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Evaluation of Flow Assurance in Onshore Production Facilities in the Niger Delta

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Authors' contributions

This work was carried out in collaboration between all authors. Author IKC designed the study and analyzed the results. Author OCV wrote the manuscript, managed the literature searches and experimental process. Author ONP performed the field simulation with PipeSim. All authors read and approved the final manuscript.

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ABSTRACT

Flow assurance is the efficient and successful flow of fluids in pipes. Some of the flow assurance challenges that can be encountered include hydrate formation, sand production, wax precipitation, scale deposits and emulsion problems. In onshore production facilities in the Niger Delta, wax deposition is the major challenge to efficient fluid flow. Consequently, it has been the focus of research to profer effective predictive and preventive solutions to a problem that has been tackled with curative methods for decades. This paper investigated paraffinic wax deposition using laboratory tests and field simulation with PipeSim; a pipeline simulator. The tests gave wax content results of 3.73% and 4.77% for samples A and B. The Simulation gave results of 3.71% and 4.78% for samples A and B, producing a good match when compared against the test results with a difference of less than <0.05%. This paper therefore recommends the use of PipeSim simulation package for wax deposition determination and prediction especially in the absence of laboratory data in addition to properly scheduled pigging and solvent injections to check wax deposition in facilities handling waxy crude oil.

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NOMENCLATURE

T =Shear stress
μ = viscosity
Υ = Shear rate
PV = Plastic viscosity
γ = Yield strength
WAT = Wax appearance Temperature
WDT = Wax deposition Temperature
CWDT = Critical Wax Deposition Temperatures
WOR = Water-Oil ratio

1. INTRODUCTION

The term "flow assurance" was coined by Petrobras in early 1990s to mean "guarantee of flow' [1]. It covers all methods to ensure the efficient delivery of hydrocarbons from wells to collection facilities. It involves the successful and economic flow of hydrocarbons from reservoirs to point of sale. It covers the efficient handling of solid deposits like hydrates, wax, asphaltenes, scale and sand.

The most prevalent flow assurance challenge in onshore production facilities is wax deposition, which is the blocking of flow lines due to the deposition of heavy organic materials present in the oil [2]. It is the precipitation, agglomeration and accumulation of organic compounds from the crude oil stream on to the walls of pipelines and in process vessels. It is one of the oldest of oil production problems. In the early 1920s, wax deposits were reported in subsurface production equipment in some wells in the US. [3]. More recently, Tube tech international lost about six-figure sums per day when a pig got stuck in wax during a subsea pipeline pigging operation. It took the company a week, using hot tapping method to resolve the problem according to Mike Watson, Tube tech technical director [4]. In the Niger delta, pipelines and production tubings have been known to wax up, necessitating frequent wax cutting, using scrapers conveyed by wireline, which is an expensive practice, as was the case at an Agip facility at Ebocha, Rivers State [5].

Wax deposits are commonly called paraffin though they may be a mixture of both paraffin and asphaltenes [6]. Waxes from Niger Delta crude oils are paraffinic [7]. They produce Macrocrystalline wax deposits [8].

Wax deposition depends on temperature and pressure, and determining the acceptable operational temperature limits is essential in tackling the problem. Proper identification and characterisation as well as accurate description of the behaviour of various deposits should be a part of field development planning and design of control measures [9].

Temperature reduction is the most common cause of wax deposition because wax solubility in hydrocarbon fluids decreases as the temperature is lowered [10]. Some of the situations that result in wax precipitation from crude oil include;

Change in oil composition which can be affected by;

1. Mixing with other streams or losing the volatile components
2. Foreign matter in the crude such as silt, scale, salts, and corrosion by-products (iron sulphide and iron oxide) which serve as nuclei around which the paraffin can crystallize. When this mechanism begins, continued growth can proceed.

Temperature drop/cooling rate which can be altered as follows;

3. The temperature of the produced fluid falls below the WAT as it comes up the well bore and into the processing facility. Paraffin may begin to come out of solution and form wax deposits on the tubing and pipe walls.
4. The cooling effect of expanding through an orifice will cause a fall temperature.
5. The cooling produced from radiation of heat from the oil and gas to the surroundings.
6. The cooling from the liberation of dissolved gas form oil.
7. The cooling resulting from the vaporization of lighter constituents.
8. The cooling effect of produced water from wells of higher water cut.

Pressure Changes

1. Decreasing pressures below the crude's bubble point, decreases solubility and thus, increases precipitation

Other factors that enhance wax precipitation and deposition are;

1. Rough, porous, or irregular surfaces can increase deposition.
2. Paraffin Concentration. As the molecular weight of paraffin increases in the solution, the cloud point increases.
3. Molecular mass of paraffin molecules. If the stream contains paraffins of high molecular mass of C_{18}^{+}, it will likely precipitate wax.
4. Occurrence of nucleating materials such as asphaltene, formation fines and corrosion products. These will encourage agglomeration of the precipitated crystals.
5. Water-Oil ratio. Increasing WOR, decreases wax solubility. Wax is not soluble in water. Water losses heat faster and produce a cooling effect.
6. Shear Movement.

2. RHEOLOGY OF WAXY CRUDE OIL

The Rheology of waxy crude oils is strongly temperature dependant and also shear rate dependant [11]. Above the crude's cloud point, it exhibits Newtonian fluid behaviour, below the cloud point, waxy crudes exhibits non-Newtonian fluid behaviour because of wax crystallisation [12].

$$\mathrm{T} = -\mu \mathrm{Y} \tag{1}$$

Between cloud and pour points, the crude is pseudo-plastic [13].

$$\mathrm{T} = PV(-\mathrm{Y}) \tag{2}$$

At pour point and below, it becomes a thixotropic/yield plastic fluid

$$\mathrm{T} = \gamma + PV(-\mathrm{Y}) \tag{3}$$

This explains why increased pump rate is required to restart pipes transporting waxy crudes especially where there is a significant temperature gradient over a long distance.

A good knowledge of the rheology of waxy crude oil is important in the production design for handling waxy crude oils.

3. METHODOLOGY

Two samples collected from different fields in the Niger Delta, ten days after pigging, were characterized and tested (cooled) and their wax contents determined at 0℃. The samples were analysed using Gas Chromatography to determine their SCN (Single Carbon Number) fractions. Fluid properties like molecular weights and densities were determined. Flow parameters like viscosity, water cut and wax content were determined for each sample (Tables 1A and 2A). The paraffin cold finger deposition test was used to determine the sample wax content. The samples were cooled to 0℃ (273 k) and the amount of wax precipitated was scrapped and measured. The amount of wax deposited at 0℃ was measured and given in percentage (%) of the sample. Results are shown in Tables 1B and 2B of the Appendix. These results are the control against which the simulation results were compared.

3.1 Wax Content Determination Using Pipesim

A pipeline simulator PIPESIM software was used to simulate field conditions using data on Pipe dimensions, Pigging schedule, pump pressures and heat transfer rates. With these conditions and the fluid composition (Tables 1A and 2A), PipeSim modelled the process (Fig. 1 of Appendix) and calculated amount of deposited wax at 0℃ for each of the sample.

Table 4. Data for simulation

Ambient temperature	20℃
Validation temperature	0℃
Thermal conductivity	150 Btu/hr/ft
Pipe dimensions	10 inches x 19.4 km
Pump discharge pressure	100 psi
Density of Sample A	806 kg/m^3
Density of Sample B	836 kg/m^3
Sample collection time	10 days after pigging (240 hours)

3.2 Wax Content Determination with Time

The simulation end time was extended from 240 hours (10 days) to 720 hours (30 days) and eventually to 4months, at the same operating conditions of temperature, pressure and flow rate to determine the effect of time on the volume of wax deposited. Results gotten were converted to percentage to account for the part volume of sample taken (0.1 kg) during laboratory experiment. This was used to recommend a time range for pipeline pigging.

The simulator results were compared against the controls in a spreadsheet.

3.3 Calculating Cloud Point

PipeSim was also used to determine the cloud point of the samples. Simulation for Critical Wax Deposition Temperatures (CWDT) was run and the values in the Tables 3A and 3B obtained.

4. RESULTS

The laboratory tests run to determine wax content of the fluid samples have the results on Tables 1B and 2B of the Appendix. A summary of the results are presented below. This result is the control against which other methods are validated.

Table 5A. Wax content of samples

Samples	Wax content (% wt of sample)
A	3.73
B	4.77
C	3.45

The PipeSim simulated wax deposition was run at 0℃ and for 240 hours (10 days) because the samples were collected ten days after pigging. The results are presented in Figs. 2 and 3 of the Appendix. Below is a summary of the results in comparism against the control:

Table 5B. Comparism of wax content results

Sample	Laboratory result	PipeSim result
A	3.73%	3.71%
B	4.77%	4.78%
C	3.45%	3.49%

Graphical presentations of this comparism for each sample is shown in Figs. 4 and 5 of the Appendix

4.1 Wax deposition with Time

Wax content simulation time as extended to 30 days (720hrs, one month) and then to 4 months for each sample. The graphs are presented in Figs. 6A to 7B of the Appendix. A summary of wax deposits with time is presented in the graph below. These results indicate that it would be dangerous to ignore pigging the pipeline transporting this crude oil up to four months (unless another control method like chemical injection is in place). It is advisable to pig monthly to avoid incidences of stuck pigs.

4.2 Cloud Point Determination using PipeSim

The results of the Critical wax deposition temperature determination using PipeSim were presented in Table 5 of the Appendix.

5. DISCUSSION AND ANALYSIS OF RESULTS

Wax deposition was investigated using two different methods; Laboratory tests and Simulation with PipeSim. Wax depositions evaluated at 0℃ were compared.

The laboratory tests results are the control. They include sample compositions with mole fractions, density, viscosity and wax content in weight percent of the samples (Tables 1A to 2B of the Appendix). The wax contents were measured at 0℃. The wax volume was calculated using mass of the wax content and the density of the sample. This volume was converted to cubic ft (ft^3).

The Simulation which took cognisance of field conditions (Fig. 1), time of sample collection and sample compositions, determined the amount of wax that can be deposited at zero degrees Celsius (Figs. 2 and 3) for both samples. Simulation and control results were compared and showed a good match (Table 4B and Figs. 4 and 5) with a difference of less than $\pm$0.05%.

Having determined wax content after ten days (24 hours), the simulation end time was extended to determine wax deposition after longer periods of one (Figs. 6A and 7A) and four months (Figs. 6B and 7B). The results of simulated wax content after one and four months indicate possible deposition rates. Hence, it can be used to draw schedules for pigging. The graphical representations of simulated percentage wax content with time (Figs. 8A and 8B) indicate that wax left unchecked in a pipeline conveying crude oil samples A, B, and C will wax up above 50% in four months. This poses such consequences as pipe replacement, production deferment, back pressure that can kill low pressure/low rate wells, inefficiency of control methods like pipe re-start because of wax aging, etc.

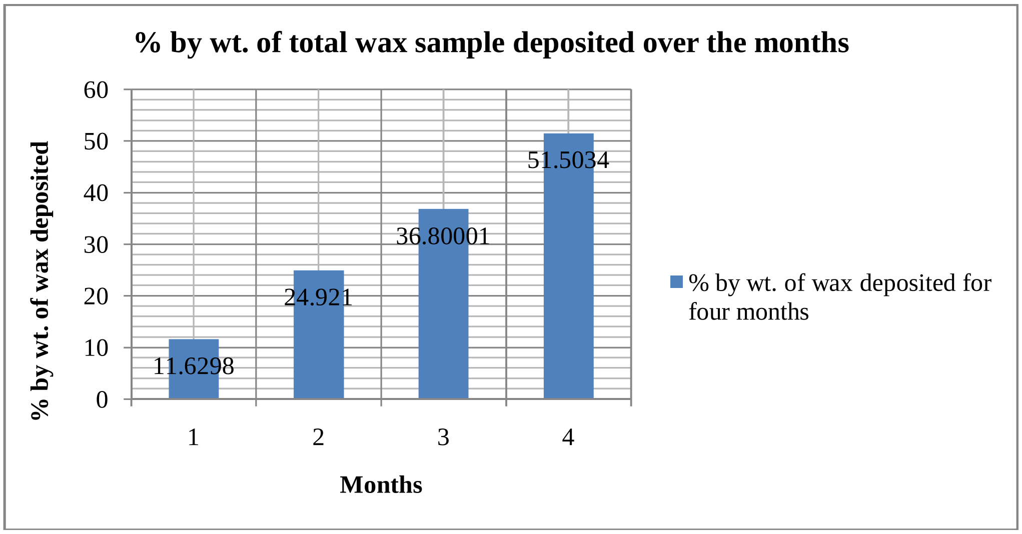

Fig. 8A. Simulated percentage wax content with time for sample A

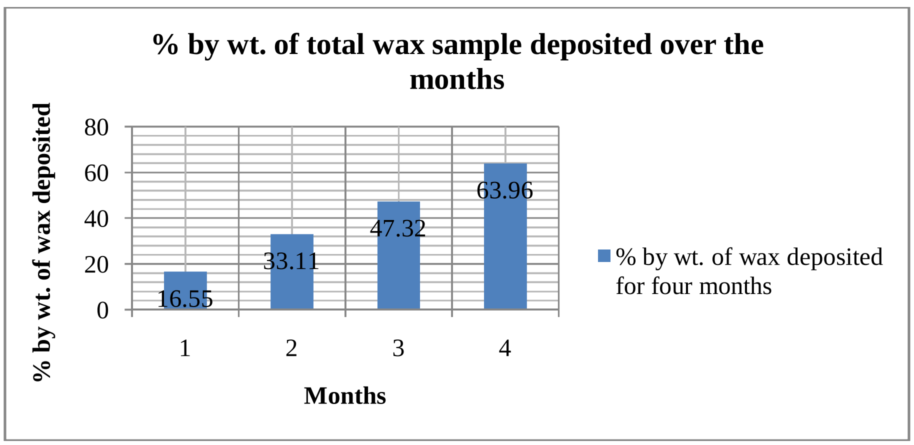

Fig. 8B. Simulated percentage wax content with time for sample B

Simulation was also run to determine the Critical wax deposition temperature (Tables 3A and 3B). The essence of this is that it should be inbuilt in the plant design ensuring that the fluid temperature does not fall as low as this value. This can be achieved using heater treaters.

6. CONCLUSION

1. Wax deposition which is the most prevalent flow assurance issue in production facilities was investigated with crude oil samples from onshore Niger delta fields.
2. The sample compositions indicate the light and paraffinic nature of crudes from this region.
3. Wax content of the samples were measured at the laboratory at 0℃
4. PipeSim software was used to simulate operating conditions and consequently, calculate wax content at 0℃. It also simulated wax deposition as a function of time.
5. The results from laboratory tests were compared with PipeSim results, producing a good match with less than $\pm$0.5% difference for each of the samples.
6. The simulated percentage wax content with time indicate that if wax deposition is left unchecked in a pipeline conveying crude oil samples A and B will wax up above 50% in four months. This poses such consequences as pipe replacement, production deferment and inefficiency of

control methods like pipe re-start because of wax aging.

7. RECOMMENDATION

1. Wax deposition strongly depends on temperature, so fluid heat loss should be minimized in plant design through pipe insulation.
2. Fluid temperatures should be maintained above the WDT and possibly above the WAT. Heater treaters should be included in plant design. Hot oiling and pipe heating can also be employed to the same aim.
3. Solvents and other chemicals used to checkmate wax deposition should be field tested for optimal results and to minimize aggravating wax deposition problems and emulsions.
4. Regular pigging is recommended in plants handling waxy crudes to avoid incidences of stuck pigs, and mitigate against wax build up.
5. Wax content calculated with PipeSim software gave a good match with the control and so can be used for predictions where laboratory data is not readily available. It was also used to predict wax depositions in the pipeline with time, indicating that when left too long, as in the case of 4months, over 50% of the pipeline will be filled with wax. This can be used to prepare pigging schedules and plan other wax control measures.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Table 1A. Sample a fluid composition

Sample A	**Separator oil composition**
Component	**Mole %**
N_2	0.15
CO_2	0.32
H_2S	0.00
C_1	3.99
C_2	0.70
C_3	0.13
i-C_4	0.12
n-C_4	0.14
i-C_5	0.24
n-C_5	0.24
C_6	1.08
C_7	1.93
C_8	8.06
C_9	7.14
C_{10}	12.28
C_{11}	13.06
C_{12}	13.60
C_{13}	12.79
C_{14}	8.96
C_{15}	7.71
C_{16}	3.09
C_{17}	1.69
C_{18}	1.48
C_{19}	0.54
C_{20}	0.25
C_{21}	0.13
C_{22}	0.07
C_{23}	0.03
C_{24}	0.01
C_{25}	0.01
C_{26}	0.01
C_{27}	0.01
C_{28}	0.01
C_{29}	0.01
C_{30}+	0.02
Total	100.00
M.wt(g/gmol)	152.11
Density (g/cm^3)	0.806
M.Wt C_7+[g/gmol]	161.09
Mol % of C_7+	92.88

Table 1B. Sample a crude oil flow assurance parameters

Parameter	**Method**	**Value**
Base Sediment and Water (%)	ASTM D97	<0.01
Copper Corrosion	ASTM D130	Slightly Tarnished (1A)
Wax Content (%) @ 0^0C	ASTM D5452	3.73

Table 2A. Sample B fluid composition

Sample B	**Recombined separator oil**
Component	**Mole %**
C_2	0.083
C_3	1.594
i-C_4	1.436
n-C_4	4.708
i-C_5	3.271
n-C_5	3.548
C_6	5.668
C_7	9.260
C_8	11.832
C_9	6.757
C_{10}	5.831
C_{11}	4.412
C_{12}	3.674
C_{13}	3.701
C_{14}	3.522
C_{15}	3.578
C_{16}	2.466
C_{17}	2.166
C_{18}	2.818
C_{19}	1.867
C_{20}	1.524
C_{21}	1.368
C_{22}	1.281
C_{23}	1.192
C_{24}	1.144
C_{25}	1.141
C_{26}	0.987
C_{27}	1.005
C_{28}	0.998
C_{29}	1.095
C_{30}+	6.076
Total	100.000
M. wt (g/gmol)	180.5260
Density(gm/cm^3)	0.8360
M. Wt C_7+[g/gmol]	208.9875
Mol % of C_7+	79.6927

Table 2B.Sample B crude oil flow assurance parameters

Parameter	**Method**	**Value**
Base Sediment and Water (%)	ASTM D97	<0.01
Copper Corrosion	ASTM D130	Slightly Tarnished (1A)
Wax Content (%) @ 0℃	ASTM D5452	4.77

Analysis for Sample A

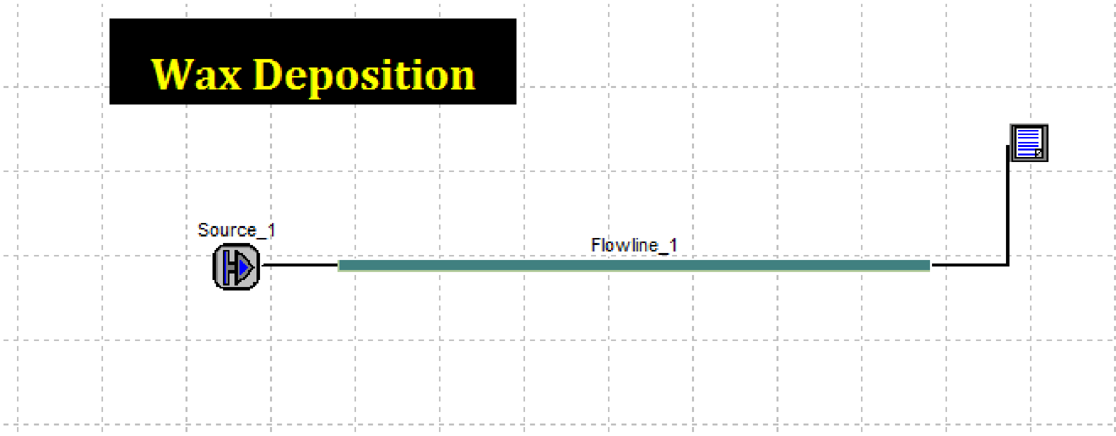

Fig. 1. Schematic of the pipeline model in PIPESIM

Table 3A. Critical Wax Deposition Temperature (CWDT) for sample A

	Dist. (ft)	Fluid Pres. (psia)	Fluid Temp. (F)	Heat transfer Coefficients (btu/hr/ft2/F) Overall	Fluid Film	Wall Temp. (F)	CWDT (F)	Wax Deposition Rate (mg/in2/hr)	Wax I.D. (in)	Wax Thickness Actual (in/1e3)	Delta (in/1e3/hr)	Wax Volume Actual (ft3)	Delta (ft3/hr)
FLOWLINE Flowline_1													
1	0.0000	100.00	68.404	64.864	34.138	68.404	104.17	0.545258	9.9714	14.29790	.0353327	0.000000	0.000000
s001	1.0000	100.00	68.404	64.864	34.138	68.404	104.17	0.545258	9.9714	14.29790	.0353327	.0031149	.0003050
s002	796.10	99.949	68.201	86.464	34.142	68.201	104.17	0.468104	9.9830	8.502890	.0303363	1.473700	0.146627
s003	1591.2	99.847	68.000	150.00	34.048	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	2386.3	99.745	68.000	150.00	34.041	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	3181.4	99.644	68.000	150.00	34.050	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
2	3182.4	99.593	68.000	150.00	34.061	68.000	104.17	0.000000	10.000	0.000000	0.000000	1.476810	0.146932
s001	3183.4	99.593	68.000	150.00	34.060	68.000	104.17	.6655e-4	10.000	.0009669	.4313e-5	.2110e-6	.2103e-7
s002	3978.5	99.542	68.000	150.00	34.060	68.000	104.17	.9999e-4	10.000	.0013537	.6481e-5	.0002348	.2357e-4
s003	4773.6	99.440	68.000	150.00	34.071	68.000	104.17	.5714e-4	10.000	.0009669	.3703e-5	.0001677	.1673e-4
s004	5568.7	99.338	68.000	150.00	34.081	68.000	104.17	.4285e-4	10.000	.0005801	.2777e-5	.0001006	.1004e-4
s005	6363.8	99.236	68.000	150.00	34.092	68.000	104.17	.3571e-4	10.000	.0005801	.2314e-5	.0001006	.1004e-4
3	6364.8	99.185	68.000	150.00	34.103	68.000	104.17	0.000000	10.000	0.000000	0.000000	.0006040	.6041e-4
s001	6365.8	99.185	68.000	150.00	34.103	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	7160.9	99.133	68.000	150.00	34.103	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	7956.0	99.031	68.000	150.00	34.114	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	8751.1	98.929	68.000	150.00	34.124	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	9546.2	98.826	68.000	150.00	34.135	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
4	9547.2	98.775	68.000	150.00	34.146	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s001	9548.2	98.775	68.000	150.00	34.146	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	10343.	98.724	68.000	150.00	34.146	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	11138.	98.621	68.000	150.00	34.157	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	11934.	98.518	68.000	150.00	34.167	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	12729.	98.416	68.000	150.00	34.178	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
5	12730.	98.364	68.000	150.00	34.189	68.000	104.17	.6655e-4	10.000	.0009663	.4313e-5	.2108e-6	.2089e-7
s001	12731.	98.364	68.000	150.00	34.189	68.000	104.17	.3882e-4	10.000	.0005798	.2516e-5	.1265e-6	.1251e-7
s002	13526.	98.313	68.000	150.00	34.189	68.000	104.17	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	14321.	98.210	68.000	150.00	34.199	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	15116.	98.107	68.000	150.00	34.210	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	15911.	98.004	68.000	150.00	34.221	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
6	15912.	97.952	68.000	150.00	34.231	68.000	104.16	0.000000	10.000	0.000000	0.000000	.1265e-6	.1251e-7
s001	15913.	97.952	68.000	150.00	34.231	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	16708.	97.900	68.000	150.00	34.232	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	17503.	97.797	68.000	150.00	34.242	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	18298.	97.693	68.000	150.00	34.253	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	19093.	97.590	68.000	150.00	34.264	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
7	19094.	97.538	68.000	150.00	34.274	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s001	19096.	97.538	68.000	150.00	34.274	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	19891.	97.486	68.000	150.00	34.274	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	20686.	97.382	68.000	150.00	34.285	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	21481.	97.278	68.000	150.00	34.296	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	22276.	97.174	68.000	150.00	34.306	68.000	104.16	0.000000	10.000	0.000000	0.000000	0.000000	0.000000

Table 3B. Critical Wax Deposition Temperature (CWDT) for sample B

	Dist. (ft)	Fluid Pres. (psia)	Fluid Temp. (F)	Heat transfer Coefficients (btu/hr/ft2/F) Overall	Heat transfer Coefficients (btu/hr/ft2/F) Fluid Film	Wall Temp. (F)	CWDT (F)	Wax Deposition Rate (mg/in2/hr)	Wax I.D. (in)	Wax Thickness Actual (in/1e3)	Wax Thickness Delta (in/1e3/hr)	Wax Volume Actual (ft3)	Wax Volume Delta (ft3/hr)
FLOWLINE Flowline_1													
1	0.0000	80.000	32.290	150.00	13.418	431.49	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s001	1.0000	80.000	32.290	150.00	13.418	431.49	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	796.10	79.986	50.290	150.00	13.456	247.72	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	1591.2	79.962	68.000	150.00	16.770	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	2386.3	79.939	68.000	150.00	16.772	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	3181.4	79.915	68.000	150.00	16.772	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
2	3182.4	79.903	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s001	3183.4	79.903	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	3978.5	79.891	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	4773.6	79.867	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	5568.7	79.843	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	6363.8	79.819	68.000	150.00	16.773	68.000	104.13	.2299e-4	10.000	.0003219	.1490e-5	.5584e-4	.2585e-6
3	6364.8	79.807	68.000	150.00	16.773	68.000	104.13	.3832e-4	10.000	.0005365	.2484e-5	.5596e-4	.2591e-6
s001	6365.8	79.807	68.000	150.00	16.773	68.000	104.13	.3832e-4	10.000	.0005365	.2484e-5	.1171e-6	.5420e-9
s002	7160.9	79.795	68.000	150.00	16.773	68.000	104.13	.2299e-4	10.000	.0003219	.1490e-5	.5584e-4	.2585e-6
s003	7956.0	79.771	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	8751.1	79.748	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	9546.2	79.724	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
4	9547.2	79.712	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	.5596e-4	.2591e-6
s001	9548.2	79.712	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	10343.	79.700	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	11138.	79.676	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	11934.	79.652	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	12729.	79.628	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
5	12730.	79.616	68.000	150.00	16.773	68.000	104.13	.2299e-4	10.000	.0003219	.1490e-5	.7023e-7	.3252e-9
s001	12731.	79.616	68.000	150.00	16.773	68.000	104.13	.3832e-4	10.000	.0005365	.2484e-5	.1171e-6	.5420e-9
s002	13526.	79.604	68.000	150.00	16.773	68.000	104.13	.2299e-4	10.000	.0003219	.1490e-5	.5584e-4	.2585e-6
s003	14321.	79.580	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	15116.	79.557	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	15911.	79.533	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
6	15912.	79.521	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	.5596e-4	.2591e-6
s001	15913.	79.521	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s002	16708.	79.509	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	17503.	79.485	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	18298.	79.461	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	19093.	79.437	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
7	19094.	79.425	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s001	19096.	79.425	68.000	150.00	16.773	68.000	104.13	.2299e-4	10.000	.0003219	.1490e-5	.7023e-7	.3252e-9
s002	19891.	79.413	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s003	20686.	79.389	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s004	21481.	79.366	68.000	150.00	16.773	68.000	104.13	0.000000	10.000	0.000000	0.000000	0.000000	0.000000
s005	22276.	79.342	68.000	150.00	16.773	68.000	104.13	.2300e-4	10.000	.0003219	.1490e-5	.5584e-4	.2586e-6
8	22277.	79.330	68.000	150.00	16.773	68.000	104.13	.2300e-4	10.000	.0003219	.1490e-5	.5598e-4	.2592e-6

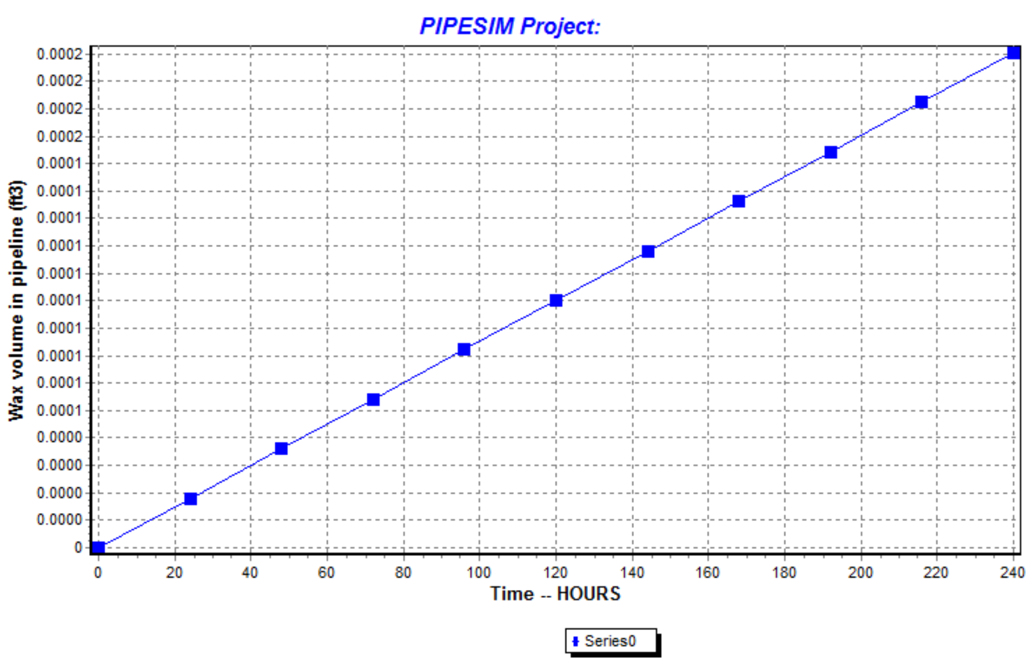

Fig. 2. Wax deposition volume in pipeline after 10 days for sample A

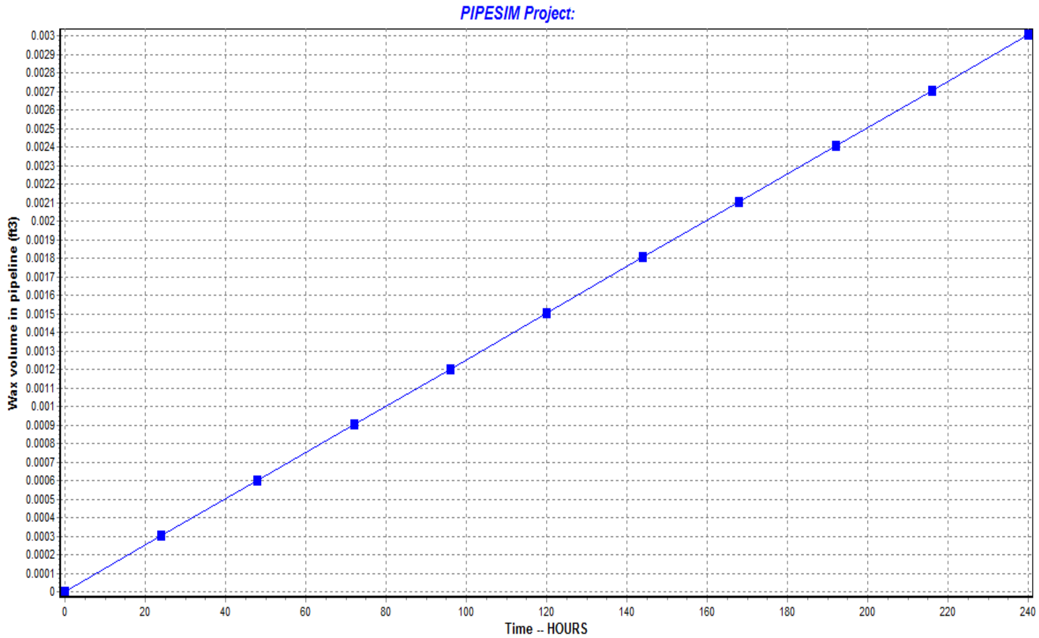

Fig. 3. Wax deposition volume in pipeline after 10days for sample B

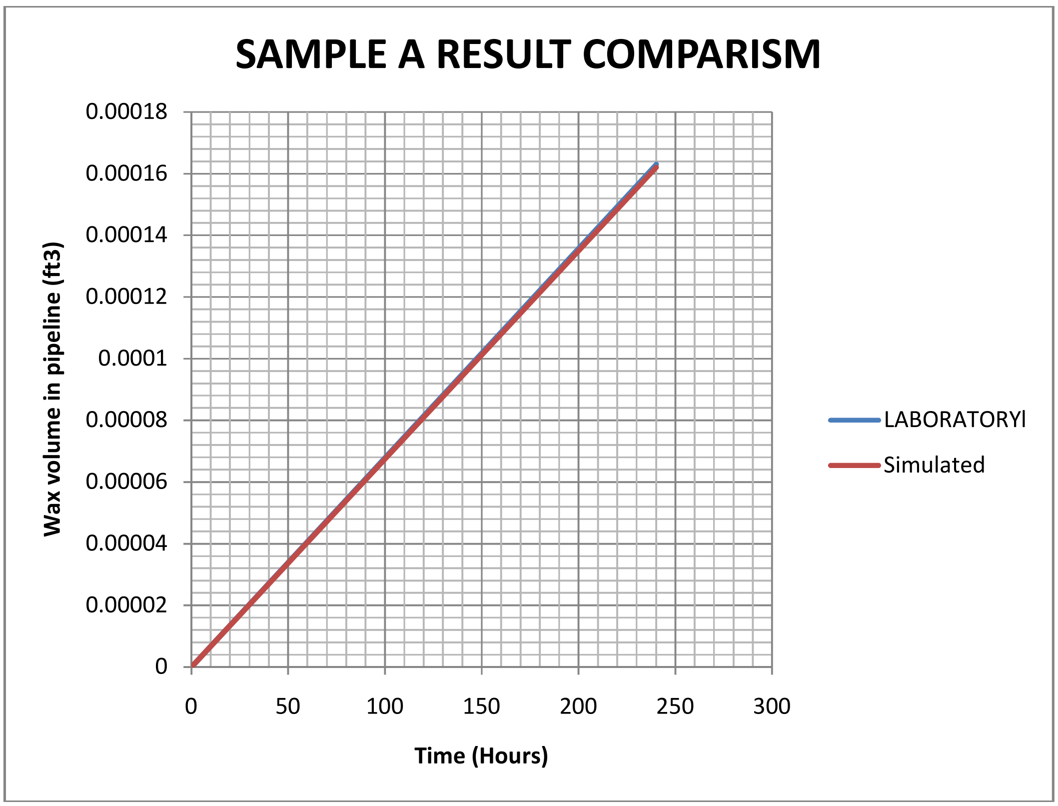

Fig. 4. Comparism of simulated and control results for sample A

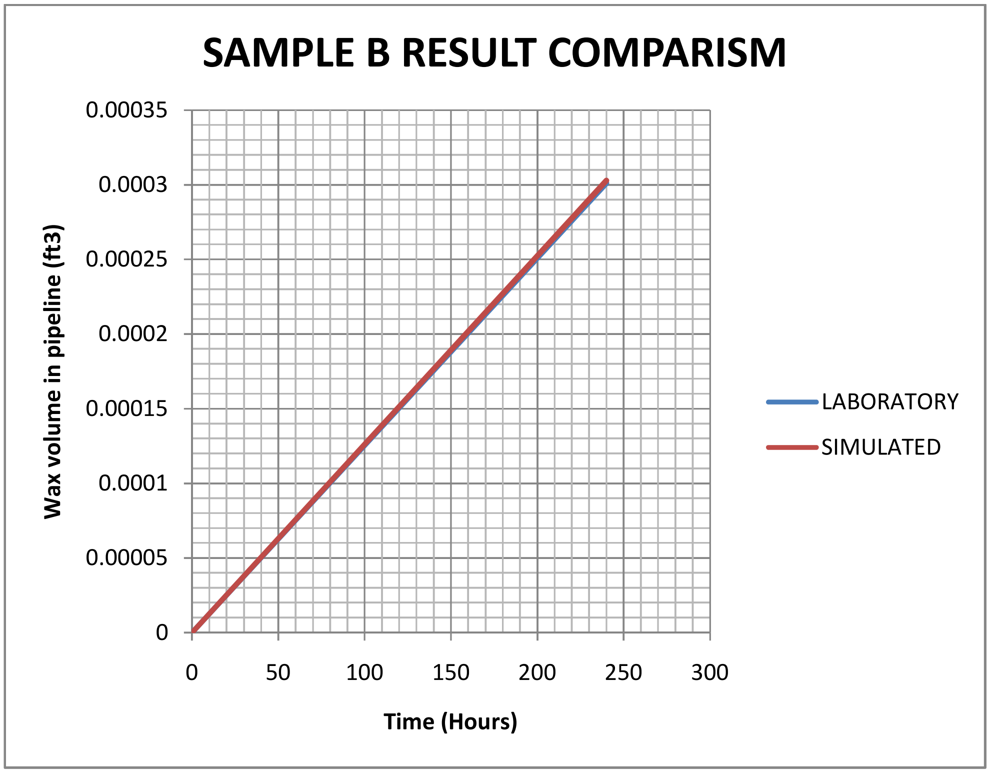

Fig. 5. Comparism of simulated and control results for sample B

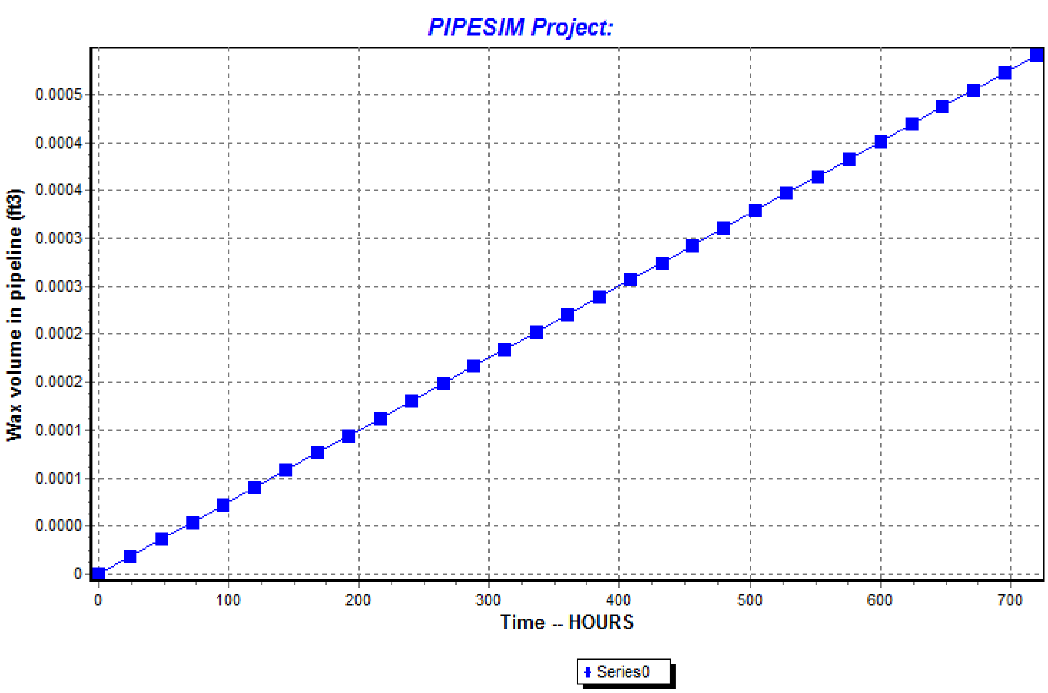

Fig. 6A. Wax deposition volume in pipeline for 1 month for sample A

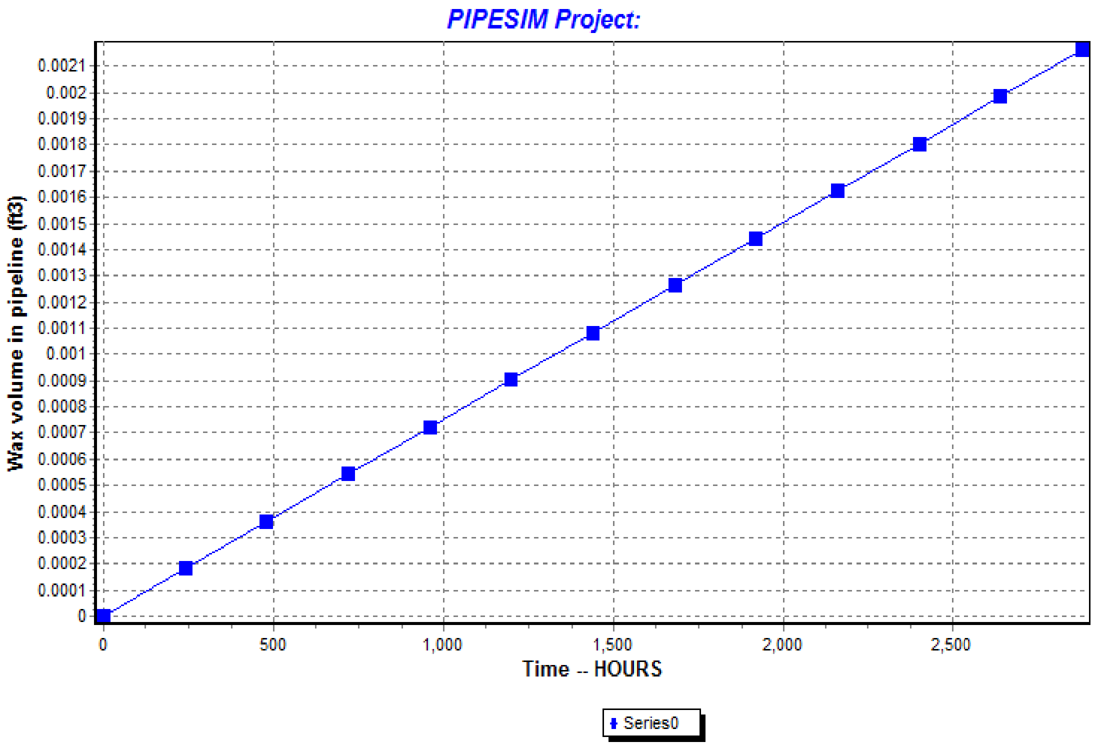

Fig. 6B. Wax deposition volume in pipeline for 4 months for sample A

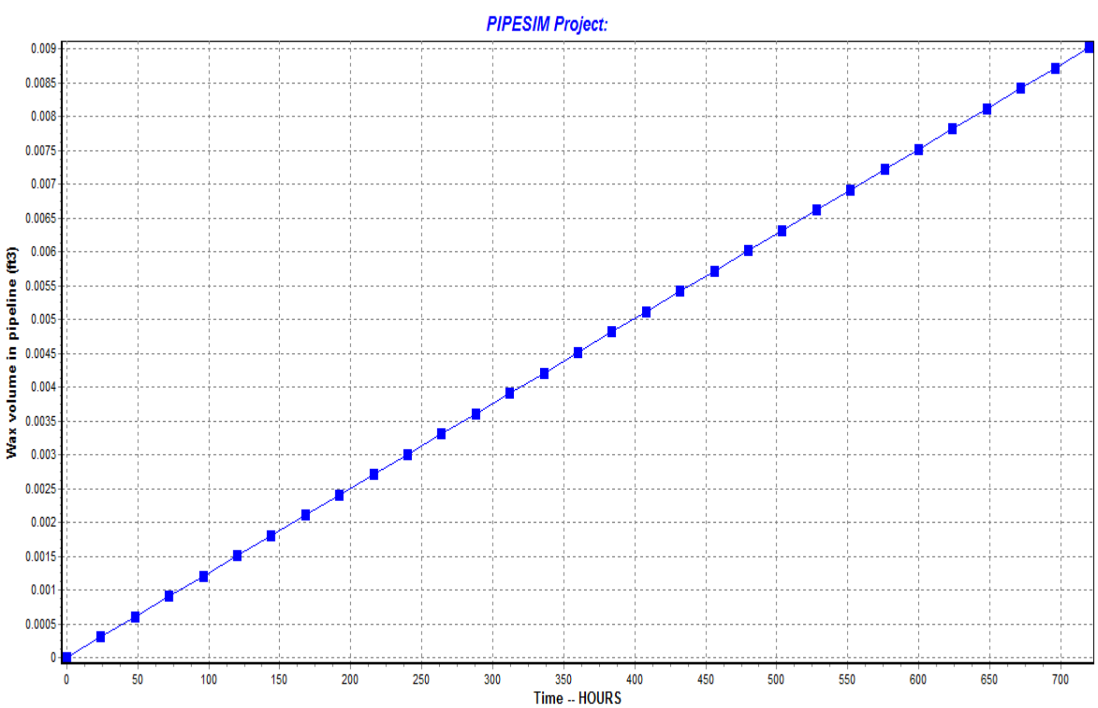

Fig. 7A. Wax deposition volume in pipeline for 1 month for sample B

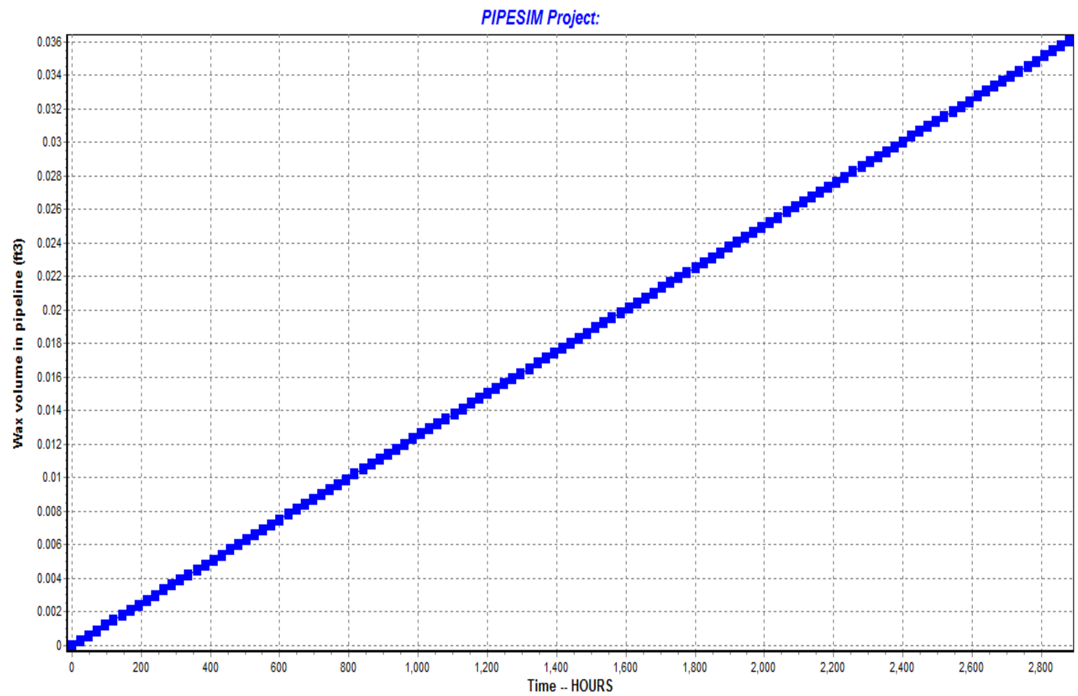

Fig. 7B. Wax deposition volume in pipeline for 4 months for sample B

Table 5. Critical Wax Deposition Temperature (CWDT) results

Samples	**CWDT**
A	**104.2°F = 40°C**
B	**104.1°F = 40°C**

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/12521