and oil form an emulsion which will separate into two phases when the amount of water is too high to be accommodated in a water-in-oil emulsion. The resulting water phase can remain stationary at certain locations (mode II), with oil flowing around it, or it may move with the fluid, thereby wetting the steel intermittently (mode III).

The accumulation of water at certain locations for mode II corrosion can even occur from oil with very low average watercuts<sup>5</sup>, as long as the water is not emulsified in the oil phase. Eventually, some water is likely to accumulate. For this reason, it is expected that mode II is only weakly dependent on watercut, and higher watercuts will increase the likelihood of modes I and III when  $\alpha$  and  $U_{liq}$  stay the same. Postulating a linear dependence on  $W$ , the likelihood of having water entrainment arising in the different modes can be expressed as a ratio, where:

$$\text{mode II} : (\text{mode I} + \text{mode III}) = 1 : W \quad (2)$$

With increasing velocities, this stationary water phase (mode II) will become dislodged more often until the steel is wetted alternately by oil and water, both flowing at the bulk velocity of the liquid. A shift from mode II to modes I and III (water moving with the oil) should be expected with increasing velocities ( $\alpha$  and  $W$  constant), possibly with a linear dependence on flow velocity:

$$\text{mode II} : (\text{mode I} + \text{mode III}) = 1 : U_{liq} \quad (3)$$

The accumulation of stationary (mode II) or moving (mode III) "pockets" of water from an oil-water mixture is dependent on the angle  $\alpha$ : the accumulation is easier when the flow is horizontal. For vertical flow, water will tend to accumulate at the start of the vertical section of tubing. This water will intermittently travel upwards and cause some corrosion of the vertical part of the tubing, but this area is expected to corrode substantially less than the more deviated areas. On the other hand, when the water is totally emulsified (mode I), the angle dependency should vanish. Thus, the likelihood of having water entrainment arising in the different modes can be expressed as a ratio, where:

$$\text{mode I} : (\text{mode II} + \text{mode III}) = 1 : \alpha \quad (4)$$

The relative likelihood of these modes of water entrainment can then be summarised as follows:

$$\text{mode I} : \text{mode II} : \text{mode III} = c_1 W U_{liq} : c_2 \frac{\dot{a}}{90} : c_3 \frac{\dot{a}}{90} W U_{liq} \quad (5)$$

where  $c_1, c_2, c_3$  are constants. This equation can also be seen as giving the relative duration of the exposure of the steel to each mode of water entrainment, which is directly proportional to the extent of corrosion each of them may support.

The averaged corrosion caused by all modes together is then:

$$V_{cor} = \left( c_1' W U_{liq} + c_2' \frac{\dot{a}}{90} + c_3' \frac{\dot{a}}{90} W U_{liq} \right) V_{base} \quad (6)$$

The constants  $c_1', c_2'$  and  $c_3'$  correspond to  $c_1-c_3$  above, but they now contain the effect on the corrosion rate for each corrosion mode. This equation may be compared to Equation 1 above.

Equation 6 corresponds to the results obtained for the specific type of crude from the field which was studied in reference 3, where the constants have the values  $c_1'=4.3$ ,  $c_2'=0.545$  and  $c_3'=4.3$ . The reason why  $c_1'=c_3'$  in that particular case is not known, but is probably caused by the quality of the data not permitting distinction between these constants.

### 3 Extrapolation to other types of crude

The watercut at the point where a water-in-oil emulsion breaks has been described in the literature in terms of the viscosity or API gravity of the oil. It has been suggested that a heavier, more viscous oil can accommodate more water before the emulsion breaks<sup>2</sup> into a separate oil phase and a separate water phase. In order to make this equation generally applicable, for a wide range of crude oils, use can be made of the data quoted by Craig<sup>2</sup>.

Using a 10% water separation as an indication of the emulsion breakpoint, a plot of the water cut in the emulsion at "emulsion break",  $W_{\text{break}}$ , vs. the API gravity suggests a linear relationship (Figure 2), with the formula:

$$W_{\text{break}} = -0.0166 * \text{API} + 0.83 \quad 50 > \text{API} > 20 \quad (7)$$

API stands for the API gravity defined by:

$$\text{API} = \frac{141.5}{d} - 131.5 \quad (8)$$

with  $d$  being the density of the oil in  $\text{g/cm}^3$ .

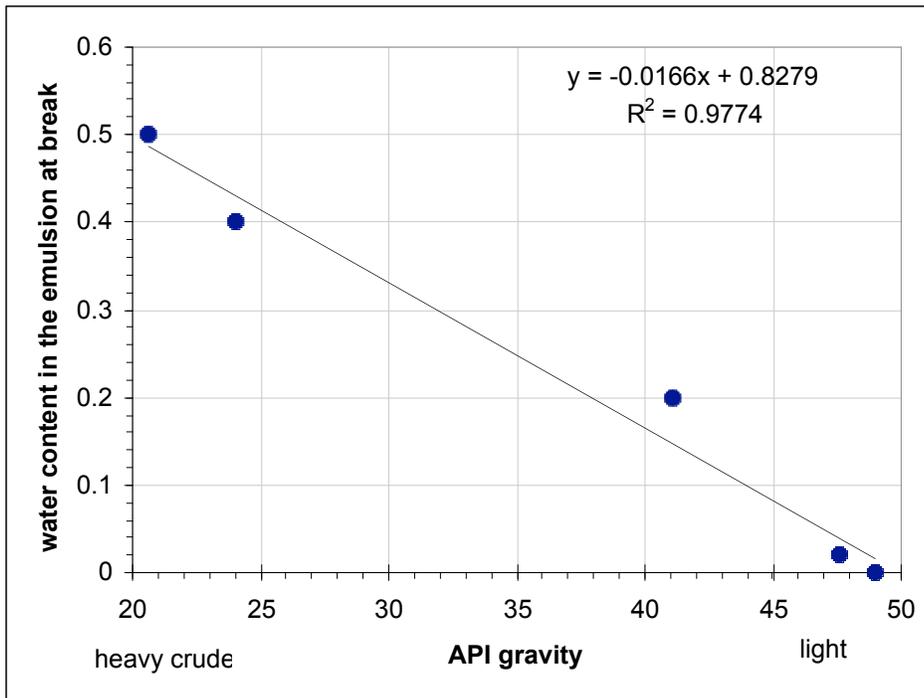


Figure. 2. Watercut readings in the emulsion at the point where at least 10% of the total water has separated from oil-water emulsions<sup>2</sup>.

$W_{\text{break}}$  is an indication of the interfacial tension between the crude and water: the lower this tension, the higher is the amount of water which can be present as an emulsion in the oil. When the interfacial

tension between oil and water is low, the interfacial tension between metal and oil will also be lower, resulting in a better wetting of the steel by the oil, thereby decreasing the rate of corrosion. Hence it should be expected that the corrosion rate varies in an inverse manner with  $W_{break}$ . Such a link between wettability and emulsion stability has been discussed earlier by Smart<sup>6</sup>.

The following analysis distinguishes two clear cases:

Case 1 for watercuts less than  $W_{break}$  where only mode I water entrainment is applicable and ;

Case 2 for watercuts equal to or greater than  $W_{break}$ , where all three modes of water entrainment are applicable.

### 3.1 Case 1, $W < W_{break}$

Considering equation 6, for watercuts below  $W_{break}$ , there would be no separate water phase, but only a water-in-oil emulsion, and  $F_{oil}$  would become (mode I only):

$$F_{oil} = c_1' W U_{liq} \quad (W < W_{break}) \quad (9)$$

Taking the effect of oil of different gravities into account by imposing a proportionality with the inverse of  $W_{break}$ :

$$F_{oil} = c_1'' \frac{W}{W_{break}} U_{liq} \quad (W < W_{break}) \quad (10)$$

Under mode I, since there is no distinct water phase, corrosion would be controlled by the conductivity of the oil/water emulsions<sup>2</sup>, which depends on the amount of water in the emulsion.

The coefficient  $c_1''$  in equation 10 can be derived from  $c_1'$  in equation 1 by calibration with  $W_{break}$  for the specific crude for which equation 1 holds. As can be seen in this equation, for this crude  $c_1' = 4.3$ . Taking this crude to have an API gravity of 49, equation 7 predicts  $W_{break} = 0.0166$  so that  $c_1'' = 4.3 \times 0.0166 = 0.071$  and

$$F_{oil} = 0.071 \frac{W}{W_{break}} U_{liq} \quad (W < W_{break}) \quad (11)$$

with the constraint that  $F_{oil} \leq 1$ .

### 3.2 Case 2, $W \geq W_{break}$

For higher watercuts ( $\geq W_{break}$ ), equation 6 would apply, and the effect of oil wetting would be described with:

$$F_{oil} = c_1'' \frac{W}{W_{break}} U_{liq} + c_2'' \frac{\dot{a}}{90} + c_3'' \frac{\dot{a}}{90} \frac{W}{W_{break}} U_{liq} \quad (W \geq W_{break}) \quad (12)$$

In a similar manner as above, the coefficients  $c_1''$ - $c_3''$  can be derived from  $c_1'$  and  $c_3'$  in equation 1 by adjusting for  $W_{break}$  for an API gravity of 49. Equation 7 predicts  $W_{break} = 0.0166$ , so that  $c_1'' = c_1' \times 0.0166 = 0.071 = c_3''$ , while  $c_2'' = c_2' = 0.545$ .  $F_{oil}$  then becomes:

$$F_{oil} = 0.071 \frac{W}{W_{break}} U_{liq} + 0.545 \frac{\dot{a}}{90} + 0.071 \frac{\dot{a}}{90} \frac{W}{W_{break}} U_{liq} \quad (F_{oil} \leq 1, W \geq W_{break}) \quad (13)$$

This equation reduces to equation 1 when  $W_{break}$  is set to the value corresponding to an API gravity 49.

At high watercuts the validity of equation 13 becomes limited, and in some cases does not obey the boundary condition that  $F_{oil}$  approaches 1 when the watercut approaches 100%. To enable extrapolation to high watercuts in these cases, a constraint is added to equation 13:

$$F_{oil} \geq W \quad (14)$$

In other words: when equation 13 yields a value smaller than the numerical value of the waterfraction  $W$ ,  $F_{oil}$  gets the value  $W$ . This corresponds to a proposal from Lotz et al.<sup>7</sup>, that at high watercuts corrosion rates for a number of different crudes could be conservatively described as being proportional to the watercut.

For very low flow velocities or near stagnant conditions, the main contribution in equation 13 stems from mode II. In most cases the resulting  $F_{oil} < 1$ , while it is not to be expected that the oil can offer much protection in such cases. In this context the conservative concept of a critical velocity  $U_{crit}$  for water dropout is used, below which water will always separate and wet the steel's surface. This leads to another constraint which has been added to equations 11 and 13:

$$\text{when } U_{liq} < \frac{\alpha}{90}, \quad F_{oil}=1 \quad (15)$$

which corresponds to a critical velocity of 1 m/s for horizontal flow. This value has been proposed earlier<sup>8</sup> on the basis of work by Wicks and Frazer<sup>9</sup>. For lower angles of deviation it is proposed with equation 15 that the critical velocity reduces in proportion; for vertical flow, water will always separate, which will flow upwards when sufficient water has accumulated.

## 4 Discussion

The dependence of  $F_{oil}$  on watercut resulting from equation 13 is demonstrated in *Figure 3*. With decreasing watercuts, it appears that the oil factor decreases rather abruptly at a watercut which is dependent on the type of crude. In fact, this watercut corresponds to the amount of water which the crude can accommodate in an emulsion. At this point, the equation for  $F_{oil}$  switches abruptly from equation 11 to 13. In actual practice it may be expected that this step is less sharp than predicted here.

For light oils  $W_{break}$  is small and the contributions in equation 13 of mode I and III become large, leading to the cut-off constraint  $F_{oil} \leq 1$  becoming active. For the heavier oils constraint of equation 14 plays a role, leading to a 45° line in the graph at high watercuts. For this example the critical velocity for water dropout is exceeded (otherwise  $F_{oil}=1$  in all cases).

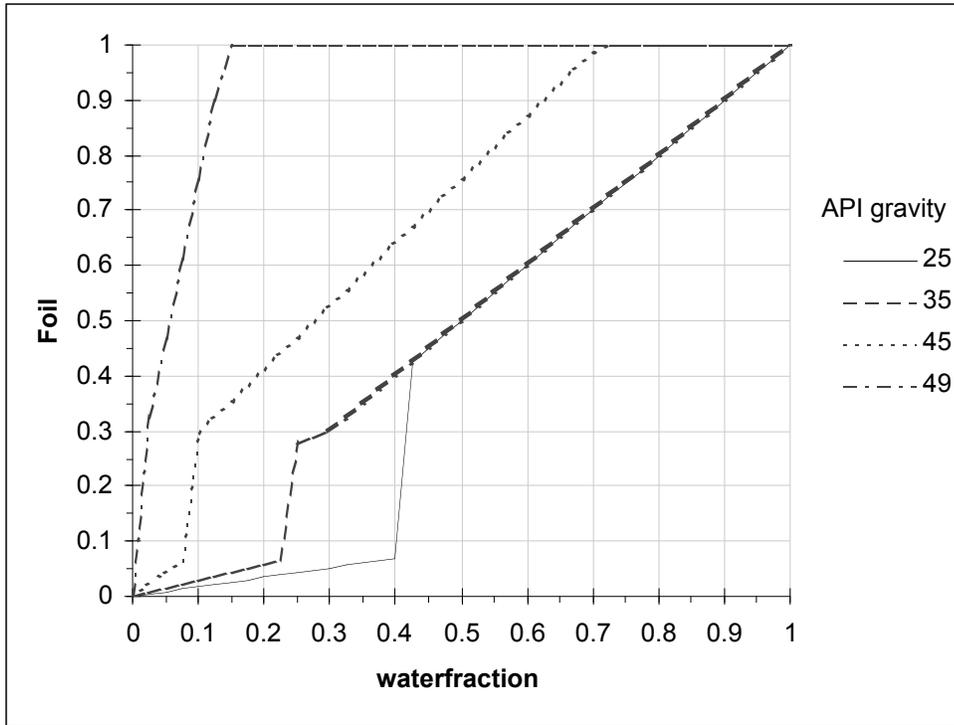


Figure 3.  $F_{oil}$  multiplier calculated for four API gravities with equation 13, with angle of deviation  $30^\circ$ , liquid velocity 1 m/s.

These curves also recreate the classical “S” curves noted by others<sup>2,7</sup> as typical behaviour for the corrosion of steel in oil/water emulsions.

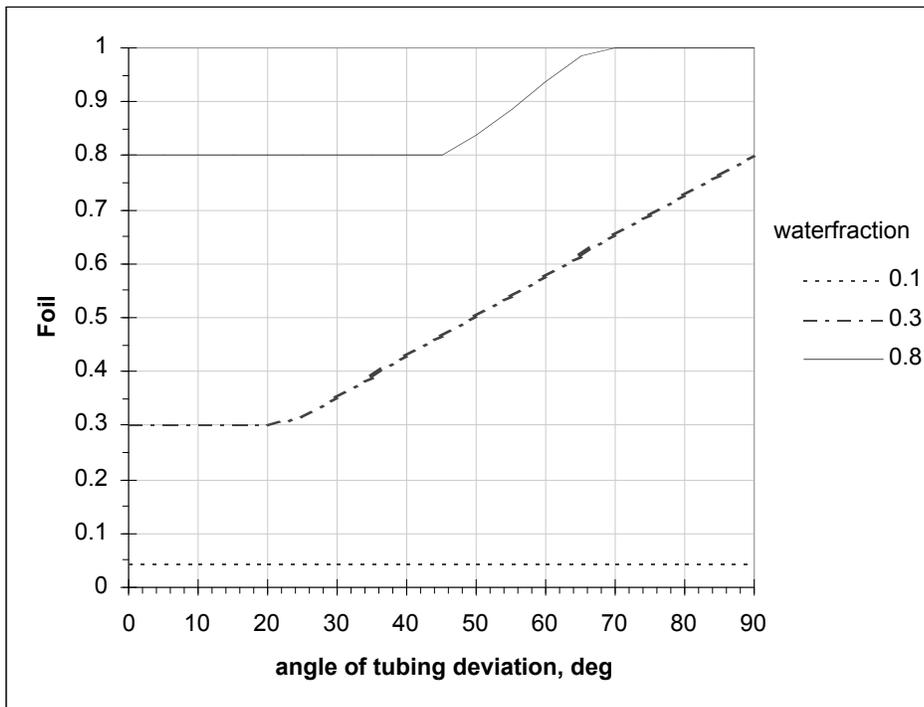


Figure 4. Dependence of  $F_{oil}$  on tubing angle, calculated with equation 13, for three watercuts. Liquid velocity 1 m/s, API gravity 40.

Figure 4 gives an example of the dependence of  $F_{oil}$  on the angle of deviation. For watercuts  $< W_{break}$ , (which is about 0.16 in this example) this dependence disappears (dotted line), since then there is only mode I corrosion, which is angle independent (equation 11). The effect of liquid velocity is shown in Figure 5.

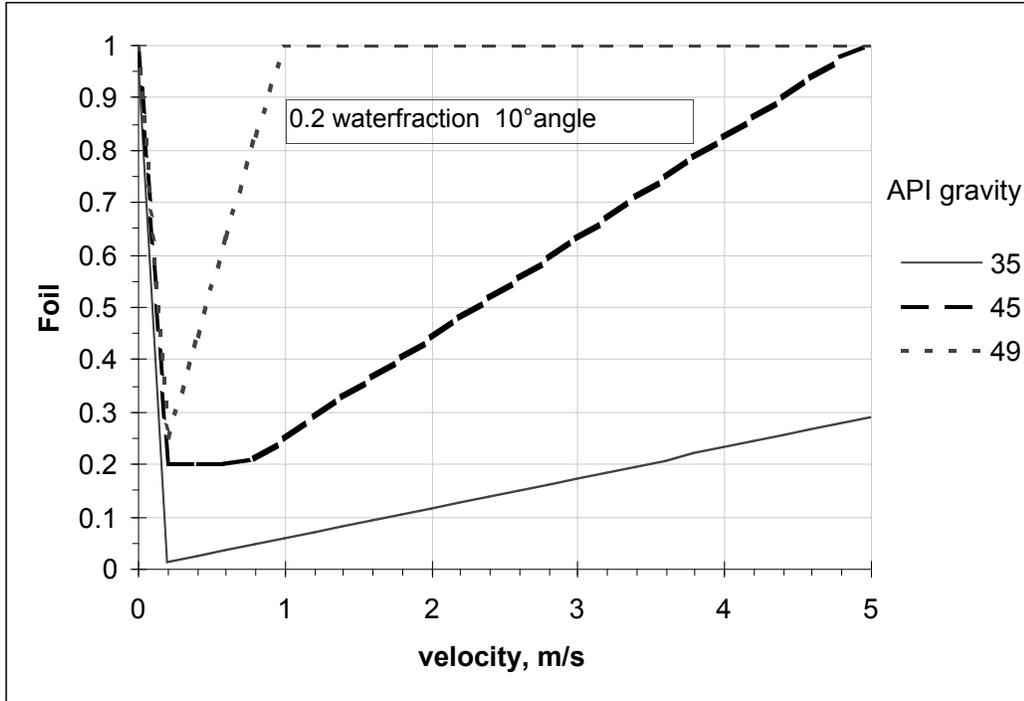


Figure 5. Oil factor as function of liquid velocity for three API gravities, angle of deviation  $10^\circ$ , watercut 20%.

When the amount of water can be accommodated in the form of an emulsion (e.g. API = 35), the resulting mode I reflects that water wetting depends linearly on flow velocity (equation 13). In the case of API gravity =  $45^\circ$ ,  $F_{oil}$  reaches a plateau for mode II corrosion at low velocities.

At a still higher API gravity of 49, the term in equation 11 corresponding to mode II is dwarfed by the other terms. Mode III wetting is the main mechanism here, and for most velocities the constraint  $F_{oil} \leq 1$  is active, demonstrating the lack of protection offered by such a light oil. Still, it is predicted that there is some protection in a narrow range of velocities with this oil, even though it is generally accepted that hydrocarbons like natural gas condensate offer no protection at all<sup>8</sup>. A shift between different flow patterns and modes of steel wetting inside tubing as a function of flow velocity has been proposed earlier by Gunaltun<sup>10</sup>. His proposed explanation of the effect of velocity is quite similar to the present one: at low velocity (0.2 m/s) there is occasional wetting with slugs of separated water, at intermediate velocities this wetting is more permanent, while at high ( $>0.5$  m/s) velocities the water is mainly entrained.

At very low velocities, the constraint of equation 15 comes into play, since at velocities below the critical velocity, water is assumed to separate always.

The above emphasizes the important role of flow velocity in conjunction with watercut and angle of flow. It should be appreciated that, for the actual corrosion prediction,  $F_{oil}$  is to be used as a multiplier

for a basic CO<sub>2</sub> corrosion rate for which the formula is given in reference 4. Since the latter is also velocity dependent, the resulting dependence on velocity can be quite complex.

Equation 13 does show general agreement with typical behaviour regarding wetting of steel in oil-water mixtures as observed by others and it also does reproduce the field data used as a starting point for its development. Although the proposed formula should be regarded as highly speculative, it reflects the fact that a heavy crude can reduce corrosion more than a light one. This is also in line with the observation that hydrocarbon condensates seldom give any protection at all.

It has also been shown that in wells which are nominally dry, corrosion can still occur through accumulation of water at locations where the tubing is deviated. The risk for this to occur is also related to the type of crude, which adds some perspective to the issue of corrosion in low watercut oil wells<sup>10</sup>.

It should be pointed out that the link between oil wetting of steel and the API gravity of the oil is subject to the many influences which can affect the stability of water in oil emulsions. Many compounds, which may be present in crude oil, can exert such an influence. Furthermore, some crude oils may contain compounds which can act as corrosion inhibitors<sup>11</sup>, an issue which is not considered in the context of this paper.

## 5 Conclusions

The CO<sub>2</sub> corrosion in oil/water systems has been analysed in terms of modes of entrainment of water in oil. It is possible to show that this model defaults to a previously proposed model derived to describe a set of field observations for wells producing a light crude oil.

The proposed extrapolation to heavier types of crude oil links the API gravity to the water in oil emulsion stability, which, in turn, is linked to the effect of oil wetting of the metal.

The resulting formula, combining the watercut, fluid velocity, angle of deviation of the tubing and API gravity of the oil is shown to reproduce the typical behaviour for the corrosion of steel in oil/water emulsions observed by others.

The proposed oil factor can be used to model the corrosion in oil well tubing when used in conjunction with a model for CO<sub>2</sub> corrosion. It then predicts trends and features to be expected for a field, and can be used for making decisions about the need for corrosion control or for the use of Corrosion Resisting Alloys.

## 6 Glossary

$\alpha$	angle of deviation ° from the vertical
API	API gravity
d	density of the oil g/cm <sup>3</sup>
D	diameter, m
F <sub>oil</sub>	oil wetting factor
F <sub>scale</sub>	scale factor
pCO <sub>2</sub>	partial pressure of CO <sub>2</sub> multiplied by fugacity coefficient, bar
pH <sub>actual</sub>	actual pH
pH <sub>CO2</sub>	pH derived only from dissolved CO <sub>2</sub>

T	temperature, °C
$V_{\text{base}}$	basic CO <sub>2</sub> corrosion rate, corrected for protective high temp. scaling
$V_{\text{cor}}$	Corrosion rate, mm/y
$U_{\text{liq}}$	liquid velocity, m/s
$V_{\text{m}}$	mass transfer rate
$V_{\text{r}}$	kinetic reaction rate
W	average water fraction of the liquid
$W_{\text{break}}$	water fraction at emulsion break point

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