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ANALYTICAL AND COMPUTER ASSISTED APPROACH FOR IN-WELL THERMAL SUPPORT METHOD FOR PREVENTING CLOGGING IN TUBING STRING

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Abstract

Production tubing clogging by wax occurs due to the effects of temperature, pressure and the chemical composition of the hydrocarbon. The thermal technique designed adopts the idea of maintaining production while preventing clogging by wax in the tubing. This technique involves injecting hot water into the production tubing through a Single String Branched Chain Supply Unit (SSBCSU), a kind of coiled tubing from the surface and a choke at the exit into the production tubing, which will help to elevate the temperature of the crude across the production tubing. FEZONE is a mathematical simulation application tool based on the Nodal analysis theory developed with a set criterion such as target average temperature of the multiphase fluid (oil and water) to simulate and keep track of physical properties of crude oil and water, pressures, temperatures, choke sizes, etc. Results from the application gave a maximum depth range of the lowermost node around 2000 feet, also presenting pictures of the entire process along the tubing string, showing number of injection nodes required, mass flowrate, temperature and pressure of injected water after analyzing several well designs and best fit for various kinds of production scenarios associated with possible wax deposition problems in the tubing string.

Keywords: Clogs, Nodes; Cloud Point temperature; Target average temperature of mixture; Single String Branched Chain Supply Unit (SSBCSU); FEZONE.

1. Introduction

The sole purpose of this work is to simulate with FEZONE how the SSBCSU thermal assist technique will help in preventing clogging by wax in production tubing in cold operating environments, along with supplementary objectives which are; (a) To determine the maximum depth whereby the lowermost node could be placed, (b) To determine how much water will be required and injected for the process in a day, (c) To ensure the temperature of the crude is elevated and maintained above the cloud point temperature of the crude oil, (d) To ensure the temperature of the mixture (oil and water) is maintained above the set required target (minimum) average temperature across the tubing, (e) Develop a user friendly GUI (graphic user interface) in the application to enable data input and simulate the technique for various scenarios, (f) To determine the best scenario and higher operating efficiency for a particular well completion, production environment and flowrate.

Before we head further into our methodology, we shall give brief definition and/or explanation of relevant terms and methods.

1.1 Clogging. Clogging is defined as prevention or obstruction of movement or flow. Clogs could form from various sources like sand, rusts, hydrates, asphaltenes, paraffins, *etc.* the most common are the clogs formed by asphaltenes and /or paraffins.

1.2 Wax. Wax is a general term used in describing asphaltene or paraffin coagulated micelles. It is formation and development in subsurface production tubing according to Noonan *et al.* [22], results from scenarios whereby the produced fluid has a high paraffin and/or asphaltene content, high cloud point temperature, cold production environment and low pressure reservoirs.

1.3 Cloud Point. Leo Noll [21] defined cloud point as the temperature where wax crystals begin to separate from solution. It is determined by measuring the viscosity as a function of temperature; the temperature at which the viscosity of the fluid markedly increases.

1.4 Deposition of Wax on tubing surface. Addison [1] described one of the means of wax deposition in shear deposition mechanism, which occurs when the temperature of crude oil has gone below the cloud point temperature and thence wax is precipitated from the solution and the wax crystals are transported to the walls of the tubular by the shearing force of oil [1,21]. The low flowrate, decline in deliverability energy leads to evaporation of lighter constituents of oil, i.e. evaporation of associated gas leaving heavier constituents in the oil which eventually becomes supersaturated with dissolved wax-forming hydrocarbons causing wax to crystallize out.

There are mechanical, thermal, microbial and chemical means of preventing clogging of production lines by wax.

1.5 Mechanical method. It involves pigging or scraping by the application of a wireline tool to achieve this purpose. Brown [6] discussed on several tools used for scraping, such as; paraffin knife, paraffin hook, cork screw, porcupine and a swab. Uren [33] made mention of mechanical rotary reaming devices. Ann Davis [12], pointed out that modern automatic wireline scraping tools can operate while production continues.

1.6 Thermal methods. The means of tubular insulation to minimize heat losses, as well as the injection of hot water or hot oil or heated gas or Electro-thermal means as a heat exchange medium to elevate the temperature of the crude oil [12,22]. Electrical heating is another means which involves using the tubing string as a heating element (Enhanced oil recovery week, 1988, Electro-thermal).

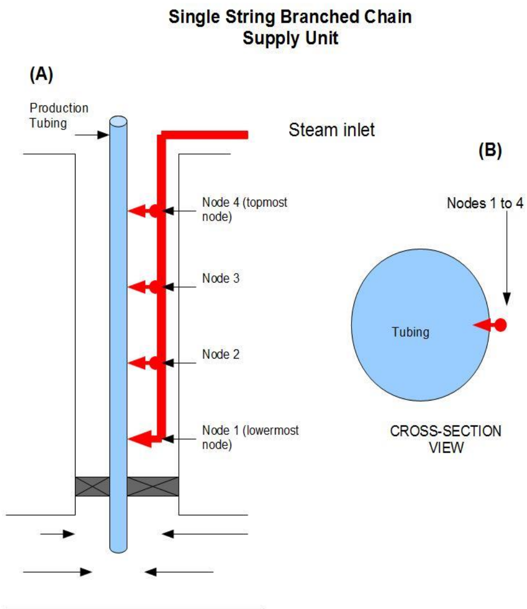
1.7 Chemical method. This involves injecting crystal modifiers, diluents and/or dispersants which help in re-dissolving the wax back into the crude. These chemicals are applied in low concentration and continually [12,21]. Crystal modifiers are chemicals that interact with the developing paraffin wax by deforming the crystal morphology in the crude oil hence breaking the sequence of crystal aggregation steps. Dispersants on the other hand act to prevent crude wax from agglomerating. They are basically surfactants and they also help by keeping the pipe wall surface water wet, thereby reducing the tendency of wax to adhere to the surface.

1.8 Microbial methods. Biswas [5] made use of a paraffin degrading Bacterial consortium, a microbial treatment which was used to refine waxy paraffin into production fluids by the microbial cultures metabolizing the paraffin into alcohol, carboxylic acids and aldehydes. Bhupendra *et al.* [4], Biswas *et al.* [5], through their works indicated that the microbial cultures must be left to incubate for a while so as to enable it to fully degrade that wax. They also indicated that the bacterial consortium is at its highest working level between 30°C to 40°C. The challenge with this method is the amount of downtime, the slow nature particularly when compared to a required faster pipeline operation.

1.9 Other methods. Reistle and Blade [25] explained that no matter the condition of production, oil needs to be produced with some amount gas (even if at minimum levels) and maintaining a steady oil flow. Adjusting pipe and choke sizes so as to keep the tubing always full of oil even at low deliverability energy. There are some processes that require the combination of two methods, such as the work by Noonan *et al.* [22] whereby the injection of heated gas enriched with pentane plus hydrocarbon fraction so as to heat the production fluid, serve as a lift gas and chemically remove wax deposits along the tubing wall.

2. Experimental (Methodology)

The model design created which is titled "**The Single String Branched Chain Supply Unit** (SSBCSU)" a kind of coiled tubing [24], shown in fig(1), was developed in such a way that the steam or hot water is applied through a steam supply tubing which is constructed through the hydrocarbon production tubing and casing annulus [13]. The steam supply tubing is connected to the production tubing via various branched chains (nodes) extending from the steam supply tubing.



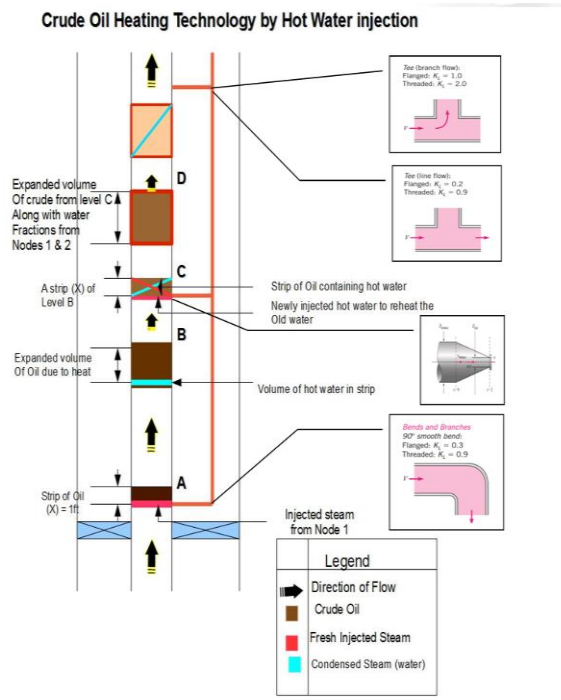


Figure 1 The SSBCSU design concept Figure 2 Operation concept

The placement of the lowermost node (branched arm) of the SSBCSU is dependent on the depth in the production tubing where the temperature of the crude is approaching the asphaltene or paraffin cloud point temperature. The pressure of the produced fluid at that depth helps in determining the required flow regime across chokes (subsonic or sonic) and the choke size to be placed so as to meet with the commingling theory [20] criteria (the pressure from both ends at both fluids meeting point must be the same). Subsequent nodal points (branched chains) are determined by simulation where the temperature goes below the system minimum target temperature. The choke size is determined from the pressure of the mixture at that depth in the production tubing.

The analytical solution simulation system is resolved by iteration guided by the principle of nodal analysis [3]. This is resolved by taking a constant interval across the entire length of the production tubing.

2.1 Assumptions

We made several assumptions in our work that helped to simplify and estimate the results under several operating scenarios.

a. A factor for temperature difference between the fluid in the tubing and the external surface of the tubing. See (Appendix X[e])

b. A factor for temperature difference between the outside formation or body surrounding the well and the inner surface of the casing. See (Appendix X[f])

c. (a) and (b) are applied into the heat loss across wellbore equations (Appendix X)

d. Production operation in a fairly cold environment.

e. 0% water-cut of crude oil produced from the bottom of the well.

f. The flow regime across the lowermost node choke is subsonic flow with a factor of 0.833 for ratio between upstream and downstream pressures.

g. The injection temperature and mass flowrate of hot water through node 1.

2.2 Procedure of operation

Figure (2) provides a diagrammatic expression of the below explained operating procedure of this technique. Figure (4) gives a systematic flowchart structure of how the developed program simulates the process in accordance to the below explained operating procedure. As flow initiates and crude oil travels along the production tubing, it loses heat to the surrounding wellbore and its temperature drops, thereby causing increase in viscosity and increase in its density. As the cloud point temperature of the paraffin or asphaltene approaches, the first node is initiated and hot water is injected at that same pressure as that of the crude oil in the production tubing at that depth and a selected temperature and mass flowrate. See (stage A, fig. 2). This hot water transfers heat into the crude and acts as a sacrificial heat loss medium for the crude. A target fluid mixture temperature is set to act as the minimum expected temperature of the fluid mixture in the production tubing. Average mixture temperature is determined from the mass, specific heat capacities and respective temperatures of both fluids within a strip size (e.g. 1ft). The drop of the average temperature of the mixture down to its minimum target temperature give rise to the inception of subsequent nodes (stage C, fig. 2) along the entire length of the production tubing.

Taking from the assumption No. 6 stated above, the subsonic flow factor for the first node will determine the pressure and temperature upstream at the other side of the choke (i.e. in the arm of the delivery tube), the choke size and the hot water's volumetric flowrate. But that of subsequent nodes flow regime across choke (sonic or subsonic) will depend on the pressures of the hot water coming through the nodal arm in the delivery tube and that exerted by the fluid mixture in the production tubing. From this we obtain choke sizes and the outlet temperatures of the hot water into the production tubing.

The pressure loss across the steam supply tubing and minor pressure head loss across bends, Tee-junctions etc., will give rise to the pressure of hot water at each nodal arm and hot water injection pressure from the surface. We also account for change in fluid velocity across the junctions (nodal arms) by multiplying the velocities from upstream with the Head loss coefficient into bends or across Tee-junctions, which thence give rise to the required mass flowrate of the hot water across each choke and finally from the surface. Heat loss from the hot water through the steam supply tubing to the surrounding wellbore will of course determine the temperature at different elevations in the tube, from thence we obtain the required input temperature of the hot water from the surface.

As the procedure continues, water-oil ratio within a strip size varies across the entire production tubing due to:

a. The expansion of the crude oil (increase in volume) because of increase in its temperature,

b. More volume of hot water injected to elevate the temperature of the fluid system in the production tubing.

The pressure at the tubing head is also determined from the mixture fluid flow. The final temperature of the mixture at the tubing head as well. More details of results are also shown in table (1).

3. Results and discussions

From figures (3 a-b) shows the diagrams of the GUI (graphical User Interface) of FEZONE. Figure (3a) shows the data input page of the program. Figure (3b) shows the results of the process in relation to the data inputted in the data input page. Table (1) shows the spreadsheet of the results gotten from nodal analysis iteration of the simulation process. Figure (5) shows a graphical representation of the fluids temperatures and temperature boundaries in the production tubing during the process. Since hot water is injected it causes rapid decline of pressure up to the surface.

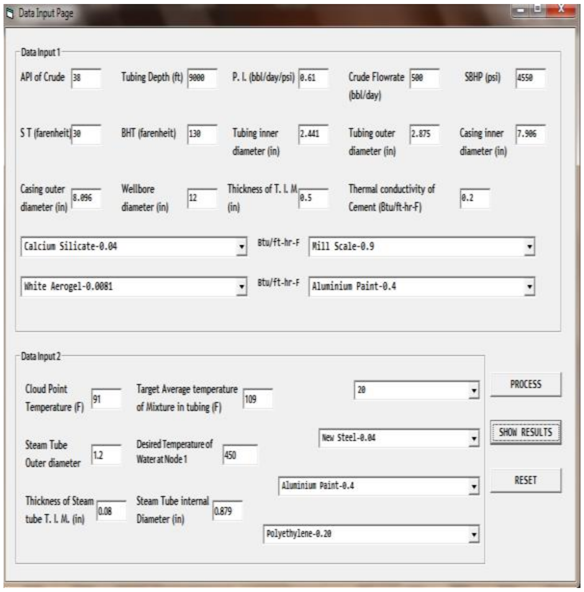


Figure 3a FEZONE Data Input Page

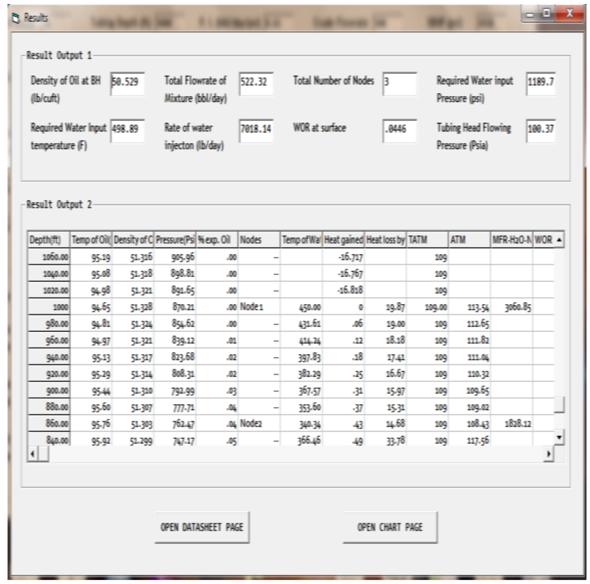


Figure 3b FEZONE Result Page

The purpose of our design was achieved via the FEZONE application results we obtained. The average temperature of mixture was maintained above the set limit (TATM=109°F) from the inception of the hot water through node 1 up to the surface and the mixture temperature was 111.9°F at the tubing head. The temperature of the crude also rose from its near cloud point temperature (91°F) at 94.65°F upto 102°F at the tubing head. The amount of water needed from the surface through the SSBCSU per day for the job was set about 22.32 barrels, the temperature and pressures required were 498.89°F and 1189.7 psi respectively.

We had to apply several well completion and production scenario that might seem to experience the problem of clogging, particularly the ones operating in fairly cold environments and has a high paraffin/Asphaltene cloud point temperature. We saw that wells operating with low flowrate and productive indexes ranging (0.55 to 0.62 bbl/day/psi) seem to give an indication of the cloud point temperature being approached by that of the crude, hence the onset. Understanding the usual pressure decline of crude along the tubing from the bottom of the well to the surface, the inception of the hot water at depths possibly below 2000 feet tend to affect the deliverability of the entire fluid to the surface by drastically reducing the tubing head flowing pressure or might possibly kill the well. Therefore, we continually adjusted the crude oil flow rate, target average temperature of mixture (TATM), tubing size, input temperature of steam through node 1 and the type of insulation materials used so that the result will be adjusted to an appreciable level.

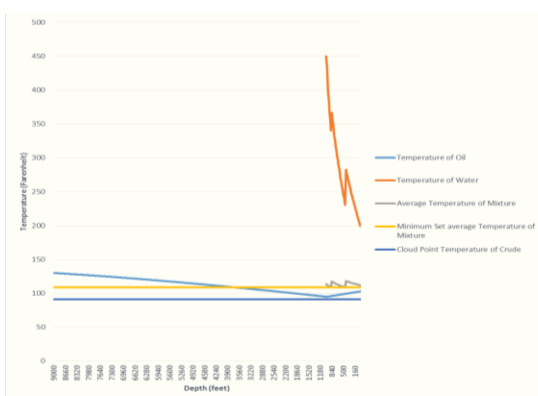


Figure 5 Temperature of fluid system in production tubing versus depth

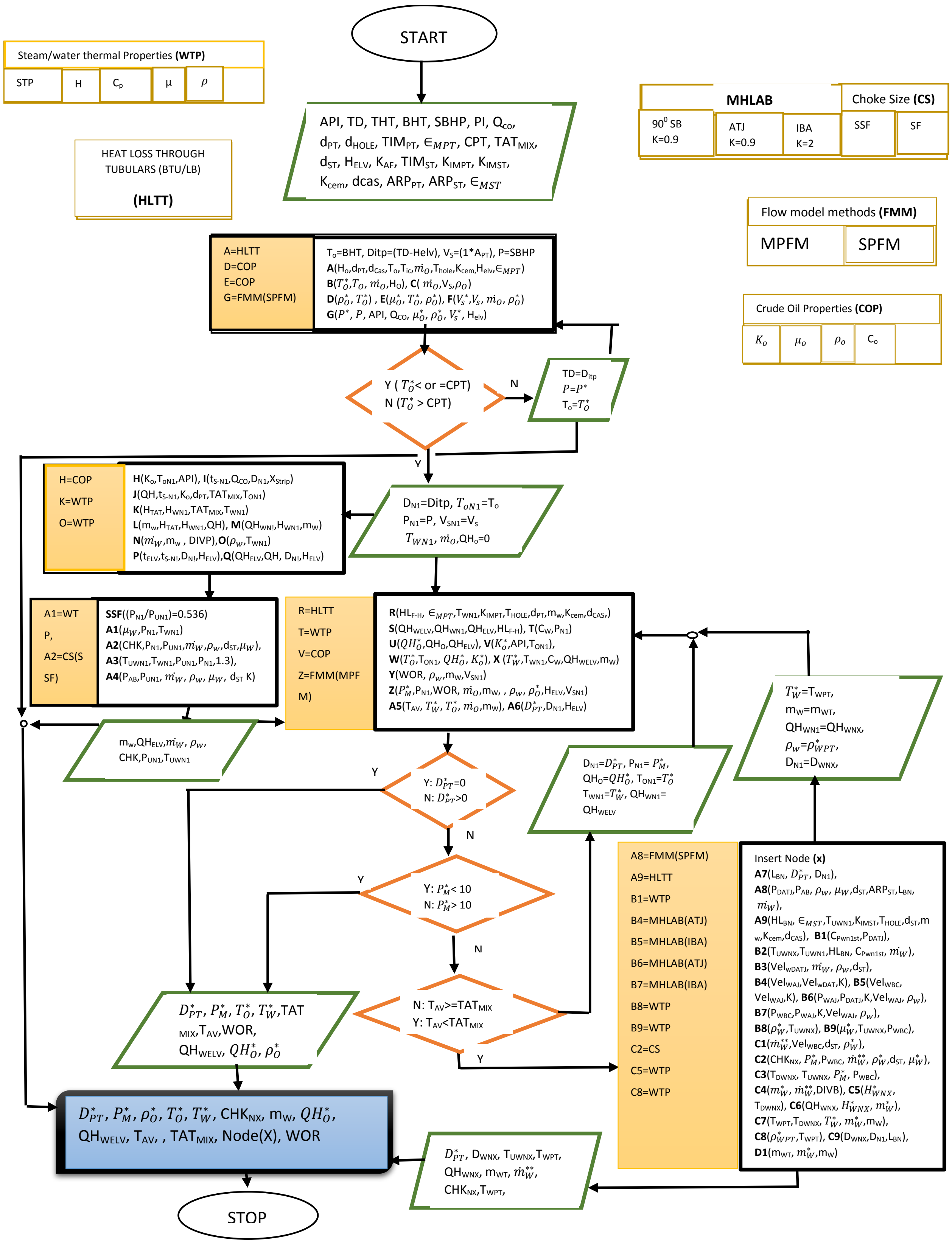


Fig 4 Flowchart of FEZONE programme

TABLE 1 Spreadsheet of FEZONE process results

Depth(ft)	Temp of Oil(F)	Density of Oil(lb/cuft)	Pressure(Psi)	% exp. Oil	Nodes	Temp of Water (F)	Heat gained by Oil (Btu)	Heat loss by Water in PT (Btu)	TATM (F)	ATM (F)	MFR-H2O-Nodes (lb/day)	WOR	TStm-Nodes (F)	Choke size (in)	HLBWST(Btu)	PHWNode (psi)	Cloud Point Temperature (F)	Heat content across ST (BTU)
9000	129.94	50.53	3723.28	0	--		-0.029		109								91	
8980	129.88	50.532	3716.23	0	--		-0.059		109								91	
5000	114.75	50.873	2309.48	0	--		-7.398		109								91	
4980	114.66	50.875	2302.38	0	--		-7.442		109								91	
4540	112.66	50.921	2146.23	0	--		-8.403		109								91	
3040	105.46	51.083	1612.81	0	--		-11.848		109								91	
3020	105.36	51.086	1605.68	0	--		-11.895		109								91	
3000	105.26	51.088	1598.56	0	--		-11.943		109								91	
1100	95.41	51.311	920.28	0	--		-16.615		109								91	
1020	94.98	51.321	891.65	0	--		-16.818		109								91	
1000	94.65	51.328	870.21	0	Node 1	450	0	19.87	109	113.54	3060.85	0.021	450	0.01356	4.7	1052.8	91	73.72
980	94.81	51.324	854.62	0	--	431.61	0.06	19	109	112.65		0.0208					91	78.42
880	95.6	51.307	777.71	0.04	--	353.6	0.37	15.31	109	109.02		0.0216					91	78.42
860	95.76	51.303	762.47	0.04	Node2	340.34	0.43	14.68	109	108.43	1828.12	0.0217	434.58	0.0079	19.15	1072.28	91	78.42
840	95.92	51.299	747.17	0.05	--	366.46	0.49	33.78	109	117.56		0.0344					91	97.57
480	98.77	51.235	472.29	0.18	--	240.8	1.59	24.4	109	109.46		0.0332					91	97.57
460	98.93	51.231	456.81	0.18	--	235.47	1.65	24	109	109.17		0.033					91	97.57
440	99.09	51.228	441.28	0.19	Node3	230.27	1.72	23.61	109	108.89	2129.17	0.0328	418.51	0.0065	15.13	1147.67	91	97.57
420	99.25	51.224	426.04	0.2	--	282.6	1.78	43.97	109	118.24		0.0493					91	112.7
20	102.42	51.152	116.23	0.34	--	202.81	3	35.8	109	112.12		0.0449					91	112.7
0	102.57	51.149	100.37	0.35	--	199.47	3.06	35.46	109	111.9		0.0446					91	112.7

***% exp. Of oil**: Percentage expansion of oil from original volume
TATM: Target Average Temperature of Mixture
ATM: Average Temperature of Mixture
MFR-H2O-Nodes: Mass Flow Rate of water across each Nodes
WOR: Water – Oil Ratio
Tstm-Nodes: Temperature of Water from each Node
HLBWST: Heat Loss By Water across Supply Tubing
PHWNode: Pressure of Hot Water upstream of Choke at each Node
ST: Supply Tubing (SSBCSU)

4. Conclusion

From our results and discussion we observed that the higher the flowrate, the lesser the required input temperature, the lesser the amount of nodes and the higher the tubing head flowing pressure. The reverse is possibly the case when the flow rate is very low. The selected input temperature of steam through node 1 will end up to dictate the required temperature of hot water from the surface. The higher the selected temperature at node 1, the higher the required temperature at the surface, thence the higher the requested amount of heat needed to raise the temperature of the supplied water.

Also, the depth of inception of node 1 and the pressure of crude in the tubing at that level, grew to dictate the required input pressure of hot water from the surface. One could possibly see how the calculation works (see Appendix XXIII)

In general, the procedure of this computer application (FEZONE) is a repeated test in order to get the best design for any production process that has an In-Well clogging challenge. Just as this procedure offers the advantage of continual production while preventive operating measures (hot water injection) is observed, the technology has its limits to the type of well and completions, production system, available materials for the job and operating environment. This designed technological analysis via the FEZONE application will give rise to the possibility of applying the technology into fields, ensuring its advantage in some wells over other preventive methods. This initiative also provides room for further modification and improvement.

Appendix I-XLIII:

I. Pressure of hydrostatic column

$P = 0.052\rho H$ (lb_m/in^2)

II. Density of oil at saturation temperature and Pressure

$\rho_{OR}=62.4278\left(\frac{141.5}{131.5+API}\right)$

III. Gros' (1984) correlation for crude oil density [16]

a. $\rho_{ox} = \rho_{OR} - C_1(T-60) + C_2(T-60)^2$ (lb/ft^3)

b. $C_1 = 0.0133 + 152.4\rho_{OR}^{-2.45}$

c. $C_2 = 0.0000081 - 0.0622 \times 10^{-(0.0764\rho_{OR})}$ T(°F)

IV. Productivity index

$P.I\,(J) = \frac{q_{co}}{\overline{p}-p_{wf}}$ $(bbl/day/psi)$

V. Specific heat capacity of oil by Gambill (1957) [15]

$c_{po} = \frac{(0.3881+0.00043T)}{\sqrt{\gamma_O}}$ $\left(\frac{Btu}{lb-°F}\right)$ @ T (°F)

VI. Thermal conductivity of hydrocarbon by Cragoe (1926) [11]

$K_o = \frac{[1.62(1-3(T-32)\times 10^{-4})]}{\gamma_O}$ $\left({}^{BTU}/_{hr-ft-°F}\right)$

VII. Enthalpy [8]

$\dot{h} = C_p\dot{T}$ $\left({}^{Btu}/_{Kg}\right)$ $(\dot{T} = °C)$

VIII. Quantity of heat [8]

$\dot{Q}H = m\dot{h}$ Btu

IX. Mass of fluid [8]

$m = \rho \times v$ (lb)

X. Heat loss from fluid to surroundings [14],[19]&[30]

a) $Q_{HL} = \frac{dQ}{dZ} \times Z$

b) $\frac{dQ}{dz} = 2\pi r_{to}U_{to} \times (T_f - T_h) \times \frac{1}{\dot{m}_f}$ $\left({}^{BTU}/_{lb-ft}\right)$

c) $U_{to} = \left[\frac{r_{to}\ln\left(\frac{r_{iw}}{r_{to}}\right)}{K_i} + \frac{1}{(\dot{h}c+\dot{h}r)} + \frac{r_{to}\ln\left(\frac{r_h}{r_{io}}\right)}{K_{cem}}\right]^{-1}$

d) $\dot{h}c = \frac{\dot{K}hc}{\left[r_{to}\ln\left({}^{r_{ci}}/_{r_{to}}\right)\right]}$

e) $T_{to} = T_f \times A_i$

f) $T_{ci} = T_h \times B_i$

g) $\dot{h}r = \sigma F_{tci}\left(T_{to}^{\ 2} + T_{ci}^{\ 2}\right)(T_{to} + T_{ci})$

h) $\frac{1}{F_{tci}} = \frac{1}{\varepsilon_{to}} + \frac{r_{ti}}{r_{ci}}\left(\frac{1}{\varepsilon_{ci}} - 1\right)$

XI. Fourier's formula on heat transfer by conduction (for fluids) [28]

$\Delta QH = {t \times K \times A \times \Delta T}/{x}$ (Btu)

XII. Chien's empirical correlation for saturation temperature [10]

XIII. Chein's empirical correlation for saturation pressure [10]

XIV. Chien's empirical correlation for specific volume of saturated liquid [10]

XV. Chien's empirical correlation for specific volume of saturated vapour [10]

XVI. Chien's empirical correlation for specific enthalpies of saturated liquid [10]

XVII. Chien's empirical correlations for specific enthalpies of saturated vapour [10]

XVIII. Chien's empirical correlation for isobaric specific heat of saturated liquid [10]

XIX. Chien's empirical correlation for isobaric specific heat of saturated vapour [10]

XX. Chien's empirical correlation for dynamic viscosity of saturated liquid [10]

XXI. Density of saturated water [17]

$\rho_W = 236.372 - 1.19187T + 0.00378125T^2 - 5.4258 \times 10^{-6}T^3 + 3.74277 \times 10^{-9}T^4 - 1.01916 \times 10^{-12}T^5$

XXII. Homogeneous Flow model (Poettmann and Carpenter) – 1952 [23]

XXIII. Mechanical Energy expression for flow in SSBSCU [7] & [18]

I. $P_{upstream} = P_{downstream} - \left\{ {\left(\frac{\rho g}{g_c}dz - \frac{2F_f v^2 dz}{2g_c d}\right)}/{144} \right\}$

XXIV. Oil viscosity correlated with the two point developed by Wright [31]

$log\left[log\left[\left(\frac{\mu_0}{\rho_0}\right)\right] + 0.6\right] = a - b[log(T + 460)]$

XXV. Dead oil viscosity [17]

$\mu_{od} = (16\ \times 10^8)T^{-2.8177}(log^0 API)^s$

$where\ s = 5.7526\log(T) - 26.9718$

XXVI. Choke size and flow determination [18]&[26]

XXVII. Choke coefficient, Guo and Ghalambor (2005) [18]

$$C_d = \frac{d_{choke}}{d_1} + \frac{0.3167}{\left(\frac{d_{choke}}{d_1}\right)^{0.6}} + 0.025[log(N_{Re}) - 4]$$

XXVIII. For flow through chokes [18]

$C_d^* = \frac{q_f}{8074 \times d_{choke}^2} \times \sqrt{{\rho}/{\Delta P}}$

XXIX. Reynolds number for Liquid flow [18]

XXX. Temperature across Choke- Joule Thomson Effect [18]

$Td_u = T_{up}\frac{Z_{up}}{du}\left(\frac{P_{du}}{P_{up}}\right)^{\frac{k_i - 1}{k_i}}$

XXXI. Pressure across 90⁰ smooth bend for threaded union [7]

$P_{LAB(up)} = P_{LAB(down)} + K_L\frac{V^2}{2g} \times \frac{\rho}{144}$ (psi)

XXXII. Tee-line flow across junction of other upper nodes for threaded union [7]

$P_{LAj(up)} = P_{LAj(down)} + K_L\frac{V^2}{2g} \times \frac{\rho}{144}$ (psi) K_L=0.9

XXXIII. Tee (branched flow) into other nodes [7]

$P_{Lij(down)} = P_{LAj(up)} - K_L\frac{V^2}{2g} \times \frac{\rho}{144}$ (psi) K_L=2.0 (threaded)

XXXIV. Velocity of fluid across 90° smooth bend for threaded union

$V_{LAB(up)} = (1 + K_L) \times V_{LAB(down)}$, K_L = 0.9

XXXV. Velocity of fluid flow across Tee-junction for threaded union

$V_{LAj(up)} = (1 + K_L) \times V_{LAj(down)}$, K_L = 0.9

XXXVI. Velocity of fluid through Tee (branched flow) into other nodes

$V_{Li(down)} = V_{LAj(up)}/K_L$, K_L= 2.0

XXXVII. Average temperature of mixture [8]

$T_{AV} = {(m_1C_{p1}T_1 + m_2C_{p2}T_2)}/{(m_1C_{p1} + m_2C_{p2})}$ T_{AV} (⁰F)

XXXVIII. Flow for single fluid through pipes [7]&[18]

$$P_{downstream} = P_{upstream} - \left\{ \left(\frac{\rho g}{g_c} dz + \frac{2F_f v^2 dz}{2g_c d} \right) \Big/ 144 \right\}$$

XXXIX. Thermal conductivity of annular fluids [14] & [17]
White Aerogel = 0.0081 (Btu/hr-ft-°F)
Black Aerogel = 0.0069 (Btu/hr-ft-°F)
Calcium Silicate = 0.04 (Btu/hr-ft-°F)
Carbon Fibre = 0.0208 (Btu/hr-ft-°F)
XL. Thermal conductivity for cement [14] = 0.2 to 0.6 (Btu/hr-ft-°F)
XLI. Thermal conductivity of insulation materials [18]
Polyethylene = 0.20 (Btu/hr-ft-°F)
Polypropylene = 0.13 (Btu/hr-ft-°F)
I. Polyurethane = 0.07 (Btu/hr-ft-°F)
XLII. Emissivity of outside tubing and inside casing [2] & [17]
Aluminium Paint = 0.4
Mill scale = 0.9
Steel = 0.15
XLIII. Absolute roughness of pipe [2]
New Steel = 0.04 mm; Galvanised Steel = 0.15 mm
Copper = 0.015 mm; Brass = 0.015 mm

Nomenclature

Codes	***Meanings***	***Referral***	***Unit***
WTP	*Water thermal properties*		
STP	*Saturation temperature and pressure*	*Appendices XII & XIII*	
H	*Enthalpy of water*	*Appendix XVI*	*Btu/lb*
C_P	*Specific heat capacity of water*	*Appendix XVIII*	*Btu/(lb-°F)*
μ	*Viscosity of water*	*Appendix XX*	*Cp*
ρ	*Density of water*	*Appendix XXI*	*lb/cuft*
MHLAB	*Minor head loss across bends*		
MHLAB (SB)	*Smooth bend*	*Appendix XXXI*	
MHLAB (ATJ)	*Across T- Junction*	*Appendix XXXII*	
MHLAB (IBA)	*Into branched arm*	*Appendix XXXIII*	
CS	*Choke sizes*	*Appendices XXVII – XXIX*	*inches*
CS (SSF)	*Sub-sonic flow*	*Appendix XXVI*	
CS (SF)	*Sonic flow*	*Appendix XXVI*	
FMM	*Flow model methods*		
FMM (MPFM)	*Multi-phase flow model*	*Appendix XXII*	
FMM (SPFM)	*Single phase flow model*	*Appendix XXIII*	
K_o	*Thermal conductivity of oil*	*Appendix VI*	*Btu/(ft-hr-°F)*
μ_O	*Viscosity of crude oil*	*Appendices XXIV & XXV*	*Cp*
ρ_O	*Density of crude oil*	*Appendix V*	*Lb/cuft*
C_O	*Specific heat capacity of oil*	*Appendix VII*	*Btu/(lb-°F)*
TD	*Tubing depth*		*Ft*
THT	*Tubing head temperature*		*°F*
BHT	*Bottom hole temperature*		*°F*
SBHP	*Static bottom hole pressure*		*Psi*
PI	*Productivity index*	*Appendix VI*	*Bbl/day/psi*
Q_{CO}	*Oil flow rate*		*Bbl/day*
d_{PT}	*Diameter of production tubing*		*Inches*
d_{Hole}	*Diameter of hole*		*Inches*
TIM_{PT}	*Thermal insulation material of production tubing*	*Appendix XLI*	*Btu/(ft-hr-°F)*

ϵ_{MPT}	Emissivity of material on production tubing	Appendix XLII	
CPT	Cloud point temperature		^oF
TAT_{MIX}	Target average temperature of mixture		^oF
d_{ST}	Diameter of steam tube		Inches
H_{ELV}	Nodal elevation in production tubing		Ft
K_{AF}	Thermal conductivity of annular fluid	Appendix XXXIX	Btu/(ft-hr-^oF)
TIM_{ST}	Thermal insulation material of steam tube	Appendix XLI	
K_{IMPT}	Thermal conductivity of insulation material in production tubing	Appendix XLI	Btu/(ft-hr-^oF)
K_{IMST}	Thermal conductivity of insulation material in steam tube	Appendix XLI	Btu/(ft-hr-^oF)
K_{Cem}	Thermal conductivity of cement	Appendix XL	Btu/(ft-hr-^oF)
d_{CAS}	Diameter of casing		inches
ARP_{PT}	Absolute roughness of pipe – production tubing	Appendix XLII	mm
ARP_{ST}	Absolute roughness of ripe – rteam tube	Appendix XLII	mm
ϵ_{MST}	Emissivity of material on steam tube	Appendix XLI	
T_o	Temperature of oil		^OF
V_S	Volume of oil strip		Cuft
P	Old pressure		Psi
Ditp	Depth after each elevation		Ft
A_{PT}	Area of production tubing pipe		Ft^2
T_{IC}	Temperature inside of casing	Appendix X	^oF
T_{OT}	Temperature outside of tubing	Appendix X	^OF
T_{Hole}	Temperature of hole	Appendix X	^OF
$\dot{m}_O$	Mass of oil in strip		Lb
T_O^*	Temperature of oil at new elevation		^OF
ρ_O^*	Density of oil at new temperature	Appendix III	Lb/cuft
μ_O^*	Viscosity of oil at new temperature	Appendix XXIV	Cp
V_S^*	Volume of oil strip at new elevation	Appendix IX	Cuft
P^*	Pressure at new elevation in production tubing	Appendix XXII	Psi
D_{N1}	Depth of node 1		Ft
T_{ON1}	Temperature of oil at node 1		^OF
P_{N1}	Pressure of oil at node 1		Psi
V_{SN1}	Volume of oil strip at node 1		cuft
QH_O	Heat gained by oil	Appendix XI	Btu
T_{WN1}	Temperature of injected water at node 1		^OF
t_{S-N1}	Time for strip of oil to rise from node 1 depth to surface		sec
QH	Quantity of heat gained	Appendix VIII	Btu
QH_{WN1}	Quantity of heat of water at node 1	Appendices VII & VIII	Btu
M_W	Mass of water with strip of oil		Lb
$\dot{m}_W$	Mass flowrate of water through node		Lb/hr
DIVP or DIVB	$\{$velocity of crude in tubing (ft/sec)$\}^{-1}$		sec/ft
QH_{ELV}	Quantity of heat gained by crude at each elevation from steam		Btu
P_{UN1}	Pressure of water upstream of node 1 after choke (Valve)		Psi
P_{AB}	Pressure after 90^o bend	Appendix XXXI	psi
CHK	Choke size of node 1		Inches
HL_{F-H}	Heat loss from fluid to hole	Appendix X	Btu
C_W	Specific heat capacity of water at node 1	Appendix XVIII	Btu/(lb-^oF)
QH_O^*	Quantity of heat gained by oil at new level		Btu
K_O^*	Thermal conductivity of oil at new level	Appendix VI	Btu/(ft-hr-^OF)
T_O^*	Temperature of oil at new elevation		^OF
T_W^*	Temperature of water at new elevation		^OF
P_M^*	Pressure of mixture at new elevation	Appendix XXII	Psi

T_{AV}	*Average temperature of mixture at new level*	*Appendix XXXVII*	*^oF*
D^*_{PT}	*Depth in production tubing at each elevation*		*Ft*
L_{BN}	*Distance between new and previous nodes*		*Ft*
P_{DATJ}	*Pressure drop across tee-tunction*		*Psi*
HL_{BN}	*Heat loss between present and previous nodes*		*Btu*
C_{PWNLST}	*Specific heat capacity of water after node in steam tube*	*Appendix XVIII*	*Btu/(lb-^oF)*
T_{UWN1}	*Temperature of water upstream at node 1*		*^oF*
T_{UWNX}	*Temperature of water upstream at node X*		*^oF*
Vel_{WDATJ}	*Velocity of water downstream across tee-junction*		*Ft/sec*
Vel_{WAJ}	*Velocity of water across junction*	*Appendix XXXV*	*Ft/sec*
Vel_{WBC}	*Velocity of water into branched arm*	*Appendix XXXVI*	*Ft/sec*
P_{WAJ}	*Pressure of water across tee-junction*	*Appendix XXXII*	*Psi*
P_{WBC}	*Pressure of water into branched arm*	*Appendix XXXIII*	*Psi*
ρ^*_W	*Density of water at node X in steam tube*	*Appendix XXI*	*Lb/cuft*
μ^*_W	*Viscosity of steam at node X in steam tube*	*Appendix XX*	*Cp*
$\dot{m}^{**}_W$	*New mass flow rate of water into node X*		*Lb/day*
CHK_{NX}	*Choke size at node X*	*Appendices XXVI, XXVII & XXVIII*	*Inches*
T_{DWNX}	*Temperature downstream of water at node X*		*^OF*
m^*_W	*Injected mass of water into strip through node X*		*Lb*
QH_{WNX}	*Quantity of heat of water at node X*		*Btu*
T_{WPT}	*Temperature of mixed water in production tubing at node X depth*	*Appendix XXXVI*	*^OF*
ρ^*_{WPT}	*Density of mixed water in production tubing at node X depth*	*Appendix XXI*	*Lb/cuft*
D_{WNX}	*Depth of water at node X*		*Ft*
M_{WT}	*Total mass of water associated with oil strip after node X*		*lb*

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