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Crude Oil Entrainment of Settled Water in Arabian Light/Medium/Heavy Pipelines

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Introduction

The existence of free water, i.e., liquid, as a separate phase in the bottom section of flowing or stagnant crude oil lines is of prime concern. This free water phase provides the electrolyte necessary for the progression of various forms of corrosion, utilizing the corrosive agents most typically found in the crude oil, such as hydrogen sulfide (H_2S). Besides the more benign or tolerable "general corrosion" caused by H_2S, both sulfide stress corrosion cracking (SSCC) and hydrogen induced cracking (HIC) may also occur, with their potential for leading to unexpected, catastrophic failure of the crude oil line pipe.

The rigorous prediction of whether a free water phase, stagnant or entrained, will form can be made for any given hydrocarbon system, based on hydrocarbon composition, initial water saturation or undersaturation condition of the hydrocarbon, and the lowest expected temperature of the flowing or stagnant system. The subject, typical crude oil considered here, exiting the desalter/dehydrator train at a gas-oil separation plant (GOSP) is theoretically saturated with dissolved water at the exit temperature of the dehydrator vessel. Any cooling of the crude in the exiting pipelines will result in oversaturation of the oil with respect to water content and subsequent free water formation.

Such a calculational exercise is generally considered academic, since free water entrainment from upstream equipment, operational upsets, hydrotesting, etc., all may lead to the existence of significant amounts of free water in the system in question, regardless of the calculation/prediction. In short, free water in some quantity is often simply considered to be present in pipelines carrying desalted crude.

With the assumption that some free water has formed in the desalted crude, the next task is to ensure that this free water remains entrained in a flowing system or becomes re-entrained in either a stagnant or low-flowing system that has allowed this water to drop to the pipe bottom. The entrainment of the free water phase will in turn ensure that the electrolyte/corrosive agent in contact with the line pipe wall is generally avoided, thus precluding, or at least minimizing, the corrosion reactions.

Work Highlights

Materials Engineering

- *Materials selection recommendations were made for the major equipment and piping systems of a new process that is being developed by a startup company. Due to the nature of the process environment, high alloy materials of various types were recommended. Because of some remaining uncertainties with respect to materials performance in the process operating environment, a materials testing program was recommended and implemented to obtain materials performance data.*

Process, Operations & Safety

- *Assisting a licensor with an FCC Optimization Study of an overseas refinery, with ongoing support on the implementation of selected design improvements.*
- *Providing process and mechanical technology development support for a chemical company's novel fluid bed conversion process.*
- *Provided HAZOP support and miscellaneous assistance to a foreign refiner for his major refinery upgrade project in the Far East.*

Entrainment Correlation

Beginning in the 1950's, Shell Development Company in the US, investigated theoretically and empirically the entrainment of settled, free water in a pipeline by flowing crude oil[1]. The impetus for Shell's work was the same corrosion concern as described above; their prime goal was the prediction of flow conditions which lead to complete entrainment of water by oil, thereby essentially eliminating the probability of corrosion. Shell's work included the study of the transportation of solids, e.g., sand, by flowing fluids and comparison of the analogous behavior of free water droplets which had been "broken" away from a stagnant water layer by flowing oil[2]. From that work, a graph and the equations of the forces working on the deposit (sand or water) sitting on the pipeline bottom are shown in the Appendix of this article. The combined results of Shell's efforts appeared in their 1975 article[3] . Shell confirmed that their correlation had been verified by subsequent model tests at their laboratories in Amsterdam; furthermore, the correlation was being used as a standard design/operational tool in Shell organizations worldwide.

The predictive correlation appearing in that article is the basis of the calculations and conclusions presented here specifically for Arab light (AL), Arab medium (AM), and Arab heavy (AH) crudes.

Application of Correlation to Saudi Arabian Crudes

The working equations/graph for the Shell correlation are included in the attached Appendix. We decided to formalize, for a wider audience, its usage for the world's\ most ubiquitous crude, Arab light. The calculation for the entraining AL flowrate is based on actual measurements of the key physical properties considered in the correlation: crude-water interfacial tension, crude viscosity, and produced water viscosity.

Actual samples of "typical" Arab light crude and water production were obtained from a producing well in Saudi Arabia and the following physical properties, including interfacial tension, measured over a range of temperatures, except as noted:

	AL Crude/Water Interfacial Tension, dynes/cm	Viscosity, cp		Density, lb/ft^3	
		AL Crude	Water	AL Crude*	Water*
Temp, °F					
50	27.2	11.59	1.37	53.86	64.61
80	26.9	7.04	1.006	52.53	64.41
110	25.0	4.60	0.77	51.77	64.04

* extrapolated from 60°F measurement

AL = 34° API (measured)

In order to cover a reasonable range of Saudi Arabian crudes with regard to specific gravity, it was decided to also perform the entrainment calculations for AM and AH crudes. Measured/published API gravities and viscosities for AM and AH were used as benchmark values; gravities/viscosities at the temperatures of interest, 50°, 80° and 110°F, were obtained by extrapolation of these numbers. Interfacial tension values were also determined by extrapolation. The physical properties of the produced water were taken from the AL measurements or extrapolated as noted. Past calculations had indicated that the calculated entrainment flowrate was relatively insensitive to reasonable variations, e.g., inaccuracies, in these physical properties. The recommended design guidelines with respect to entrainment flowrate resulting from this work were intended to address typical variations in crude/water physical properties in any event.

The following properties therefore were used in the calculational procedure presented here:

	AM Crude/Water Interfacial Tension, dynes/cm	Viscosity, cp		Density, lb/ft^3	
		AM Crude*	Water	AM Crude*	Water*
Temp, °F					
50	32.2	20	1.37	54.69	64.61
80	31.9	10	1.006	53.34	64.41
110	30.0	5.8	0.77	52.56	64.04

*extrapolated from 60°F measurement; water from AL production

AM = 31.3° API

	AH Crude/Water Interfacial Tension, dynes/cm	Viscosity, cp		Density, lb/ft^3	
		AH Crude*	Water	AH crude*	Water*
Temp, °F					
50	37.2	50	1.37	56.26	64.61
80	36.9	32	1.006	54.88	64.41
110	35.0	20	0.77	54.08	64.04

*extrapolated from 60°F measurement; water from AL production

AH = 26.8° API

Correlation Results

The results of applying the correlation to the three noted Saudi Arabian crudes are contained in Figures 1/2/3 for AL, AM and AH, respectively. Shell's work with a given crude oil has indicated a typical concave-down curve of crude velocity (ordinate) vs. pipeline inside diameter (abscissa), reflecting the effects of all the involved physical properties of the crude and water. The attached plots for AL and AM have been effectively "smoothed" primarily because of round-off in the calculations. All three crudes do exhibit some degree of concavity, per the noted calculation, and accented in the graph for AH, which exhibits a more pronounced concave shape.

An interpretation of the crude/water physical properties as reflected in the Figures as well as the correlation equations illustrate the following:

General:

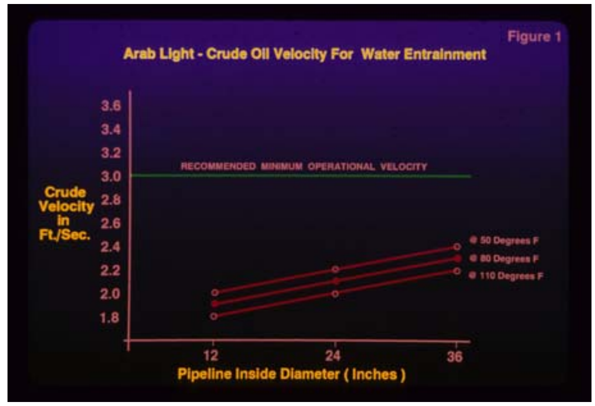
- The entrainment velocity increases with
  - an increase in pipeline inside diameter
  - an increase in crude viscosity, i.e., more viscous
  - a decrease in crude density, i.e., less dense
  - an increase in crude/water interfacial tension

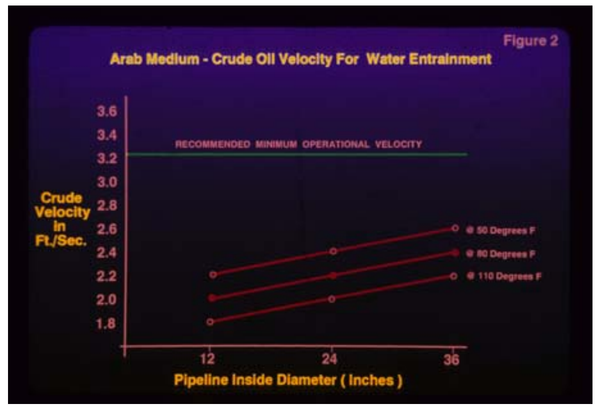
For a given crude oil:

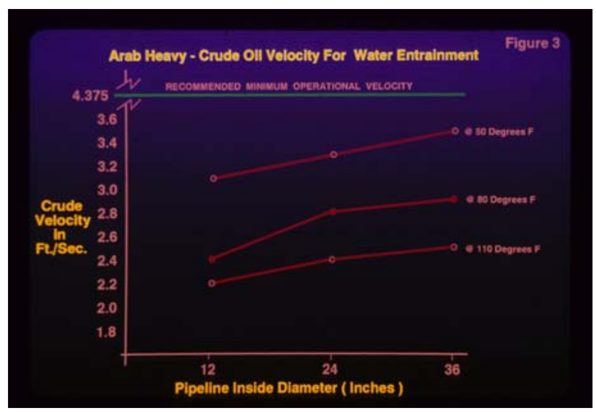
- The entrainment velocity increases with
  - lower temperature, i.e., the higher crude viscosity and crude/water interface tension apparently outweighs the increase in crude density.

It would be prudent to apply a healthy safety factor in determining a minimum, operational crude flowrate which will either a) maintain a flowing water phase in the entrained state, or b) re-entrain settled water from the pipe bottom. A somewhat arbitrary 25% safety margin, addressing the variation in physical properties of the crude/water phases, thus yields the recommended "operational" lines on the attached Figures.

Alternatively, pipeline operators could conceivably select minimum crude velocities on a seasonal basis for given diameter pipelines.







Conclusion

Minimum crude flowrates have been determined which will maintain production water in the entrained state and avoid bottom settling and its consequent, pipeline corrosion problems. A combined theoretical/empirical correlation, published by Shell, and proven by model testing, was employed for these calculations. The flowrates have been calculated for typical Arab light, Arab medium and Arab heavy crudes, over a range of temperatures and pipeline inside diameters. Measured physical properties, for the most part, for the actual AL crude and production water have been used in the calculation; published/extrapolated data were utilized for the AM and AH oils. Examination of the results allow analyses of the effects of the pertinent variables, as they influence the calculated minimum crude flowrates, and conservative recommendations of minimal operational crude flowrates to obtain the desired water entrainment.

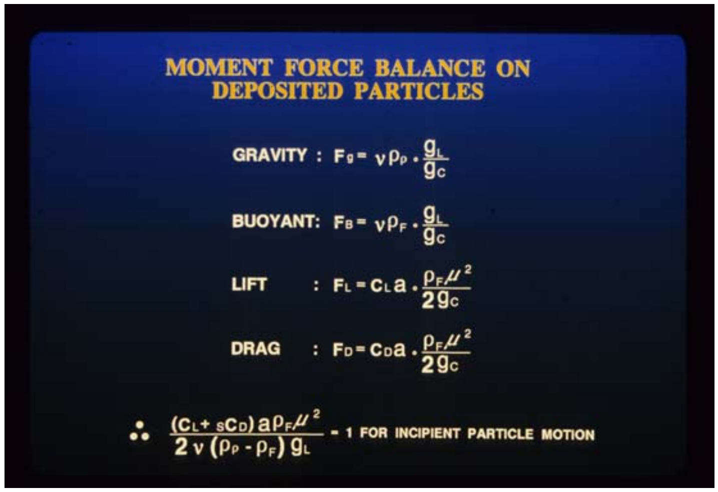
REFERENCES

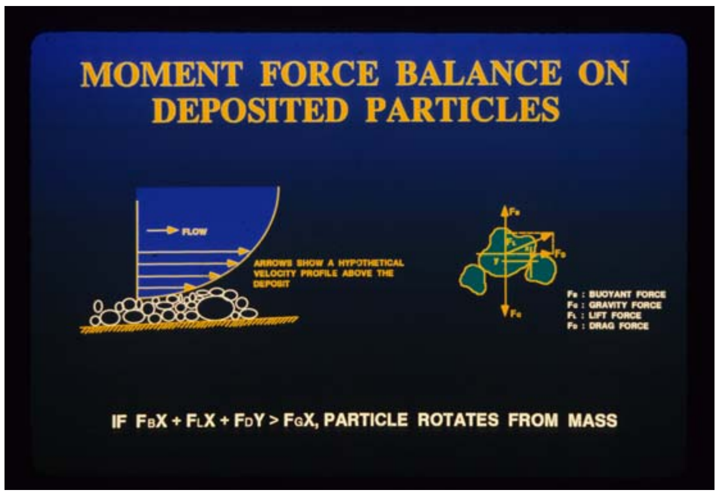
1. Hinze, J.O., AIChE Journal, Vol. 1, p. 289 (1955)

2. Wicks, M., Transport of Solids at Low Concentration, Paper 7, Advances in Solid-Liquid Flow in Pipes and Its Application, edited by I. Zandi, Pergamon Press, New York (1971)

3. Wicks, M., Fraser, J.P., Materials Performance, p. 9 (May 1975)

APPENDIX





About the Author

Robert Petrie is a Senior Advisor with a wide range of experience ranging across crude oil processing, gas/LPG processing, refinery engineering, project design management in all three areas, environmental engineering, incident investigation and analysis, and loss prevention and corrosion/metallurgy/welding. Rob's responsibilities have included process design as well as troubleshooting in most of these areas, often in collaboration with technical specialist colleagues. More recent activities include technical and contractual support to legal counsel in arbitration cases, from both owner and contractor sides, respectively.

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