Advances in Engineering Software 100 (2016) 176–197

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

A database and workflow integration methodology for rapid evaluation and selection of Improved Oil Recovery (IOR) technologies for heavy oil fields

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A R T I C L E   I N F O

Article history:
Received 10 August 2015
Revised 31 March 2016
Accepted 6 April 2016

Keywords:
Oil
Gas
Fossil fuels
Petroleum engineering
Technology evaluation
Systematic selection
Improved Oil Recovery (IOR)
Enhanced Oil Recovery (EOR)
Software architecture
Software integration

A B S T R A C T

Conventional crude oil is the currently dominant but a non-renewable energy resource. Despite the development and improvement of alternative energy technologies, there is still a large gap between the capability of renewable energy systems to capture and reliably supply power, and the ever-increasing global energy demand requirements. Therefore, until technological innovations facilitate sufficient energy generation through alternative fuels, other means of sustaining crude oil production, such as Improved Oil Recovery (IOR) methods, must be systematically explored. Beyond increasing production of conventional oil, IOR methods can effectively facilitate the extraction of oil from unconventional reservoirs, such as heavy oil fields. This capability is of high strategic importance due to the considerably large size of global heavy oil reserves.

There are several IOR technologies available, but each of them is suitable only for certain oil field types. The aim of this paper is to illustrate an alternative, low-cost, quick screening method which is competitive to more technically laborious and costly methods for selecting the most suitable technology for a given heavy oil extraction project, using a limited dataset. A two-stage technology screening method is hereby proposed: the first stage is based on previous project literature data evaluation, and the second stage is based on simple empirical oil production correlation methods (such as the Marx & Langenheim model) coupled with Ingen's RAVE (Risk and Value Engineering) and Schlumberger's PIPESIM software applications. The new method can achieve reasonably accurate results and minimise cost and time requirements during the preliminary stages of an oilfield development project, as evidenced via a comprehensive case study.

Abbreviations

AMPCP	All-Metal Progressive Cavity Pumps
API	American Petroleum Institute
ASP	Alkali-Surfactant-Polymer Flooding
BHP	Bottom Hole Pressure
BPD	Barrels Per Day
CAPEX	Capital Expenditure
CHOPS	Cold Heavy Oil Production with Sand
CSS	Cyclic Steam Stimulation
EOR	Enhanced Oil Recovery
ESP	Electrical Submersible Pump
GBP	Pounds Sterling
GOR	Gas to Oil Ratio
HASD	Horizontal Alternating Steam Drive
HSP	Hydraulic Submersible Pump
HWF	Hot Water Flooding
IAM	Integrated Asset Model
IFT	Interfacial Tension
IM CO_2	Immiscible Carbon Dioxide Flooding
IM HC	Immiscible Hydrocarbon Flooding
IM N_2	Immiscible Nitrogen Flooding
IM WAG	Immiscible Water Alternating Hydrocarbon Gas Flooding
IOR	Improved Oil Recovery
M HC	Miscible Hydrocarbon Flooding
Mid	Medium
M&L	Marx and Langenheim model
M&S	Myhill and Stegemeier model
M&V	Mandl and Volek model

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http://dx.doi.org/10.1016/j.advengsoft.2016.04.002

Nomenclature

Symbol	Parameters
a	Costing constant
A	Swept reservoir area, ft^3
b	Costing constant
C	Heat capacity of the reservoir rock, $BTU.ft^{-3}.°F^{-1}$
C_O	Specific heat capacity of oil, $BTU.lb^{-1}.°F^{-1}$
CF	Cash flow, $
C_r	Specific heat capacity of rock, $BTU.lb^{-1}.°F^{-1}$
C_w	Specific heat capacity of water, $BTU.lb^{-1}.°F^{-1}$
CX_m	Capital cost of equipment, $
D	Thermal diffusivity of reservoir rock, $ft^3.h^{-1}$
H	Formation thickness, ft.
h_{hf}	Enthalpy of hot fluid, $BTU.lb^{-1}$
k	Thermal conductivity of rock, $BTU.\ ft^{-1}.h^{-1}.°F^{-1}$
M_{hf}	Mass flowrate of hot fluid, $lb.h^{-1}$
P	Pressure, psi
Q	Thermal energy, 10^6. $BTU.h^{-1}$
Q_L	Heat loss during production, %
r	Interest rate, %
S_O	Oil saturation, %
S_{Or}	Residual oil saturation, %
S_w	Initial water saturation, %
t	Time, h
T_{amb}	Ambient temperature, °F
T_{hf}	Temperature of hot fluid, °F
T_r	Reservoir temperature, °F
T_w	Production well bottomhole temperature, °C
x	Dimensionless time
Z	Size parameter
ΔT	Temperature difference, °F
ϕ	Porosity, %
ρ_o	Oil density, $lb.ft^{-3}$
ρ_r	Reservoir rock density, $lb.ft^{-3}$
ρ_w	Water density, $lb.ft^{-3}$
μ	Viscosity, cP

NPV	Net Present Value
OPEX	Operating Expenditure
PCP	Progressive Cavity Pump
PVT	Pressure-Volume-Temperature
SAGD	Steam Assisted Gravity Drainage
SCF	Standard Cubic Feet
SF	Steam Flooding
SRP	Sucker Rod Pump
STB	Standard Barrel
RAVE	Risk And Value Engineering
THAI	Toe-to-Heel Air Injection
WC	Water Cut
WF	Water Flooding
WAG	Water Alternating Gas Flooding

1. Introduction

As societies become more prosperous, the demand for energy and consequently oil has increases incessantly. However, as the light oil reserves mature and are gradually depleted, other energy resources are needed so as to replace them in order to maintain energy prices at reasonable levels. Considering the cost and performance potential of currently available renewable (solar, wind, wave, tidal) energy generation technologies, other less cost-efficient fossil fuels (bitumen, heavy oil) will be necessary to supplement the production of light oil as the primary energy source which can fulfill the high global energy as well as petrochemical product demand requirements. Despite the lower depth of heavy oil reservoirs compared to conventional oil reservoirs, heavy oil specifications do not render it capable of flowing naturally from the reservoir to the surface, due to the comparatively lower reservoir pressure, higher viscosity and higher density, as illustrated in Table 1 [9,30]; consequently, external assistance is required so as to facilitate crude heavy oil production. These technologies are collectively defined as Improved Oil Recovery (IOR) methods.

Table 1
Properties of conventional oil compared to heavy oil and bitumen.

Identity	Unit	Conventional Oil	Heavy Oil	Bitumen
API Gravity	Degree	38.1	16.3	5.4
Depth	m	1567	991	373
Viscosity (25 °C)	cP	13.7	100,947	1,290,254
Viscosity (55 °C)	cP	15.7	278.3	2371
Asphalt	wt%	8.9	38.8	67
Asphaltenes	wt%	2.5	12.7	26.1
Carbon	wt%	85.3	85.1	82.1
Nitrogen	wt%	0.1	0.4	0.6
Oxygen	wt%	1.2	1.6	2.5
Sulphur	wt%	0.4	2.9	4.4
Flash Point	°C	−8	21	–
Pour Point	°C	−8	−6	23
Aluminum	ppm	1.174	236.021	21,040.03
Iron	ppm	6.443	371.05	4292.96
Nickel	ppm	8.023	59.106	89.137
Lead	ppm	0.933	1.159	4.758

Production of heavy oil through IOR is cost-intensive due to the requirement for extra Capital Expenditure (CAPEX) and Operating Expenditure (OPEX), therefore their utilisation is heavily dependent on the price of oil. Because of the macroeconomic expectation for higher oil prices due to the gradual depletion of reservoirs containing easily accessible oil, the detailed cost evaluation of IOR projects in early stages is essential towards reducing the financial and development risks. Therefore, developing reliable software tools for systematic technoeconomic evaluation of heavy oil IOR projects rapidly and accurately at the early stages can provide a significant advantage to oil producing companies over their competitors. Systematic process modelling, simulation and optimisation on the basis of first-principle models encompassing mass, heat and momentum transport phenomena have been successfully used in order to study, design and operate a wide variety of high energy intensity [12–14], power generation [26] and complex chemical reaction processes [19,20,33], particularly when the interest to maximise their high added value justifies the effort for process intensification and technoeconomic evaluation.

This paper is organised as follows: first, the concept and purpose of IOR technologies is outlined and illustrated with a detailed classification thereof. Sections 2 and 3 elaborate on evaluating the feasibility of different IOR methods by means of benchmarking oil field properties and technology performance indices against previous and current IOR projects, using an original comprehensive database. Sections 4 and 5 present the technoeconomic evaluation methodology for systematic analysis of IOR methods, which are analysed by means of a theoretical case study in order to select the method with the highest attainable profit margin. A combination of production system (heavy oil reservoir, injection and production wells) flow simulations carried out in PIPESIM [34] and empirical pressure and heat loss calculations integrated with Ingen's proprietary technoeconomic analysis software tool, RAVE [17] has been employed for the present study, thereby accomplishing a rapid and cost-effective prediction of the optimal IOR