

# Modeling of Wax Buildup in a Subsea Pipeline

<sup>1</sup>Adeloye, Olalekan Michael  
Raidah Engineering Works Limited  
Port Harcourt, Nigeria

<sup>2</sup>Abu, Robin Nyemenim  
Kerob Nigeria Limited  
Port Harcourt, Nigeria

<sup>3</sup>Abu, Kevin Uwauma  
Rivers State Ministry of Energy and Natural Resources  
Port Harcourt, Nigeria.

**Abstract** - This study focuses on wax deposition in a compositional model with more gas phase in the fluid composition using molecular diffusion as the predominant factor in developing the mathematical model equation. Results from the analysis indicates higher amount of wax is deposited as a result of hydrate formation and erosion of internal corrosion material that encourage wax deposition due to turbulent effect. The steady decrease in the inner radius of pipeline with time, increase in the amount of wax deposited with time and growth of wax thickness in the pipeline with time respectively confirms wax deposition and buildup in the subsea pipeline as fluid flows through the pipeline with time.

**Keywords:** Wax buildup, Compositional model, Molecular diffusion

## INTRODUCTION

Flow assurance is an aspect of the petroleum industries used to address flow risk associated with production and transportation systems in subsea pipelines. It takes into account issues that predict, estimate and control solid deposits in form of hydrate, scale, corrosion particles and wax deposits[1]. The challenges encountered in flow assurance mishap can be astronomical but the complexity of flow assurance is the interaction among these solid particles[2]. Offshore or subsea processes become deeper as there is increase in operational cost and pipelines are more at risk of blockage due to the formation of hydrate, wax deposition etc[3]. The major factor for the development of an oil and gas field is to yield a maximized production of oil and gas from reservoir to receiving facilities. The two parameters that are pertinent to the selection process are pressure and cost[4]. Some conditions must be attained for pipelines deposition to take place and such conditions are[5]:

- The wax appearance temperature (WAT) for the fluid must be greater than wall temperature of the pipeline
- The flow must possess negative radial temperature gradient. That is, the centerline temperature is higher than the wall temperature. A zero gradient implies that no deposition will occur.
- The frictional force at the wall must be large enough so that wax crystals can stick to the wall.

Studies have shown that temperature drop, pressure drop and oil composition are the major parameters that promotes solid deposits in subsea pipeline[6]. When crude oil, water and gas are transported inside a subsea pipeline, few issues can occur; water and hydrocarbon fluids form hydrate, scale; high enough water cut leads to corrosion; changes in pressure and temperature along a pipeline leads to formation of wax precipitate[7]. All these impurities lead to blockage of pipelines thereby restricting the flow. Wax can be categorized into two main groups: microcrystalline and macrocrystalline wax [8]. The deposition of wax occurs in two forms.

Nucleation is a process in which clusters are formed from wax molecules. Clusters formed are as a result of the temperature of liquid solution been lower than the wax appearance temperature. When this occurs, randomly moving molecules come together to form cluster until it reaches a critical size where they become stable. Nucleation can either be homogeneous or heterogeneous. Homogeneous nucleation is the most common in petroleum fluid where impurities like asphaltenes, corrosion products, etc act as nucleating materials for wax crystal. These samples are pure and nucleating sites are dependent on time. While for heterogeneous nucleation, its nucleation sites are activated immediately[9].

Crystal growth occurs when there is a continuous growth of clusters on the nucleation sites as a result of the temperature of the liquid solution is kept at or below wax appearance temperature[9].

The main phenomena by which wax deposits in pipelines are molecular diffusion, shear dispersion, Brownian diffusion and gravity settling[10].

The molecular diffusion mechanism of wax deposition has been concluded to be the most dominant one and the driving force behind this is the wax concentration gradient. When transporting fluid along pipelines; wax crystals precipitates as the temperature falls below the WAT. When wax crystal grow larger and become stable with nucleating materials (asphaltenes, scale, hydrate, corrosion product), these clusters agglomerate into larger particles and form solid deposits (wax deposits). The wax deposits formed flow with the oil which is in equilibrium with the liquid. The temperature is colder toward the pipe wall, thus concentration gradient would result in mass transfer of wax

deposit from the centre of pipe to pipe wall by molecular diffusion.

The Brownian diffusion mechanism is similar to molecular diffusion, however in the former, wax crystal agglomerate and collide with oil molecules resulting to Brownian movement which leads to transportation of wax deposits in the direction of decreasing concentration (pipe wall)[5].

The gravity settling mechanism relies on the principle that precipitated wax crystals are denser than crude oil if they do not interact or react, thus could settle at the bottom of the pipeline. Result from experiment shows that the amount of wax deposit for both vertical and horizontal flow is the same, thus the role of gravity settling on wax deposition is not understood maximally[5].

The objective of this research is to investigate wax deposition in pipeline wall during transportation of crude in a subsea environment by developing mathematical model that depicts the mass flux, amount of wax deposited and wax thickness with respect to time and pipe internal radius for a compositional model. This will be achieved by using molecular diffusion as the predominant factor for the deposition of wax.

#### MATERIALS AND METHODS

##### MODEL DEVELOPMENT ASSUMPTIONS

To estimate the amount of wax deposited along the pipeline during turbulent flow of fluid, the following assumptions were made in the development of the model equation.

1. Molecular diffusion is the predominant mechanism for wax deposition
2. Uniform pressure through the pipeline.
3. Gas phase of 59% by mole fraction for turbulent flow consideration.
4. Flow-rate variation along the pipeline.

##### MODEL EQUATION

Based on the assumption of molecular diffusion as the predominant mechanism for wax deposition, the radial mass flux of a mixture of  $n$  hydrocarbon components by using the Fick's law and considering solid-liquid phase equilibria can be expressed as:

$$J = \sum_{i=1}^n j_i = Dm \frac{d\rho_x}{dr} = D_m \rho_m \left[ \sum_{i=1}^n [j_i - \xi_i] \right] \frac{1}{T} \frac{dT}{dr} \quad (1)$$

The density of fluid mixture and density of solid wax deposition can be approximated as a linear function of temperature:

$$\rho_m = a_m(T - T_r) + P_{ma} \quad (2)$$

$$\rho_w = a_w(T - T_r) + P_{wa} \quad (3)$$

The coefficient of thermal expansion for the mixture at constant pressure

$$\alpha_t = -\frac{1}{\rho m} \left( \frac{d\rho_m}{dT} \right) \quad (4)$$

The dimensionless functions are expressed as:

$$\delta_i = \frac{w_i \left[ T(1 + \theta)^2 \frac{dL_x}{dT} + \theta \frac{\Delta H_i^f}{RT} \right] k_i}{(1 + \theta K_j)^2} \quad (5)$$

$$\xi_i = \frac{w_i T \alpha_i}{1 + \theta k_i} \quad (6)$$

#### WAX DEPOSITION AND WAX THICKNESS

The total amount of wax deposition at time  $t$  and the distance from the inlet  $z = 0$  to  $z = z$ ,  $M_w(t, z)$ , considering the removed mass due to the sloughing mechanism,  $M_{wr}(t, z)$ , can be developed as:

$$\begin{aligned} M_w(t, z) &= \sum_{i=1}^n M_{wi}(t, z) - M_{wr}(t, z) \\ &= \sum_{i=1}^n 2\pi \int_0^z \int_0^t R_w J_i dz dt - 2\pi \int_0^z \int_0^t R_w J_r dz dt \end{aligned} \quad (7)$$

Therefore, variation of mass of wax deposition along the pipe,  $M_w / z$ , at time  $t$  is expressed as:

$$\begin{aligned} \frac{dM_w}{dz} &= \sum_{i=1}^n \frac{dM_w}{dz} - \frac{dM_{wr}}{dz} \\ &= \sum_{i=1}^n 2\pi \int_0^t R_w J_i dt - 2\pi \int_0^t R_w J_r dt \end{aligned} \quad (8)$$

Supposing sloughing effect has no contribution on the net or total deposition during the laminar flow, the second terms in the above equations are neglected and the wax thickness  $h(z, t)$  is calculated as:

$$h = R_0 - R_w \quad (9)$$

and

$$R_w = \left[ R_0^2 - \frac{1}{\pi \rho_{wa}} \frac{dM_w}{dz} \right]^{1/2} \quad (10)$$

**INPUT PARAMETERS**

Table 1: Input parameter for model pipeline design (standard pipe diameter)

Initial Pipeline Design Properties	
Radius of clean pipe	0.229m
Distance from inlet	0
Distance from outlet	2.29m
Length of pipe	2.29m
Lx	0.41
Flow rate	0.00000666m <sup>3</sup> /sec
Diffusion coefficient	2.91339E-06

The length of the pipe was ten times the radius of the pipe to capture the rate of wax deposition across the pipeline with time. Fluid flow rate of 0.00000666m<sup>3</sup>/sec (6.333gal/hrs) was considered for modeling the flow regime in this study. However, the phase fraction of 41% used for the liquid indicates more gas phase(59%) in the model which account for turbulent within the model.

Table 2: Properties of flow and wax deposition[11]

Properties of Flow and Wax Deposition		
Parameter	Value	Unit
K	0.14884	W/m.K
$\alpha_m$	-0.91796	Kg/m3.K
$\rho_{ma}$	866	Kg/m3
$\rho_{wa}$	812	Kg/m3
$\alpha_t$	0.00106	K-1
L in turbulent model	2.286	M
$T_r$	293	K

To estimate the amount of wax deposited and its thickness along the pipeline, key thermo-chemical and heat properties for the fluid component are utilized. The thermal conductivity of the mixture of the eleven components is 0.14884 W/m.K with density of the fluid mixture and solid wax deposited ranging between 812 and 866 Kg/m<sup>3</sup>. The heat capacity of each component at standard condition was used to obtain the enthalpy at specified temperature condition of 293°K. Thermal expansion coefficient of 0.00106 K<sup>-1</sup> was used to account for the heat change at different temperature condition within the model.[11].

Table 3: Fluid composition along the pipeline

Components	Mole Fraction	Mean Molecular Weight
CO <sub>2</sub>	0.0005	44.01
C <sub>1</sub>	0.496	16.04
C <sub>2</sub>	0.0461	30.07
C <sub>3</sub>	0.0426	44.1
C <sub>4</sub>	0.0295	58.12
C <sub>5</sub>	0.0224	72.15
C <sub>6</sub>	0.0159	86.2
C <sub>7</sub>	0.0161	100.2
C <sub>8</sub>	0.0184	107
C <sub>9</sub>	0.016	121
C <sub>10+</sub>	0.2965	285.4

For compositional modeling, ten hydrocarbon components C<sub>1</sub> to C<sub>10+</sub> and CO<sub>2</sub> are used to represent the hydrocarbon fluid composition in the model. The inlet temperature was at 250°K at the initial condition and the standard molecular weight of each component was used in estimating the apparent weight fraction at initial condition.

RESULTS AND DISCUSSIONS

Table 4: Dimensionless weight function parameters calculation

comps	Weight ratio	Temp	$\theta$					Dimensionless Weight Function $\delta$	
			$\theta$	$(1+\theta)^2$	$dLx/dT$	$(dH/RT)$	num	den	
CO <sub>2</sub>	0.0005	250	1.439	5.949	-00095	0.57715	-0.0010	1.4742	-0.0007
C <sub>1</sub>	0.4960	250	1.439	5.949	-00095	1.52652	-0.9342	1.4742	-0.6337
C <sub>2</sub>	0.0461	250	1.439	5.949	-00095	1.93540	-0.0840	1.4742	-0.0570
C <sub>3</sub>	0.0426	250	1.439	5.949	-00095	1.42057	-0.0809	1.4742	-0.0549
C <sub>4</sub>	0.0295	250	1.439	5.949	-00095	1.37737	-0.0562	1.4742	-0.0381
C <sub>5</sub>	0.0224	250	1.439	5.949	-00095	1.35143	-0.0428	1.4742	-0.0290
C <sub>6</sub>	0.0159	250	1.439	5.949	-00095	1.33288	-0.0304	1.4742	-0.0206
C <sub>7</sub>	0.0161	250	1.439	5.949	-00095	1.32737	-0.0308	1.4742	-0.0209
C <sub>8</sub>	0.0184	250	1.439	5.949	-00095	1.51869	-0.0347	1.4742	-0.0235
C <sub>9</sub>	0.0160	250	1.439	5.949	-00095	1.04995	-0.0313	1.4742	-0.0212
C <sub>10+</sub>	0.2965	250	1.439	5.949	-00095	1.14967	-0.5751	1.4742	-0.3901

Table 5: Dimensionless weight function parameters calculation

Components	Weight Ratio	Temp	$\theta$	Dimensionless Weight Function $\zeta$
CO <sub>2</sub>	0.0005	250	1.439	0.000109
C <sub>1</sub>	0.0496	250	1.439	0.108254
C <sub>2</sub>	0.0461	250	1.439	0.010061
C <sub>3</sub>	0.0426	250	1.439	0.009298
C <sub>4</sub>	0.0295	250	1.439	0.006438
C <sub>5</sub>	0.0224	250	1.439	0.004889
C <sub>6</sub>	0.0159	250	1.439	0.003470
C <sub>7</sub>	0.0161	250	1.439	0.003514
C <sub>8</sub>	0.0184	250	1.439	0.004016
C <sub>9</sub>	0.016	250	1.439	0.003492
C <sub>10+</sub>	0.2965	250	1.439	0.064712

Table 6: Radial mass flux of a mixture of  $n$  hydrocarbon estimation

comps	$\rho_m$	Dimensionless Weight Function $\delta$	Dimensionless Weight Function $\zeta$	Temp	DT/dr	$\theta(\delta-\zeta)$	J
CO <sub>2</sub>	905.47	-0.000687	0.000109	250	4.3745	-0.0008	0.0001
C <sub>1</sub>	905.47	-0.633658	0.108254	250	4.3745	-0.7419	0.1334
C <sub>2</sub>	905.47	-0.056991	0.010061	250	4.3745	-0.0671	0.0121
C <sub>3</sub>	905.47	-0.054879	0.009298	250	4.3745	-0.0641	0.0115
C <sub>4</sub>	905.47	-0.038132	0.006438	250	4.3745	-0.0446	0.0080
C <sub>5</sub>	905.47	-0.029013	0.004889	250	4.3745	-0.0339	0.0061
C <sub>6</sub>	905.47	-0.020624	0.003470	250	4.3745	-0.0241	0.0043
C <sub>7</sub>	905.47	-0.020892	0.003514	250	4.3745	-0.0244	0.0044
C <sub>8</sub>	905.47	-0.023521	0.004016	250	4.3745	-0.0275	0.0050
C <sub>9</sub>	905.47	-0.021210	0.003492	250	4.3745	-0.0247	0.0044
C <sub>10+</sub>	905.47	-0.390070	0.064712	250	4.3745	-0.4548	0.0818

Table 7: Mass of wax deposition along the pipe estimation

time	Ro	J	Wax Deposited (g) -MGP	Wax Thickness Deposited
60	0.229	0.27122	53.440	0.000
120	0.208	0.27122	97.058	0.021
180	0.189	0.27122	132.353	0.040
240	0.172	0.27122	160.781	0.057
300	0.157	0.27122	183.663	0.071
360	0.144	0.27122	202.128	0.084
420	0.133	0.27122	217.098	0.096
480	0.123	0.27122	229.309	0.106
540	0.114	0.27122	239.337	0.115
600	0.106	0.27122	247.633	0.123
660	0.099	0.27122	254.547	0.130
720	0.093	0.27122	260.350	0.136
780	0.087	0.27122	265.255	0.141
840	0.082	0.27122	269.431	0.146
900	0.078	0.27122	273.003	0.151
960	0.074	0.27122	276.101	0.155

EFFECTS OF WAX DEPOSITION ON INNER RADIUS OF PIPE

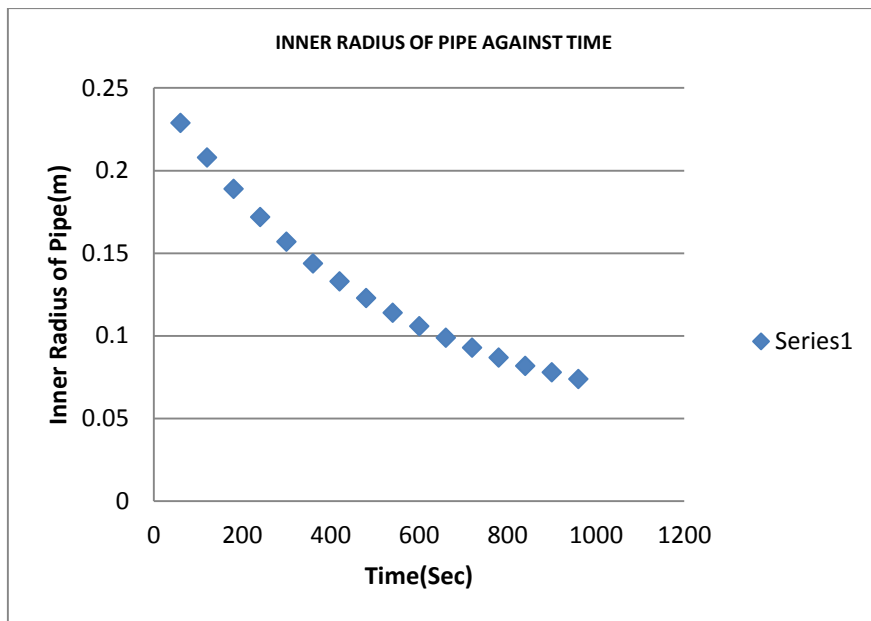


Fig 1: Variation of inner radius of pipeline with time

The effect of wax deposition on the inner radius of pipe with time is shown in Fig 1. It can be deduced from Fig 1 that as the fluid flows through the inner radius of the pipe, there is wax buildup at the pipe wall that leads to reduction or size decrease in the inner radius of the pipe.

EFFECT OF THE AMOUNT OF WAX DEPOSITION

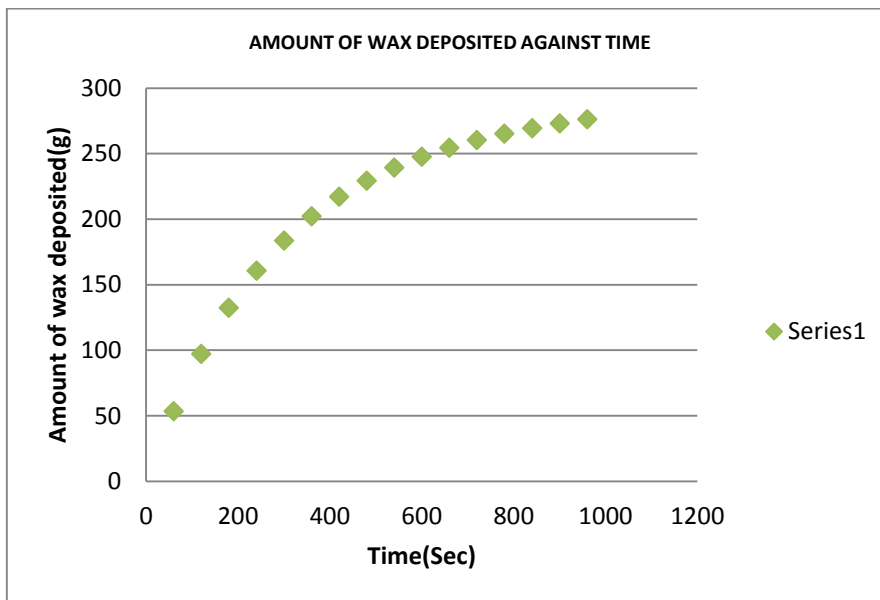


Fig 2: Relationship between amount of wax deposited with time

The quantity or amount of wax deposited in the pipeline inner wall increases as the fluid flows with time. The variation trend of the quantity of wax deposited in the inner pipe wall with time is shown in Fig 2

EFFECT OF WAX THICKNESS IN PIPELINE

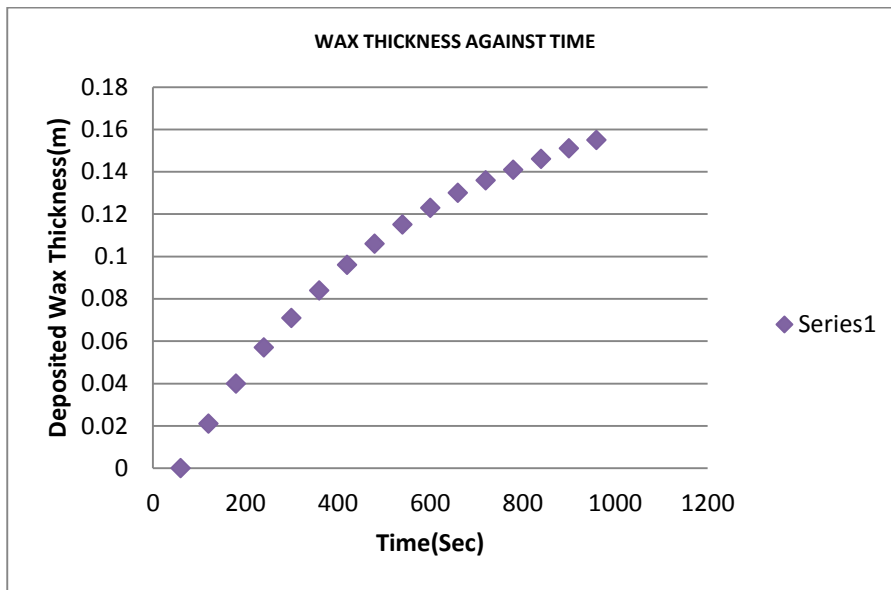


Fig 3: Dependency of the amount of wax thickness with time

The thickness of the amount or quantity of wax deposited on the inner pipe wall also shows an increase in wax thickness as the fluid flows through the pipe with time as highlighted in Fig 3. This is as a result of wax buildup in the pipe inner wall as fluid flows through the pipe.

CONCLUSION

The problem of wax buildup in the inner diameter of pipe in subsea pipeline cannot be over emphasized. The above analysis for variation of inner pipeline radius as a result of wax buildup, amount of wax deposited and wax depositional thickness shows an increase as the fluid flows through the pipeline with time. The compositional model with more gas phase in the flowing fluid also favours higher amount of wax deposition due to turbulency. Also, the reduction or decrease in pipe diameter with respect to time as a result of the amount of wax deposited along the pipeline is a problem to fluid flow as less radi is available for fluid flow

NOMENCLATURE

A	=	deposition area
$a_m$	=	parameter in oil density model
$a_w$	=	parameter in wax density model
$D_w$	=	diffusion constant ( $m^2/s$ )
h	=	wax thickness
i	=	component
j	=	mass flux of wax ( $Kg/m^2s$ )
$j_r$	=	removal flux of wax
K	=	liquid / solid equilibrium constant
k	=	thermal conductivity of the mixture
$k^*$	=	empirical constant
$L_x$	=	number of moles in liquid phase per mole mixture.

$M_w$	=	mass of wax deposit on the pipe wall at time of measuring (kg)
n	=	number of component
R	=	gas constant ( $8.314j/molK$ )
r	=	radial distance
$R_o$	=	inner radius of clean pipe (m)
$R_w$	=	time dependent inner radius of pipe (m)
T	=	temperature (K)
t	=	time (sec)
$T_r$	=	reference temperature
w	=	weight fractions
WAT	=	wax appearance temperature
$W_i$	=	weight fraction of component i
z	=	distance from pipe inlet (m)
$\rho_m$	=	density of fluid mixture
$\rho_w$	=	density of solid wax deposition
$\rho_x$	=	density of the liquid
$\gamma$	=	shear rate
$\delta_i$	=	dimensionless function
$\Delta H_i^f$	=	heat of fusion
$\alpha_i$	=	coefficient of thermal expansion
$\zeta_i$	=	dimensionless weight function

REFERENCES

- [1] Guo, B. (2005). *Offshore Pipelines*. U.S.A: Gulf Professional Publishing. pp. 169-170, 182-186
- [2] Shuqiang G (2008). Investigation of interactions between gas hydrates and several other flow assurance elements, *Energy fuels* 22(5) 3150-3153 doi: 10.1021/ef800189k
- [3] Demonstrating How Flow Assurance Professionals are ensuring Production for Deep and Ultra Deepwater Operations. March 31-April 1, 2015, Houston, Texas.
- [4] Milind D (2011). Wax Control in the Presence of Hydrate, Department of Chemical Engineering, University of Utah, Salt Lake City, UT 84112.

- [5] Kok, M.V. and Saracoglu, O. (2000). *Mathematical Modeling of Wax Deposition in Crude Oil Pipeline System*. 16-18 October 2000. Australia: Society of Petroleum Engineers. pp. 1- 6.
- [6] Leontaritis, K.J. and Leontaritis, J.D. (2003). *Cloud Point and Wax Measurement Techniques*. 5-7 February 2003. Texas: Society of Petroleum Engineers. pp. 1-2.
- [7] Bailey, J. C and Allenson, S. J(2009). Paraffin cleanout in a single subsea flowline environment. SPE Journal Paper 125131-PA
- [8] Lake, L.W. and Fanchi, J.R. (2006). *Petroleum Engineering Handbook*. 1<sup>st</sup> ed. U.S.A: Society of Petroleum Engineers. pp. 397-453.
- [9] Hammami, A., Robinson, D. B. and Raines, M.A (1997). Paraffin Deposition from Crude Oil: Comparison of Laboratory Results to Field Data. October 1997, Texas, SPE Journal
- [10] Burger,E. D. (1981). Studies of Wax Deposition in the Trans Alaska Pipeline, Journal of Petroleum and Technology
- [11] Nazar, A.R.S. (2001). *Experimental and Mathematical Modeling of Wax Deposition and Propagation in Pipes Transporting Crude Oil*. 24-27 March 2001. Oklahoma: Society of Petroleum Engineers. pp. 1- 3, 5-7.