ANALYSIS OF DEPOSITION FROM PARAFFIN-SOLVENT MIXTURES UNDER TURBULENT FLOW

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ABSTRACT

Paraffin deposition is a common problem in the flow of paraffinic and heavy oils. Solids deposition in the pipe wall results in rising process costs due to an increase in energy cost of pumping, a decrease in production, an increase in pressure on the line and risk pipeline blockage. In this work, a simulator was developed to allow the analysis of paraffin deposition under different operating conditions, to understand the influence of the variables (inlet and external temperatures, wax appearance temperature, composition, and time) on paraffin deposition under turbulent flow. A mathematical model for quantitative prediction of wax deposition for paraffin-solvent mixtures was proposed. The methods used in the estimation of physical, thermal, and transport properties of mixtures were suitable when compared with literature data. The simulator calculated the profiles of temperature and thickness of the deposit, with consistent results. The results showed the important role of operating temperatures in paraffin deposition.

KEYWORDS

simulation; paraffinic deposits; petroleum; modeling; flow assurance

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1. INTRODUCTION

Petroleum (or crude oil) consists of a mixture of saturated hydrocarbons (paraffins, isoparaffins, naphthenes), aromatics, resins, and asphaltenes. In the reservoir, where temperatures vary from 70 to 150°C and pressures are higher than 2000 psi, paraffin molecules are dissolved in crude oil. As the petroleum flows within pipes at the bottom of the sea (at temperatures around 4°C), heat losses promote the decrease of temperature below the clouding point or WAT (wax appearance temperature). At this point, the deposition solubilized paraffin on the colder pipe wall starts. This process of deposition is one of the main problems for flow assurance, as it restricts petroleum flow, due to the resultant piping losses.

Recent oil discoveries in the Brazilian coast present challenges related to flow assurance, as they are located at depths of 2000 m, 350 km far from shore: the explored oil, as a consequence, has to flow through long distances, at low temperatures, overcoming high pressure differentials. High piping losses imply the increase of operational and repair costs. In most critical cases, the continuous deposition of paraffin may result in layers with thicknesses sufficient to obstruct tabulation, causing production interruption (Akbarzadeh & Zougari, 2008).

Several mathematical models were proposed to describe the paraffinic petroleum flow, associated to the deposition of solid paraffin on pipe inner surface (Ramirez-Jaramillo et al., 2004; Corraera et al., 2007; Huang et al., 2011a; Wang & Huang, 2014). Additionally, significant efforts have been employed to study and model paraffin deposition, involving thermodynamics, heat/mass transfer, crystal growth, and fluid dynamics (Eskin et al., 2013; Cabanillas et al., 2016; Soedarmo et al., 2016).

Bagatin et al. (2008) compared different commercial softwares to experimental data related to the deposition of paraffins and concluded that the models reported in the literature still presented some limitations, many of them related to the practical reliability of their previsions. These limitations seem to be a consequence of an incomplete knowledge of important physicochemical parameters related to the

mechanism of deposition, resulting in fitting of poorly defined models to experimental data.

The scarcity of detailed studies with data from oil fields results in a tremendous obstacle for the certification of deposition models for real situations. As a consequence, the need for developing alternative deposition models and softwares capable to forecast deposition process in different situations subsides. The aim of this work is to fulfill part of these needs, by developing a software capable of describing paraffinic deposition during a turbulent flow using a model and testing it with data from an oil field. A graphical interface was created to input data and the model equations proposed were solved using MATLAB 7.4. The simulator developed was used to analyze the effects of inlet temperature, external temperature, WAT, time, and composition of paraffin-solvent mixtures on paraffinic deposition.

2. MATERIALS AND METHODS

2.1 Methodology

The work was carried out in four steps, all of them depicted in Figure 1 and detailed below:

- Step 1: Application of semi-empiric methods to estimate the properties of pure components and paraffin-solvent mixtures.
- Step 2: Calculation of solid-liquid equilibrium of paraffin-solvent mixtures for the determination of WAT and paraffin solubility curve.
- Step 3: Presentation of a mathematical modeling of the process of deposition during turbulent flow in a pipe taking into account mass and heat transfer phenomena in a steady-state regime.
- Step 4: Development and execution of software with graphical interface to allow the simulation of different conditions of operation. As a result, one can achieve the simulation to better understand the influence of all the important variables on the deposition process (inlet temperature, external temperature, WAT, mixture composition, and time).

Figure 1. Scheme depicting the steps involved in the development of this work.

2.2 Paraffin-solvent mixtures

The mixture components (shown in Table 1) were chosen to study the influence of paraffin molar mass on deposition during flow: the paraffinic chain size varied from C_{34} to C_{40} , maintaining C_{15} as solvent in all the systems.

Table 1. Binary systems studied in this work.

System	Mixtures
1	$C_{15}H_{32}$ - $C_{34}H_{70}$
2	$C_{15}H_{32}$ - $C_{36}H_{74}$
3	$C_{15}H_{32}$ - $C_{38}H_{78}$
4	$C_{15}H_{32}$ - $C_{40}H_{82}$

Table 2. Correlations used for the estimation of properties of pure n-alkanes.

Property	Symbol	Equation	Correlation
Fusion enthalpy (J/mol)	ΔH_f	$\Delta H_f = 0.597MT_f$	(1) Won (1986)
Absolute density (g/cm ³)	ρ	$\rho = A_\rho B_\rho^{-\left(1-\frac{T}{C_\rho}\right)^n}$	(2) Yaws & Pike (2009)
Dynamic viscosity (mPa.s)	η	$\eta = 10^{(A_\eta + \frac{B_\eta}{T} + C_\eta T + D_\eta T^2)}$	(3) Yaws & Dang (2009)
Thermal conductivity (W/m.K)	k	$k = A_k + B_k T + C_k T^2$	(4) Yaws (2009)
Molar heat capacity (J/mol.K)	C_p	$C_p = R \left[U + W \left(\frac{T}{100} \right) + Y \left(\frac{T}{100} \right)^2 \right]$	(5)
		$U = \sum_{i=1}^{n_t} n_i u_i$	(6) Růžicka-Domalski
		$W = \sum_{i=1}^{n_t} n_i w_i$	(7) (Poling et al., 2001)
		$Y = \sum_{i=1}^{n_t} n_i y_i$	(8)

Table 3. Correlations used for the estimation of mixture properties (Poling et al., 2001).

Property	Symbol	Equation	Correlation
Absolute density (g/cm ³)	ρ_m	$\rho_m = \frac{\sum_i x_i M_i}{\sum_i x_i \frac{M_i}{\rho_i}} \quad (9)$	Rule of mixture
Dynamic viscosity (mPa.s)	η_m	$\ln \eta_m = \sum x_i \ln \eta_i + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n x_i x_j G_{ij} \quad (10)$	Grunberg-Nissan
		$G_{ij} = 1 - \left[1 - G_{ij, 298K} \right] \frac{573 - T}{275} \quad (11)$	
Thermal conductivity (W/m.K)	k_m	$k_m = \left(\sum_i x_i k_i^{-2} \right)^{-1/2} \quad (12)$	Vredevelde
Molar heat capacity (J/mol.K)	$C_{p,m}$	$C_{p,m} = \sum_i x_i C_{p,i} \quad (13)$	Růžicka-Domalski
Diffusion coefficient (cm ² /s)	D	$D = 13.3 \times 10^{-8} \left(\frac{T^{1.47} \eta_{sol}^\lambda}{V_A^{0.71}} \right) \quad (14)$	Hayduk-Minhas
		$\lambda = (10.2/V_A) - 0.791 \quad (15)$	

2.3 Estimation of properties of pure n-alkanes and mixtures

Table 2 lists the methods used in the estimation of physical, thermodynamic, thermal, and transport properties of pure components. Table 3 lists the methods as they were used for the four chosen binary systems.

Fusion and boiling temperature (T_f and T_b , respectively) of pure components were obtained from experimental data from the literature and are presented in Table 4.

Table 4. Experimental values of T_f and T_b for alkanes C₁₅, C₃₄, C₃₆, C₃₈, and C₄₀ (Yaws & Narasimham, 2009).

Component	T_f^{exp} (K)	T_b^{exp} (K)
C ₁₅ H ₃₂	283.07	543.83
C ₃₄ H ₇₀	343.25	755.15
C ₃₆ H ₇₄	349.05	770.15
C ₃₈ H ₇₈	352.15	784.15
C ₄₀ H ₈₂	354.65	798.15

2.4 Solid-liquid equilibrium calculation

The determination of WAT for the binary systems was carried out using the model proposed by Won (1986), shown in Equation (16):

$$\frac{x_i^S}{x_i^L} = \frac{\gamma_i^L}{\gamma_i^S} \exp \left[\frac{\Delta H_{f,i}}{RT} \left(1 - \frac{T}{T_{f,i}} \right) \right] \quad (16)$$

If the solution in question is regarded as regular, activity coefficients can be determined as a function of solubility parameters (Won, 1986). Applying this assumption to Equation (16) results in Equation (17), which relates WAT to the molar fraction of paraffin in the liquid phase, x_i^L :

$$WAT = T = \frac{V_i^L (\delta^L - \delta_i^L)^2 + \Delta H_{f,i}}{-R \ln x_i^L + \frac{\Delta H_{f,i}}{T_{f,i}}} \quad (17)$$

2.5 Deposition modeling

The following assumptions were applied to the deposition model:

- The flow regime was described as stationary turbulent flow;

- Concentration profile was effective only in the thermal boundary-layer;
- The properties of solid and liquid paraffin were considered to be the same;
- Molecular diffusion was the sole mechanism for deposition;
- The complex rheology of paraffinic mixtures was not taken into account in the model.

Fick's Law (molecular diffusion) governs mass transfer:

$$\vec{J}_{par} = -D \frac{dC_s}{dT} \nabla T, \quad (18)$$

Where $\vec{J}_{par}$ is the paraffin mass flow, D is paraffin diffusion coefficient, and $C_s(T)$ is the paraffin solubility in oil. Considering that the deposit is formed by oil and solidified paraffin, paraffin flux is a fraction of the total deposit flux:

$$\vec{J}_{par} = \psi \vec{J}_{dep}, \quad (19)$$

Total deposition flux is given by:

$$\vec{J}_{dep} = -\frac{1}{\psi} D \frac{dC_s}{dT} \nabla T, \quad (20)$$

Where ψ represents the solid fraction of paraffin solids in the deposit.

Deposit consolidation and ablation-related phenomena were taken into account in the model developed in this work. Ablation is a result of drag force action on paraffin molecules located in the deposit, compensating for adhesion. In this work it was assumed that ablation rate is proportional to shear stress at the pipe wall:

$$\vec{J}_{abl} = -A \frac{\tau}{\psi} \quad (21)$$

A is an experimental coefficient that may be constant or a function of ψ (in this work A was considered to be constant).

The consolidation of paraffin deposit may be interpreted as a gradual release of confined oil, increasing the value of ψ , promoting deposit "hardening". Assuming that the rate at which oil is released by the deposit is related to the velocity gradient at the limit layer and, consequently, to τ , the reduction in the rate of deposit layer thickening will be proportional to the fraction of oil contained in the deposit. The equation of deposit consolidation kinetics used in this work was (Correra et al., 2007):

$$\frac{\partial \psi}{\partial t} = \frac{1}{t_a} (1 - \psi) \quad (22)$$

In this equation, t_a is the deposit consolidation time, usually much longer than deposition time scale.

Deposition profile, i.e., thickness of deposited layer along pipeline, was obtained via mass balance carried out in the deposit interface, involving molecular diffusion, ablation, and consolidation, resulting in Equation (26).

The equations that constitute the used deposition model are listed in Table 5. The choice for a simplified deposition model, proposed by Correra et al. (2007), was based on the goodness to fit of the referred model to turbulent flow data coming from real field installations.

Table 5. Equations used in the model for deposition under turbulent flow.

Description	Equation
Temperature profile in the thermal limit layer	$T(r, z, t) = -a(z, t) R_T(z, t) \ln \left(\frac{r}{R_T(z, t)} \right) + T_n(z, t) \quad (23)$
	$a(z, t) = \left(\frac{1}{R_T} \right) \frac{1}{\left[\frac{k}{hR} + \ln \left(\frac{R}{R_T} \right) \right]} [T_n - T_{ext}] \quad (24)$
Temperature profile in the turbulent nucleus	$T(r, z) = [T_{in} - T_{ext}] \exp \left\{ -\frac{2\pi\alpha}{\mu Q} z \right\} \left\{ 1 - \frac{1}{\mu} \ln \left(\frac{r}{R} \right) \right\} + T_{ext} \quad (25)$
Thickness of formed deposit	$\sigma_d \approx \frac{D\beta t}{\psi \rho R} \left[\frac{(T_{in} - T_{ext})}{\mu} \exp \left\{ -\frac{2\pi\alpha}{\mu Q} z \right\} - \frac{A\eta Q}{\pi \varepsilon_v D \beta R^2} \right] H(WAT - T_w) \quad (26)$

Table 6. Parameters from Svendsen (1993) used in the simulation.

Parameter	Value
Radius (m)	0.15
Pipe length (m)	5000
Flow rate (m ³ /s)	0.14
Inlet temperature (K)	303
External temperature (K)	278
Density (kg/m ³)	$-0.65[T(K) - 293] + 855$
Reynolds Number	57970
Paraffin mass fraction	0.15

2.6 Deposition simulation

In order to achieve a better understanding of paraffin deposition as a function of the several variables involved in the process, a software was developed for flow simulations. The software was named *DepoSim* and was capable of calculating fluid temperature and deposition profiles, using the deposition model described in this work.

The first simulation was carried out using the work of Svendsen (1993) as a reference for comparison with the results found in this work. This choice was based in the lack of experimental parameters reported for the equations that describe the process of deposition in turbulent flow. When using system 3 (C₁₅-C₃₈), similar to the Svendsen (1993), the same conditions of flow and temperature reported in the literature were fed into the software. The parameters used in the simulation are shown in Table 6.

Subsequently, a study of deposition for the other binary systems was carried out and the effect of operation temperature on the process of deposition was evaluated. The parameters' radius, pipe length, flow rate, and paraffin fraction mass were fixed for this study.

Table 7. Estimated values of fusion enthalpy for the n-alkanes C₁₅, C₃₄, C₃₆, C₃₈, and C₄₀.

Component	$\Delta H_f^{est} \text{ (kJ/mol)}$
C ₁₅ H ₃₂	36.153
C ₃₄ H ₇₀	98.646
C ₃₆ H ₇₄	105.322
C ₃₈ H ₇₈	112.048
C ₄₀ H ₈₂	188.803

3. RESULTS AND DISCUSSION

3.1 Estimation of properties of pure n-alkanes and mixtures

Table 7 lists estimated values of fusion enthalpy for the n-alkanes chosen for this study. The estimated value of ΔH_f for C₁₅ presented a deviation of 4.5%, when compared to the one experimentally obtained by Yaws and Lin (2009). This deviation can be considered satisfactory for the developed deposition modeling, so that the extrapolation of the correlation of Won (1986) was considered adequate to estimate the values of fusion enthalpy for the other n-alkanes.

Density, viscosity, thermal conductivity, and calorific capacity were evaluated as a function of the range of operation temperature. To verify estimated values, experimental data for these properties were extracted from DIPPR database, using the software DIADEM Database v.1.1 (This program only makes available data for C₁₅). Table 8 and Table 9 present experimental and estimated values (as well as the percent deviations) for C₁₅. As a result, correlation was validated for the component C₁₅ and an extrapolation was assumed for the other components.

Density, viscosity, thermal conductivity, and heat capacity for the four binary systems were plotted as a function of operation temperature range. The graphics obtained for the four systems are shown in Figures 2 to 5.

From the figures, one can observe that density and viscosity were more affected by molar mass when compared to thermal conductivity and calorific capacity. On the other hand, the difference between any property values in binary systems was

Table 8. Comparison between the values of density and viscosity obtained for C₁₅ using DIPPR and the correlations of Yaws-Pike and Yaws-Dang.

T (K)	ρ^{DIPPR} (kg/m ³)	$\rho^{Y\&P}$ (kg/m ³)	Deviation (%)	η^{DIPPR} (kg/m ³)	$\eta^{Y\&D}$ (kg/m ³)	Deviation (%)
285.5	772.9884	773.5839	0.08	3.310	3.398	2.7
288.0	771.5014	771.8942	0.05	3.130	3.204	2.4
290.5	769.8021	770.2012	0.05	2.970	3.025	1.8
293.0	768.1028	768.5049	0.05	2.820	2.859	1.4
295.5	766.4034	766.8054	0.05	2.680	2.707	1.0
298.0	764.7041	765.1027	0.05	2.550	2.566	0.6
300.5	763.2172	763.3965	0.02	2.430	2.435	0.2
303.0	761.5178	761.687	0.02	2.310	2.314	0.2

Table 9. Comparison between the values of thermal conductivity and calorific capacity obtained for C₁₅ using DIPPR and the correlations of Yaws and Růzicka-Domalski.

T (K)	k^{DIPPR} (W/m.K)	k^Y (W/m.K)	Deviation (%)	C_p^{DIPPR} (J/kg.K)	$C_p^{R\&D}$ (J/kg.K)	Deviation (%)
285.5	0.1439	0.1425	0.99	2180.09	2135.69	2.04
288.0	0.1434	0.1420	0.97	2187.10	2144.30	1.96
290.5	0.1428	0.1415	0.94	2194.12	2153.00	1.87
293.0	0.1423	0.1410	0.91	2201.23	2161.79	1.79
295.5	0.1417	0.1405	0.87	2208.34	2170.66	1.71
298.0	0.1412	0.1400	0.85	2215.54	2179.63	1.62
300.5	0.1407	0.1395	0.82	2222.74	2188.67	1.53
303.0	0.1401	0.1390	0.79	2229.99	2197.81	1.44

Figure 2. Densities of binary paraffinic systems as a function of temperature.

rather small, due to the small mass fraction of paraffin in the system (0.15).

3.2 Solubility curve

Molar mass, melting temperature, and molar fraction of paraffinic component that deposit affect

phase equilibriums. A value increase promotes an increase in WAT, increasing paraffin precipitation. Table 10 shows WAT and solubility (at 303K) values for the systems studied.

Solubility curves for the paraffins as a function of temperature are shown in Figure 6.

Figure 3. Viscosities of binary paraffinic systems as a function of temperature.

Figure 4. Thermal conductivities of binary paraffinic systems as a function of temperature.

Figure 5. Heat capacities of binary paraffinic systems as a function of temperature.

Figure 6. Paraffin solubility as a function of temperature for systems 1, 2, 3, and 4.

The calculation of solubility curves is important because their derivatives are used in the calculation of paraffinic deposition flux via molecular diffusion mechanism.

3.3 Simulation of paraffin deposition

A typical implemented *DepoSim* deposition simulator window is presented in Figure 7. When executed, the software presents a window containing areas for the insertion of data, presentation of results, as well as icons for performing calculation and graphic plotting.

For a simulation carried out using system 3, composed of a C_{15} - C_{38} mixture, with the same conditions of flow and temperature already reported in the literature (Svendsen, 1993), the deposition profile, presented in Figure 8, indicates how deposit thickness varies as a function of pipe length after 30 days of flow. The thickness profile curve obtained in this work is less extended and presents a behavior different from the one reported by Svendsen (1993). This difference can be explained as a consequence of the model used

Table 10. WAT and x_i^L (at 303 K) values for binary paraffinic systems obtained by Equation.

System	WAT (K)	x_i^L (303K)
1	320.2	8.74E-3
2	324.5	6.52E-3
3	328.4	3.56E-3
4	332	1.5E-3

Figure 7. Window of deposition simulator software, *DepoSim*, developed using MATLAB.

in the present work, which takes into account ablation that promotes a higher deposit thickness reduction. More specifically, when the deposit is formed on a pipe wall, the inner pipe radius decreases, resulting in an increase of fluid velocity and shear, increasing, consequently, the effect of ablation.

All the results obtained in this work considered the ablation phenomena, similarly to the ones done in experimental terms by Pan et al. (2009)

and Tiwary and Mehrotra (2009). In both works, turbulence was shown to decrease deposit thickness, in contrast with the work already cited of Svendsen (1993).

From the observations, maximum thickness always occurs next to pipe entrance; this is consistent with the fact that as oil enters the pipe it is saturated with paraffin crystals.

3.3.1 Influence of paraffin-solvent composition

As the paraffin molar mass is increased, its melting point increases, resulting in the decrease of paraffin solubility and an increase in WAT. Simulations were carried out in systems 1, 2, 3, and 4, to verify how these physicochemical facts appear in the simulation results for deposition. The results are displayed in Figures 9 and Figure 10.

Temperature profiles in nucleus (Figure 9), obtained by Equation 25, are similar for the studied binary systems. This is a coherent result, as the estimated thermal properties for the systems are very close to each other.

Figure 8. Deposition profiles for system 3.

Figure 9. Temperature profile in the turbulent nucleus for some binary systems after 30 days.

Figure 10. Thickness profiles for some binary systems after 30 days.

Regarding the amount of deposited paraffin, system 4 (C_{15} - C_{40}) was the one to present the highest amount of deposit during flow, yielding a deposit thickness of 10 mm, according to Figures 10. The results also show that as molar mass increases, a higher amount of deposit is formed, stressing its influence (and the influence of WAT, consequently) on deposit formation.

3.3.2 Effect of inlet (T_{in}) and external temperature (T_{ext})

Some experimental studies have reported that the amount of deposit may decrease or increase with the increase in the difference between the oil and surrounding temperatures (Huang et al., 2011b). The exact behavior will depend on diffusion parameters as well as on the difference between paraffin equilibrium concentrations in oil

and on pipe wall (solubility curve). These two parameters influence paraffins mass flow and, consequently, the amount of deposit formed.

The evaluation of the amount of deposited paraffin for system 3, with the change in oil temperature in pipe inlet (T_{in}) and external temperature (T_{ext}), was performed through simulations using *DepoSim*. The results are presented in Figure 11 and Figure 12.

Figure 11 shows that as oil inlet temperature is increased, the amount of deposit increases. That can be explained as the result of temperature gradient increase and, consequently, of the deposition mass flux, due to the increase in paraffin diffusivity towards wall pipe and the behavior exhibited by the solubility curve.

Figure 11. Paraffin thickness profile for system 3 after 30 days, varying the pipe inlet temperature.

Figure 12. Paraffin thickness profile for system after 30 days, for different external temperatures.

According to the solubility curve for system 6 (Figure 6), the concentrations of paraffin in oil is superior to the concentration on the wall, resulting in a higher difference in concentration (stronger mass deposition driving force).

Finally, the expected result for the increase in external temperature is the decrease in the amount of formed deposit, as a result of the decrease in mass deposition flux. The results obtained confirm this hypothesis and can be visualized in Figure 12.

The results for the effect of T_{in} and T_{ext} on the deposit thickness are in good agreement with the previously reported results (Arumugam et al., 2013; Haj-Shafiei et al., 2014). The deposit thickness profiles obtained for the simulated case is characteristic of the cold flow regime, when there are paraffin crystals suspended in the liquid phase ($T_{in} < WAT$), and under turbulent flow. However, in the hot flow regime ($T_{in} > WAT$), the deposit thickness increases along the pipeline length until reaching a maximum at the transition from hot flow to cold flow, and then decreases in the cold flow regime.

4. CONCLUSIONS

The simulation of different operation conditions using the software *DepoSim* could be used to get a better understanding of the influence of mixture composition and operation temperatures in the amount of formed deposit as well as the role of solubility curve in the deposition mass flux. The chosen model to describe paraffin deposition seemed adequate to the simulated turbulent flow, as the obtained results presented a behavior closer to real paraffinic oil transport operations. The results of this study have also shown that the process of paraffin deposition has temperature gradient as the main driving force, directly influencing deposit formation.

The methodology developed in this work for simulating the deposition of paraffins, using established correlations to estimate the properties of paraffin-solvent mixtures has the potential to be applied to more comprehensive studies, including ones on multicomponent mixtures.

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NOMENCLATURE

Symbols:

a	Coefficient of temperature profile
A_ρ	Yaws-Pike parameter of density correlation
A_k	Yaws parameter for thermal conductivity
A_η	Yaws-Dang parameter for viscosity
B_ρ	Yaws-Pike parameter for density
B_k	Yaws parameter for thermal conductivity
B_η	Yaws-Dang parameter for viscosity
C_ρ	Yaws-Pike parameter for density
C_k	Yaws parameter for thermal conductivity
C_η	Yaws-Dang parameter for viscosity
C_p	Molar calorific capacity (J/mol.K)
D	Diffusion coefficient (m^2/s)
D_η	Yaws-Dang correlation parameter for viscosity correlation
G_{ij}	Interaction parameter for Grunberg-Nissan correlation
ΔH	Molar enthalpy variation (J/mol)
j	Mass flux ($kg/m^2.s$)
h	Convective coefficient of heat transfer
L	Pipe length
n_ρ	Yaws-Pike correlation parameter
n_t	Total number of groups in molecule
m	Mass (kg)
M	Molar mass (kg/kmol)
N_C	Number of carbon atoms
P	Pressure (Pa)
Q	Volume flow rate (m^3/s)
R	Universal gas constant (8.314 J/mol.K)
R	Radius (m)
R_T	Radius at which velocity is constant (m)
Re	Reynolds number
r	Radial coordinate
k	Thermal conductivity ($W/m^2.K$)
t	Time (s)

t_a	Time for deposit consolidation (s)
T	Temperature (K)
WAT	Wax appearance temperature (K)
V	Molar volume (m^3/mol)
v	Velocity (m/s)
u_i	Rùzicha-Domalski correlation parameter for group i
U	Rùzicha-Domalski correlation parameter
x	Molar fraction
w_i	Rùzicha-Domalski correlation parameter for group i
W	Rùzicha-Domalski correlation parameter
z	Axial coordinate
Z	Grunberg-Nissan correlation parameter
y_i	Rùzicha-Domalski correlation parameter for group i
Y	Rùzicha-Domalski correlation parameter

Greek symbols:

α	Thermal diffusivity (m^2/s)
ρ	Density (kg/m^3)
ρ_{ma}	Svendsen density correlation parameter
η	Viscosity (cP)
σ	Thickness (m)
δ	Solubility parameter (cal/cm^3) ^{0.5}
ε	Effective radius fraction with stationary gradient
Δ_i	Grunberg-Nissan parameter
Δ	Variation
ψ	Fraction of total deposition flux
τ	Shear stress (Pa)

Superscripts:

$DIPPR$	DIPPR database
Exp	Experimental
est	Estimated
L	Liquid phase
S	Solid phase
Y	Yaws correlation parameter
$Y\&D$	Yaws-Dang correlation parameter
$Y\&P$	Yaws-Pike correlation parameter

Subscripts:

abl	Ablation
b	At boiling point
d	Deposit
dep	Deposition
ext	External
f	Fusion
i	Component i
in	Inlet
j	Component j
m	Mixture
n	Nucleus
mol	Relative to molecular diffusion
o	Initial
p	Wall
s	Solid
sol	Solvent
T	Thermal
v	Velocity

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