

An Inertial two-phase model of wax transport in a pipeline during pigging operations *

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Abstract

Pig in pipelines performs operations for cleaning the pipe interior and internal inspection. In the past few years many 1D models have been developed to simulate the process because of their reduced computational cost; however, they rely on simplifications which are not always valid. In this paper, the results of a three-dimensional (3D) numerical investigation of the interaction between a waxy-oil and a dynamic sealing pig in a pipeline are presented. The results are obtained at a reduced computational cost by using a moving frame of reference, and an “injection” boundary condition for the wax deposited on the wall. The effect of the temperature and the wax particles’ size has been investigated. The 3D results show the structure assumed by the debris field in front of the pig. In particular, a lubrication region at the bottom of the pipe, whose dimensions are temperature dependent, is shown. This information cannot be deduced from 1D modeling. The influence of the oil on the mixture viscosity and the internal bed dynamics are discussed. This work provides insights into the interaction between the debris field in front of the pig and pipeline hydraulics.

Keywords: pigging, oil, wax, deposition, pipeline, modeling

□ Modeling wax transport during pigging operations

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1. Introduction

Pipelines are the most common and safest way to transport oil and gas products. During operation, the pipeline walls suffer a deterioration process and can fail if they are not properly maintained. One part of pipelines maintenance procedure is “pigging” them regularly to prevent the increase of the wall roughness and the reduction of the internal diameter. The device known as “pig” is driven through the pipe by the flow of oil, scraping deposits from the pipe wall as it travels and is used to perform “pigging” operations. Pigging has been widely studied in the past few decades.

McDonald & Baker (1964) derived the first mathematical model on pigging. The model, valid for spherical pigs, was meant to be used for prediction of the liquid hold-up. Barua (1982) improved the model by removing some limiting assumptions and by considering the slug acceleration.

Kohda et al. (1988) proposed the first two-phase transient pigging model based on correlations. Minami & Shoham (1995) used a mixed Eulerian-Lagrangian approach to couple the transient two-phase flow with the pig motion. Hosseinalipour et al. (2007b) followed a similar approach, testing a transient model and comparing the results against experimental data.

Azevedo et al. (1996) developed an algebraic, 1D, hydrodynamic model to describe the bypass pig dynamics. The model coefficients were determined through two-dimensional (2D) Computational Fluid Dynamics (CFD) simulations of a Newtonian, incompressible fluid flowing in steady state conditions. The $k - \epsilon$ model was employed for the simulations.

Lima et al. (1998) and Lima et al. (1999) modeled the liquid removal operation in a gas pipeline. The 1D two-phase model has been solved via a semi-implicit finite difference scheme and the results have been successfully compared with experimental data. Nguyen et al. (2001b) solved the gas mass and momentum equations by using the method of characteristics (MOC) and the Runge-Kutta method. Nguyen et al. (2001c) and Nguyen et al. (2001d) applied the model to a bypass pig case, Nguyen et al. (2001a) to a curved pipe case, and Kim et al. (2003) experimentally verified the model.

Nieckele et al. (2001) developed a single phase fluid model, taking into account wall deformations, and coupled it with the pig momentum equation. A similar approach has been followed by Hosseinalipour et al. (2007a) to simulate the pig motion in gas pipelines.

35 Xu & Gong (2005) developed a simplified pigging model to predict the pig-
37 ging operation in gas-condensate horizontal pipelines with low liquid-loading.
38 The model has been successfully compared with the OLGA code results.
39 Tolmasquim & Nieckele (2008) developed a numerical code to simulate the
40 transient oil flow in a pipeline during pigging operations and the results have
41 been compared with field data.

42 In some works, the pig dynamics in dry conditions (no fluid flow) has
43 been investigated. Hu & Appleton (2005) developed a dynamic model for
44 a novel pig, designed to move both upstream and downstream, and verified
45 the results against experimental data. Saeidbakhsh et al. (2009) analyzed 45 the
dynamics of small pigs in complex-shaped pipelines. The effect of the
47 flow field was modeled by a time dependent force acting on the pig. The
48 influence of the flow field was successively introduced. The fluid was consid-
49 ered incompressible by Lesani et al. (2012) and compressible by Mirshamsi
50 & Rafeeyan (2015). In these three works, the dynamics of the system has
51 been solved via a single ordinary differential equation.

52 Esmaeilzadeh et al. (2009) used the MOC to model the transient motion
53 of a pig through liquid and gas pipelines. The simulation results showed good
54 agreement with the gas-liquid pipeline field data. Deng et al. (2014) used
55 the MOC to study the problem of column separation in gas-liquid pipelines 55
during pigging operations. The simulation results were in good agreement
57 with the field data.

58 Despite many models have been developed to describe the pig dynamics,
59 most of them deal with gas flows and some of them with liquid removal in gas
60 pipelines. In addition, all the cited models are limited to 1D domain. Waxy
61 oils (wax-particles in oil mixture) in pipelines have been largely studied.
62 Most of the literature focuses on two aspects: wax deposition in oil pipelines
63 (Aiyejina et al. (2011)), and wax removal from pipelines wall (Lima et al.
64 (1995)). Wang et al. (2005) studied the mechanics of wax removal in pipelines
65 in dry conditions, while Wang et al. (2008) repeated the experiments with 55 the
oil flowing in the test facility. The tribological behavior of waxy oil
67 subject to pipeline pigging has been investigated in the past few years using
68 the fluorescence technique by Tan et al. (2014, 2015a) and with the portable
69 microscopy technique by Tan et al. (2015b).

70 A few mathematical models tackle the the wax removal from pipeline
71 walls. An example is the one developed by Azevedo et al. (1999) and experi-
72 mentally verified by Barros Jr et al. (2005). Other pigging models, based on
73 experimental results, have been developed to predict wax deposition (Wang

74 & Huang (2014)) and removal in pipelines (Huang et al. (2016)). Wang et al.
75 (2015) studied experimentally the influence of several parameters on the wax
76 breaking process in order to determine the optimal de-waxing frequency and
77 evaluating the pigging risks. A good review illustrating the forces acting on
78 a bypass pig in operation was written by Galta (2014) .

79 A few models studying the forces involved in the wax-removal process
80 have been developed based on a mixed experimental-numerical procedure.
81 In particular, Braga et al. (1999) considered the wax deposit as a linear
82 elastic material and neglected the fluid flow, while Southgate (2004) included
83 the oil flow, but considered the wax deposit as rigid and part of the pipe
84 wall. The multiphase wax-oil flow in pipelines during pigging operations has
85 been scarcely studied. An example is the 1D model developed by Hovden
86 et al. (2003) with the OLGA 2000 code, where three different wax deposition
87 models have been tested.

88 In this paper, a series of three-dimensional (3D) CFD simulations de-
89 scribing the interaction of the waxy oil with the moving pig are presented.
90 Simulating the 3D flow is computationally demanding but has a two-fold ad-
91 vantage compared to the 1D approach: (i) it increases our understanding of
92 the phenomenon, as it allows the visualization of the interaction between the
93 pig surface and the wax chips; (ii) the results are less affected by modeling
94 approximations.

95 **2. Mathematical Modeling**

96 In this section, the mathematical model describing the dynamics of the
97 oil-wax system in a pipeline, subject to pigging operations, will be illustrated.

98 *2.1. Pig Model*

99 The main problem in representing the 3D pig motion numerically is due
100 to the computational grid which must be warped in order to represent the pig
101 displacement. Even though this can be realized with modern computational
102 techniques, it is a computationally demanding operation.

103 A more convenient approach is to solve the problem in a frame of reference
104 fixed to the pig center of mass, instead to an external observer, as done
105 by Minami & Shoham (1995); Hosseinalipour et al. (2007b); Nieckele et al.
106 (2001); Tolmasquim & Nieckele (2008) for 1D modeling. This is possible
107 when the pipeline is straight, with a constant section, and the process is
108 not investigated close to the pumping station or the outlet. Under these

109 conditions, the computational domain does not change as the time goes by.
 110 As the pig advances, the wax is scraped to accumulate in front of the pig.
 111 Despite the debris field grows in time, it only occupies a small portion of the
 112 pipeline.

113 The relationship between the velocity in the absolute frame of reference,
 114 $\mathbf{v}_a$, and the one in the relative frame of reference, $\mathbf{v}$, is

$$\mathbf{v} = \mathbf{v}_a - \mathbf{v}_{pig} \quad (1)$$

115 where $\mathbf{v}_{pig}$ is the pig velocity. In order to determine this parameter, two
 116 hypothesis were introduced: the pig under investigation is of *sealing* type,
 117 i.e. no flow between the two sides of the pig, and the oil flow rate,

$$Q_{oil} = \int_{A_{\pi \pi \varepsilon}} \mathbf{v}_{a,oil} \cdot \hat{n} dA \quad (2)$$

118 is constant. The mean oil velocity upstream the pig, U , is defined as

$$U = \frac{4Q_{oil}}{\pi D_{pipe}^2} \quad (3)$$

119 In order for the mass to be conserved at the interface between the up-
 120 stream oil and the pig, it must be

$$v_{pig} = U \quad (4)$$

121 Eq.(4) can be written because the sealing pig has only one degree of
 122 freedom (1DOF), therefore: $\mathbf{v}_{pig} = v_{pig} \cdot \hat{n}$. In general, the pig could also
 123 spin around its axis. Nevertheless, the friction against the wall has been
 124 assumed high enough to prevent this. Since the oil flow rate is supposed to
 125 be constant, the pig velocity should be constant as well, by virtue of Eq.(4),
 126 therefore the pig inertial force, will not influence the dynamics of the oil-wax
 127 system. This is a reasonable approximation as the pig is most effective when
 128 it advances at a nearly constant, but not too high, speed as reported by
 129 Nguyen et al. (2001a); Esmailzadeh et al. (2009); Deng et al. (2014).

130 The pig operation is performed when the wax layer reaches a certain
 131 thickness h_{ip} . Normally, for security purposes, h_{ip} is very small compared
 132 to the pipe diameter. In order to represent this, the computational grid
 133 thickness should be of the same order of the deposit thickness, resulting in a
 134 large computational cost.

Supposing that the wax is uniformly distributed in the circular pipe, and it is pushed along the pig axis at the pig velocity, the flow rate of scraped wax during the pigging operation is given by:

$$Q_{wax} = v_{pig} \frac{\pi}{4} (D_{pipe}^2 - (D_{pipe} - 2h_w)^2) \quad (5)$$

where Q_{wax} is the flow rate of the scraped wax. The pig-wax interfacial area, which is Q_{wax}/v_{pig} , is calculated as the wax removal efficiency was 100%, though in reality is always smaller. Nevertheless, this approximation is widely used to model the pig-wax deposit contact force, e.g. Braga et al. (1999); Barros Jr et al. (2005); Galta (2014), and it is used here to promote the slurry formation in a short time.

In order to reduce the computational cost, the effect of the scraped wax was embedded in a new boundary condition. A small area on the pipe surface called *injection area* has been introduced, where a positive flow rate of scraped wax corresponding to Q_{wax} , is imposed. Calling v_{inj} the velocity of the injected wax, and h_{inj} the injection area thickness, the flow rate of scraped wax reads:

$$Q_{wax} = v_{inj} \pi D_{pipe} h_{inj} \quad (6)$$

therefore,

$$v_{inj} = v_{pig} \frac{\overline{h_w}}{h_{inj}} \left(1 - \frac{h_w}{D_{pipe}} \right) \quad (7)$$

In the moving frame of reference, the axial velocity is zero for the pig and the injection area, while in the rest of the pipe wall it is equal to $-v_{pig} \hat{x}$, where $\hat{x}$ is the unit vector in the direction of the pipe axis.

2.2. Physical Properties of the System

The debris field in front of the pig is composed of cut wall wax (gel) and oil. The debris field can be considered as a slurry of cut wall wax and oil with variable cut wax content dependent on the wall wax-pig-pipe flow dynamics.

The physical properties of oil and wax-in-oil slurry are temperature dependent. They have been derived experimentally, and are illustrated in Fig.(1), where the dependence of the slurry dynamic viscosity on temperature Fig.(1,a) and wax volume fraction Fig.(1,b), are shown. In Fig.(2), the density Fig.(2,a) and the viscosity Fig.(2,b) of the oil are shown. As Fig.(1) suggests, the pour point of the deposit-contaminated oil is below $-25F$.

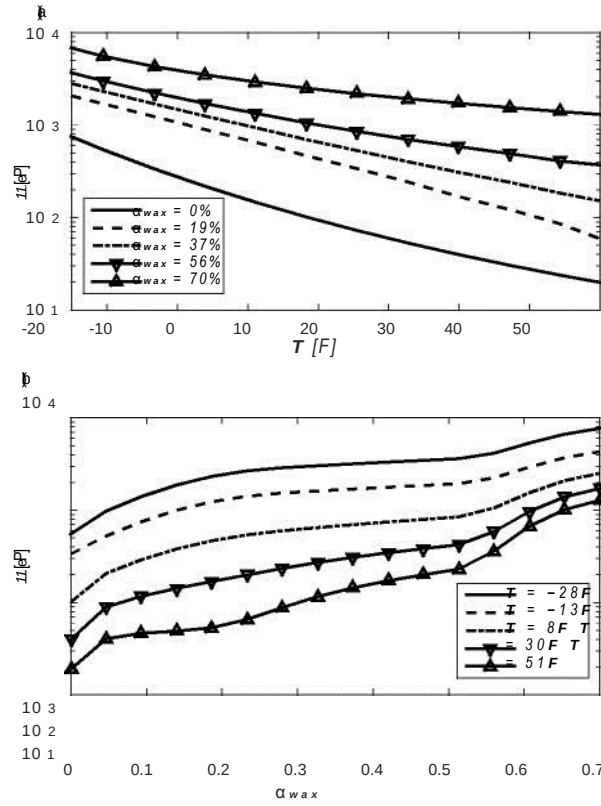


Figure 1: Dynamic viscosity of the wax-in-oil slurry: (a) vs Temperature; (b) vs Volume Fraction.

2.3. Fluid dynamic model

The flow of the mixture has been simulated with the *drift flux* model, which is widely used in multiphase modeling (Aarsnes et al. (2016); Varadarajan & Hammond (2015); Bhagwat & Ghajar (2014); Chen et al. (2012); Asheim & Grødal (1998); Gavrilyuk & Fabre (1996); França & Lahey (1992); Clark et al. (1990)), and solves the conservation of mass, momentum and energy of the mixture only. This implies that the momentum of each phase is not calculated explicitly and the inter-phase phenomena, such as settling, require modeling. In addition, a transport equation for the volume fraction of each phase is provided. In this work, the wax-in-oil slurry flow is considered to be laminar. This can be achieved if the pipe diameter is sufficiently small, because of the high wax viscosity. Moreover, the flow has been considered isothermal and therefore the energy equation has not been considered.

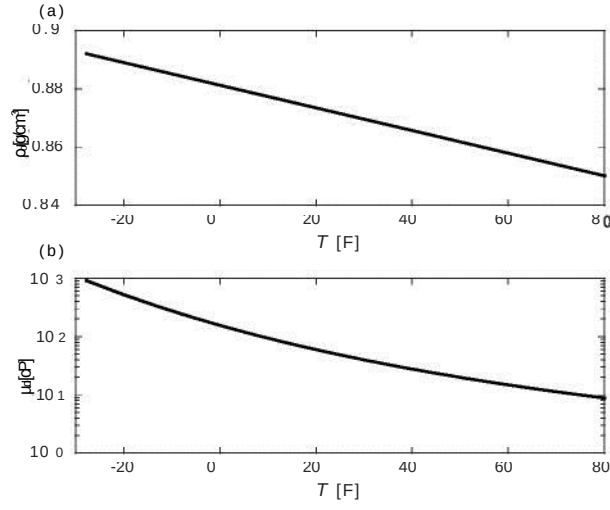


Figure 2: Oil properties: (a) density; (b) dynamic viscosity

177 The reduced pipe diameter and length limit the surface of heat exchange,
 178 justifying that this assumption is valid if the observation time is small and
 179 is suitable for non-heated pipelines.

180 The wax volume fraction in the slurry, a_{wax} , is defined as:

$$\square_{wax} = \frac{V_{wax}}{V_{rev}} \quad (8)$$

181 where V_{rev} is the Representative Volume Element (REV) which is the
 182 smallest volume over which a measurement can be made that will yield a
 183 value representative of the whole. Since in the domain of investigation there
 184 are only oil and wax particles, the following relationship applies:

$$\square_{oil} = 1 - \square_{wax} \quad (9)$$

185 The continuity equation for the wax phase can be written as:

$$\frac{a}{a t} (P_{wax} a_{wax}) + \text{div} (P_{wax} a_{wax} (\square v_m + \square v_{d_w})) = 0$$

186 where

$$\square v_{d_w} = \square v_{wax} - \square v_m \quad (11)$$

187 is the drift velocity,

$$\mathbf{v}_m = \frac{\rho_{oil} \mathbf{v}_{oil} + \rho_{wax} \mathbf{v}_{wax}}{\rho_m} \quad (12)$$

188 the mixture velocity, and,

$$\rho_m = \rho_{oil} \phi_{oil} + \rho_{wax} \phi_{wax} \quad (13)$$

189 the mixture density. Adding up the mass conservation of each phase, e.g.
190 Eqs.(9,10), the conservation of mass for the mixture can be obtained
as:

$$\frac{\partial \rho_m}{\partial t} + \text{div} (\rho_m \mathbf{v}_m) = 0 \quad (14)$$

191 The mixture momentum equation can be written as

$$\frac{\partial}{\partial t} (\rho_m \mathbf{v}_m) + \text{div} (\rho_m \mathbf{v}_m \otimes \mathbf{v}_m) = -\nabla p_m + \text{div} ([\tau_m] + [\tau_{dm}]) + \rho_m \mathbf{g} \quad (15)$$

192 where p_m is the mixture pressure, or just pressure,

$$[\tau_{dm}] = \phi_{oil} \rho_{dw} \mathbf{v}_{dw} \otimes \mathbf{v}_{dw} \quad (16)$$

193 is the *drift stress tensor*, and

$$[\tau_m] = \mu_m (T, \phi_{wax}) [\nabla \mathbf{v}_m] + [\nabla \mathbf{v}_m]^T - \frac{2}{3} \text{div} (\mathbf{v}_m) [I] \quad (17)$$

194 the *viscous stress tensor* with $[I]$ the identity tensor and $\mu_m (T, \phi_{wax})$
195 the mixture viscosity which, as can be seen from the experimental data in
196 Fig.(1), is a function of both the temperature and the wax volume fraction.
197 Further details on the Drift Flux Model can be found in Rusche (2003).

198 As it can be seen from Eqs.(10,16,17), the model is complete once the
199 expression of the drift velocity and mixture viscosity are supplied.

200 2.4. Mixture Viscosity Model

201 The mixture viscosity has been derived experimentally and the results
202 are shown in Fig.(1). The slurry viscosity was measured in a rotational vane
203 rheometer at constant constant shear rate of 301/s as the temperature was
204 reduced uniformly from the wax appearance temperature (80F) to -28F

Table 1: Coefficients of the Mixture Viscosity Model

$T(F)$	b_1	b_2	b_3	b_4	r^2
-25	7.9805	-3.342	2.1055	0.48004	0.9770
0	18.516	-7.3499	3.1263	0.38464	0.9905
25	18.583	-6.515	3.3366	0.53254	0.9790
50	8.9526	-1.7972	3.4096	0.63734	0.9490

over 18 hours. The measurement have been performed at varying volumetric fractions of cut wax. At each temperature, the mixture viscosity shows a discontinuous slope for $\phi_{wax} = 0.5$, appearing to reach an asymptote near $\phi_{wax} = 0.7$, which is the maximum packing fraction. This is consistent with the change of particle arrangement. For $\phi_{wax} < 0.5$ the wax chips are more free to move and their orientation is random; above this value the chips start packing and the mixture viscosity increases abruptly. In order to fit the experimental data, the following relationship is introduced:

$$\ln \frac{(\mu_m(T, \phi_{wax}))}{\mu_m(T, 0)} = \max \left(\frac{b_1(T)\phi_{wax}}{1 - b_2(T)\phi_{wax} - b_4(T)\phi_{wax}}, \frac{b_3(T)\phi_{wax}}{1 - b_2(T)\phi_{wax} - b_4(T)\phi_{wax}} \right) \quad (18)$$

In Tab.(1) the b_i coefficients, along with the square correlation coefficient r^2 , which shows how well the model in Eq.(18) reproduces the experimental results, are reported. It must be noted that the value $\mu_m(T, 0)$ is not in that table, because it corresponds to the oil viscosity and will be shown in Tab.(3)

2.5. Drift Velocity Model

The Stokes' velocity, which is the terminal velocity of a particle in a laminar regime, reads:

$$\phi v_s = \frac{1}{18} \frac{(\phi_{wax} - \phi_{oil}) \phi g d_{wax}^2}{\mu_{oil}}$$

In case of hindered settling, an alternative expression has been proposed by Camenen (2008)

$$\phi v_{hs} = \phi v_{wax} \quad \phi v_{oil} = \phi v_s \left[1 - \frac{\phi_{wax} \phi_{\omega \alpha \xi, \max}}{\phi_{wax, \max}} \right] \quad (20)$$

Table 2: Settling velocity

$T(F)$	$d_{wax}(mm)$	$v_s(mm/s)$	Re_p	n
-25	2	-0.251	$5.8 \cdot 10^{-4}$	4.6
0	2	-1.369	$1.5 \cdot 10^{-2}$	4.6
25	2	-4.857	$1.7 \cdot 10^{-1}$	4.6
50	2	-12.97	1.1	4.35
-25	0.4	-0.010	$4.6 \cdot 10^{-6}$	4.6
0	0.4	-0.055	$1.2 \cdot 10^{-4}$	4.6
25	0.4	-0.194	$1.4 \cdot 10^{-3}$	4.6
50	0.4	-0.519	$8.9 \cdot 10^{-3}$	4.6

where $\phi_{wax,max}$ is the maximum volume fraction, which in this work has been assumed equal to 0.7, and n is an exponent defined as

$$n = \begin{cases} 4.6 & \text{for } Re_p < 0.2 \\ 4.4Re_p^{-0.03} & \text{for } 0.2 < Re_p < 1 \\ 4.4Re_p^{-0.1} & \text{for } 1 < Re_p < 500 \\ 2.4 & \text{for } Re_p > 500 \end{cases} \quad (21)$$

where Re_p is the particle Reynolds number defined as

$$Re_p = \frac{\phi_{oil} |\phi_{vs}| d_{wax}}{\mu_{oil}} \quad (22)$$

The settling velocity in Eq.(20) has been validated against experimental data on particles of different shapes and dimensions (Camenen (2008)). Therefore, in this context the particle diameter is the largest distance between two points of the particle.

Finally, the drift velocity reads:

$$v_{dw} = \frac{\phi_{oil} \phi_o}{\phi_m} v_{hs} \quad (23)$$

In Tab.(2) the settling velocity values for different temperatures and particle diameters have been reported along with the particle Reynolds number and the exponent n appearing in Eqs.(20,22).

233 3. Materials and Method

234 The simulations have been performed using the `driftFluxFoam` solver,
235 available in OpenFOAM v3.0, which solves the fluid dynamics equations with
236 the Finite Volume Method (FVM) and uses the SIMPLE algorithm for the
237 pressure-velocity coupling. The computational grid has been realized with the
238 `blockMesh` utility of OpenFOAM v3.0. Only the pipe in front of the pig,
239 which has a diameter of 3in and is 60 diameters long, has been considered as
240 the domain of investigation, since a constant oil flow rate of 37USgal/min has
241 been imposed. These dimensions are not typical of oil pipelines but can be
242 found in test facilities (Barros Jr et al. (2005); Team (2011); Wang et al.
243 (2015); Huang et al. (2016)). The front pig wall is steady, because of the
244 moving frame of reference, while the pipe wall is moving backwards at the pig
245 speed. In order to ensure mass conservation, both pig and mean oil velocity
246 are equal to 1.7ft/s(0.51m/s).

247 At the *injection area* only wax is present, with an injection velocity given
248 by Eq.(7) and directed radially inwards. This condition represents the scraping
249 of a 2mm thick wax deposit. The resulting flow rate of scraped wax is about
250 3.78USgal/min, regardless of the particle diameter. Therefore, the smaller the
251 particles, the higher their number. Since the injection boundary condition,
252 defined in Eq.(7), decouples the flow rate of scraped wax from the particle
253 diameter, it is possible to study the influence of these two parameters
254 separately.

255 The velocity normal derivative is set to zero at the outlet boundary (Neu-
256 mann boundary condition). As far as the volume fractions are concerned,
257 the normal derivative is set to zero everywhere except at the injection area,
258 where a fixed volume fraction is imposed. This corresponds to zero mass flux
259 at the boundary (Vorobev & Boghi (2016)).

260 Eight simulations have been set up. Four different temperatures, i.e.
261 -25F, 0F, 25F, 50F , and 2 particle diameters, i.e. 2mm, 0.4mm, have been
262 investigated. The uniform particle diameter is an approximation made to
263 study the effect of this parameter. In reality, during the scraping process,
264 particles of different dimensions are injected into the pipe. The temperatures
265 chosen are very low, and the particle diameters high. Nevertheless, these
266 extreme conditions can be found in the trans Alaska pipeline system (Team
267 (2011)) and have been chosen to provoke crystallization in a short length,
268 and obtain a developed wax-in-oil slurry in a short model time.

269 4. Results

270 The simulations have been performed on the Astral Cluster with Xeon
271 5160 dual core processors at Cranfield University. Each simulation run on 32
272 processors and took approximately 4 hours and 40 minutes, on a grid made
273 of 518400 hexaedra, to be completed.

274 The results are grouped in two categories: *Results at 2mm wax particle*
275 *diameter*, and *Results at 0.4mm wax particle diameter*. The results will be
276 expressed in terms of section averaged variables as well, since many pipeline
277 codes provide them.

278 The wax area fraction is defined as:

$$\alpha_{wax}(t, x) = \frac{\int_0^{2\pi} \int_0^R \alpha_{wax}(t, r, \theta, x) r dr d\theta}{\int_0^{2\pi} \int_0^R 1 r dr d\theta} \quad (24)$$

$$\alpha_m(t, x) = \alpha_{oil} + (\alpha_{wax} - \alpha_{oil}) \alpha_{wax}(t, x) \quad (25)$$

280 the section averaged momentum is defined as:

281 the section averaged pressure drop is defined as:

$$\alpha_m(t, x) U_m(t, x) = \frac{\int_0^{2\pi} \int_0^R \alpha_m(t, r, \theta, x) v_m(t, r, \theta, x) \cdot \hat{x} r dr d\theta}{\int_0^{2\pi} \int_0^R \alpha_m(t, r, \theta, x) r dr d\theta} \quad (26)$$

$$p(t, x) = \frac{1}{\int_0^{2\pi} \int_0^R \alpha_m(t, r, \theta, x) r dr d\theta} \quad (27)$$

282 For a single phase flow, the pressure drop can be calculated according to
283 the following formula:

$$p_{oil}(t, x) - p_{out} = \alpha_{oil} \left(\frac{4Q_{oil}}{D} \right)^2 \left(\lambda' + \lambda (Re_{oil}, \epsilon/D) L_D \right) \quad (28)$$

284 Where Q_{oil} is the mean oil velocity, D the hydraulic diameter and λ' is the
285 local friction factor which takes into account the localized loss of charge due
286 to the fact that the velocity profile at the pig surface is not fully developed
287 (Al-Nassri & Unny (1981)). This coefficient has been derived by performing a

Table 3: Properties used for the simulations

$T(F)$	$p_{oil}(g/cm^3)$	$p_{wax}(g/cm^3)$	$\mu_{oil}(cP)$	$\mu_{wax}(cP)$	Re_{oil}	$\Delta p_{ref}(kPa)$
-25	0.891	0.98	771.71	7103.6	45	9.96
0	0.881	0.98	157.68	3150.5	218	2.03
25	0.871	0.98	48.92	2026.2	695	0.63
50	0.861	0.98	20.00	1487.7	1680	0.26

series of numerical simulations at different temperatures with only oil flowing in the pipeline, and its value has been found equal to 0.1 approximately for every temperature.

In Tab.(3) the properties used for the simulations have been reported. The density and viscosity values have been experimentally determined and have been shown in Fig.(1) and Fig.(2). It must be noted that $\mu_{oil} = \mu_m(T, a_{wax} = 0)$ and $\mu_{wax} = \mu_m(T, a_{wax} = 0.7)$. The last two values in Tab.(3) refer to the simulations in which only pure oil is flowing. As μ_{oil} is the minimum value for the mixture viscosity and Re_{oil} is the highest Reynolds number for the wax-in-oil slurry flow, the mixture flows in laminar regime. Moreover, Δp_{ref} is the pressure drop in the domain when only pure oil is flowing, and it is the lowest pressure drop which can occur in the domain.

4.1. Results at 2mm wax particle diameter

The cut wax volume fraction field is shown in Fig.(3). The solutions at different temperatures are compared. The volume fraction field appears to be more diffuse at lower temperatures. This is due to the fact that the oil viscosity increases with the decreasing temperature. This reduces the settling velocity v_s and increases the wax particles dispersion.

When the pig scrapes the wax deposit at $T = -25F$, the wax particles travel a relatively long distance, because of the small settling velocity. Therefore, at the bottom of the pipe a region can be observed, 40 diameters long and half a diameter high, in which the wax volume fraction is relatively low ($\square$ 35%). This will be called “lubrication region”, because it is characterized by a low viscosity, as Fig.(1) suggests.

At $T = 0F$ a lubrication region at the pipe bottom, 28 diameters long, can be observed as well. This region is shorter than the previous case but its wax content is higher ($\approx 50\%$). A high wax content region can be seen downstream the lubrication region. Nevertheless, due to the low settling, its boundaries cannot be clearly defined. In this region, also present for $T = -25F$, the particles settle. Further downstream another low wax content region can be seen.

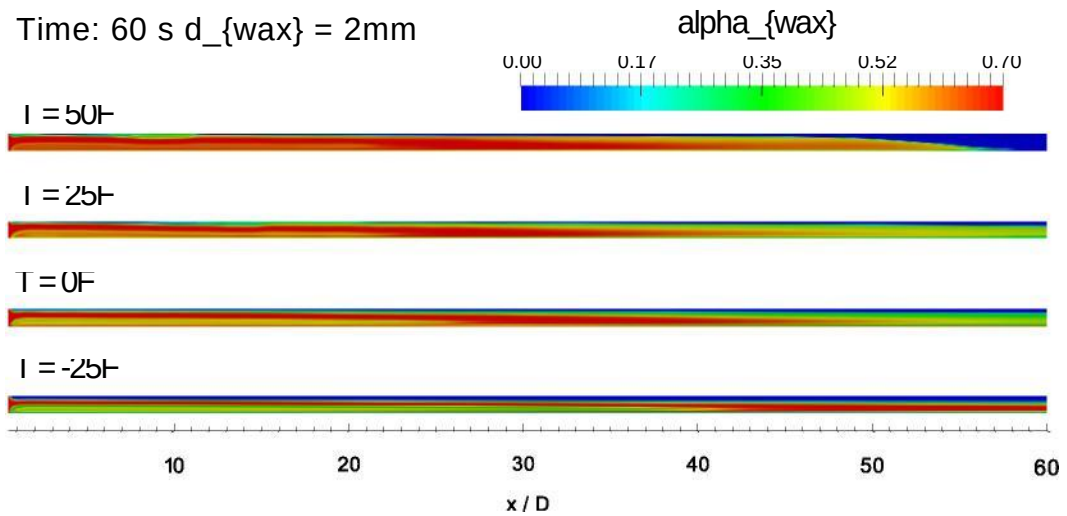


Figure 3: Wax volume fraction field for $2mm$ particle diameter at 60 seconds after the beginning of the process.

The wax debris field is similar to the previous cases for $T = 25F$ and $T = 50F$ with a shorter and more viscous lubrication region. A remarkable difference can be observed for $T = 50F$, where only pure oil can be seen downstream the high wax content region. This is due to the high settling velocity which promotes wax deposition.

In Fig.(4) the section averaged wax debris field, defined in Eq.(24), at different instants of time is shown. The stratified debris field assumes a “dune” shape. The wax distribution increases slightly in height compared to the length. This means that the height of the dune, is mostly set at the beginning of the operations. Therefore, the fluid dynamic conditions at the pig front surface must play an important role in determining this parameter.

It is interesting to compare the 3D information given in Fig.(3), with the

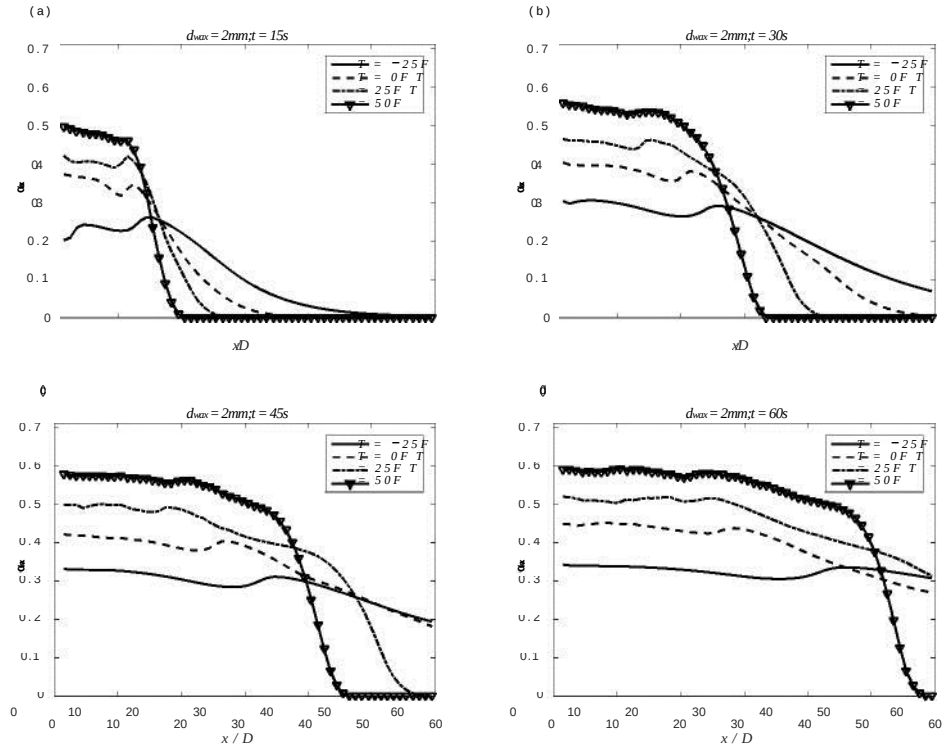


Figure 4: Section averaged cut wax volume fraction field for 2mm particle diameter. (a) $t = 15s$; (b) $t = 30s$; (c) $t = 45s$; (d) $t = 60s$.

1D in Fig.(4,d). The section average is more representative of the instantaneous field at higher temperatures because the debris distribution is more uniform. The presence of a lubrication region cannot be deduced from the 1D field.

For a_{wax} at $T = -25F$ the wax-in-oil slurry is stratified: the top layer contains 0% of wax (oil layer), the second layer contains about 70% of wax, and the bottom layer contains 35% of wax. However, it is not possible to retrieve this information from the section averaged field.

This is very important as the pressure drop across the pipe is influenced by the local viscosity that depends on the wax distribution. A simplified 1D model which does not take into account the wax distribution, risks to give an unreliable estimation of the pressure drop.

The time growth of the wax-in oil slurry is an interesting output for

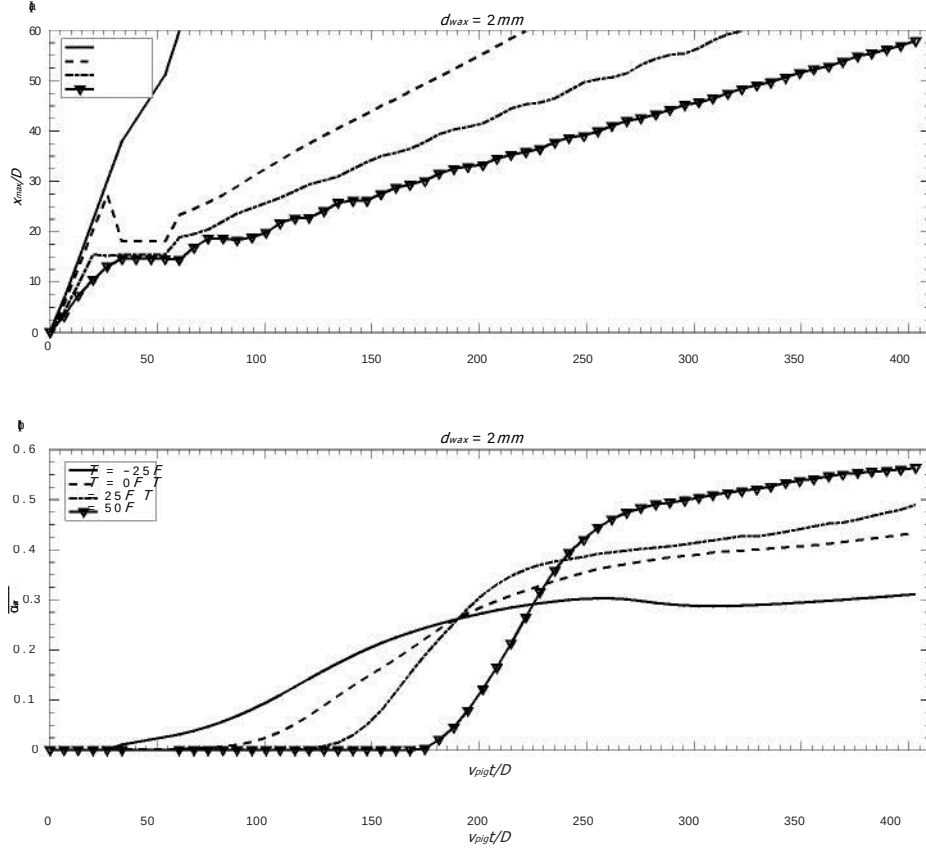


Figure 5: Time growth of wax-in-oil slurry for $d_{wax} = 2mm$. (a) wax-in-oil slurry length vs time; (b) wax volume fraction at $x/D = 30$ vs time.

the operators. The injection boundary condition, i.e. Eq.(7), for a sealing pig ensures that the wax debris content increases linearly in time for every temperature and particle diameter. Therefore, in Fig.(5,a) the growth of the wax-in-oil slurry length in time is shown, while in Fig.(5,b) the increase of wax volume fraction at $x/D = 30$ is shown. The time has been non-dimensionalized using the time scale D/v_{pig} . As far as the wax-in-oil slurry length is concerned, after an initial establishment period, the growth is essentially linear in time.

Moreover, the slope of the curve is inversely proportional to the temperature. This is due to the settling, which is higher at higher temperatures. As far as the wax volume fraction at $x/D = 30$ is concerned, the variables

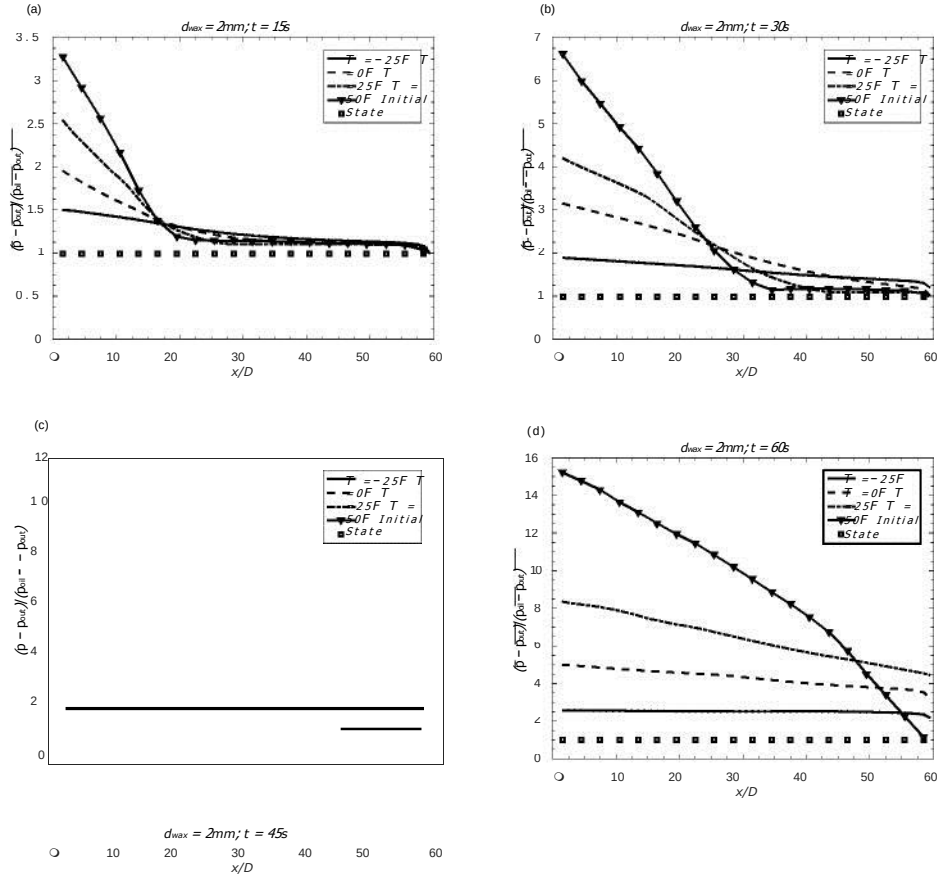


Figure 6: Ratio between the section averaged and the pure oil pressure drop for $d_{max} = 2mm$ vs axial distance. (a) $t = 15s$; (b) $t = 30s$; (c) $t = 45s$; (d) $t = 60s$.

undergo a phase of fast growth and then stabilize to a certain value. For lower temperatures the growth occurs earlier, but the final volume fraction is smaller. This is also due to the difference in settling.

The ratio between the section averaged pressure drop of the mixture, defined in Eq.(27), and the pure oil, defined in Eq.(28), is shown in Fig.(6). The aim of this variable is to show the increase in pressure drop due to the debris field. Despite the absolute pressure drop is lower at the higher temperatures, the pressure drop ratio is higher at higher temperatures.

This is due to the fact that the viscosity is inversely proportional to the temperatures. Therefore, the increase of pressure drop is more significant at higher temperatures compared to lower ones. Nevertheless, the increase in

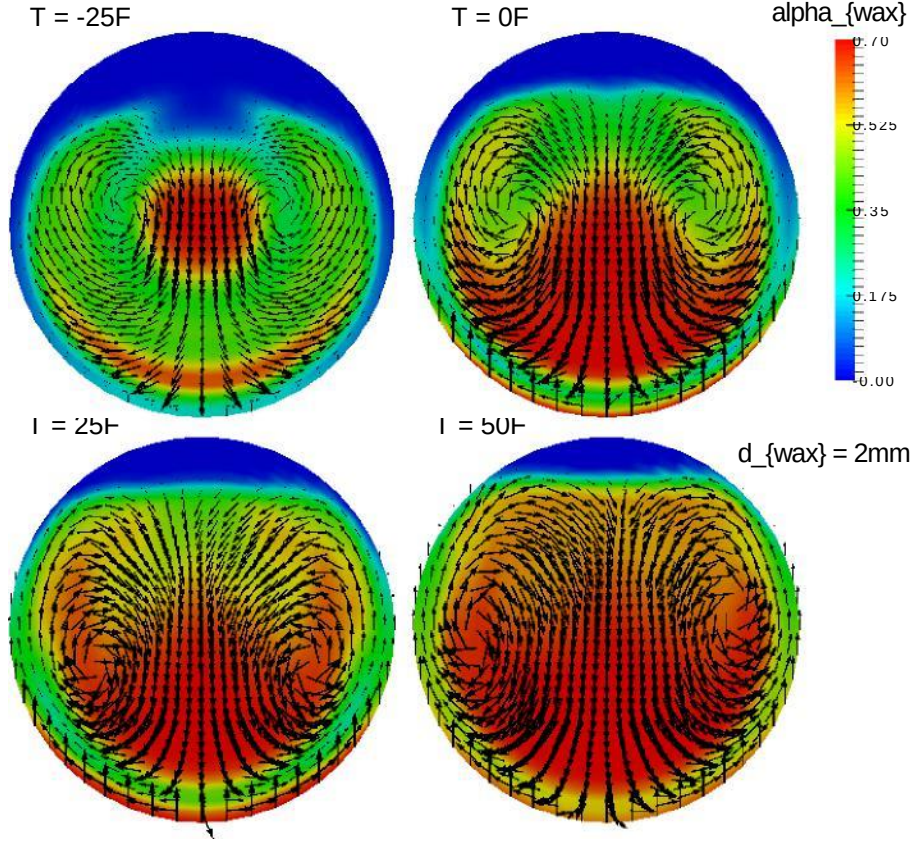


Figure 7: Cut wax planar velocity for $d_{wax} = 2mm$, $t = 60s$, $x/D = 30$

366 pressure drop due to the debris is not negligible at small temperatures, as it
 367 can be seen in Fig.(6) where at $T = -25F$, the pressure drop ratio is 2.5,
 368 while at $T = 50F$ it is 15.5.

369 In Fig.(7) the planar velocity vectors along with the wax volume fraction
 370 field are shown. The velocity vector pattern is highly dependent on the
 371 wax debris distribution. At each temperature there is a central region with
 372 $a_{wax} = 0.7$ surrounded by two counter-rotating vortices. There is a crescent
 373 shaped region with $a_{wax} = 0.7$ towards the bottom. Close to the wall the
 374 wax volume fraction is lower, which is responsible for the lubrication effect.
 375 The wax chips move towards the bottom and the average volume fraction
 376 increases at higher temperatures, as it can be seen in Fig.(4).

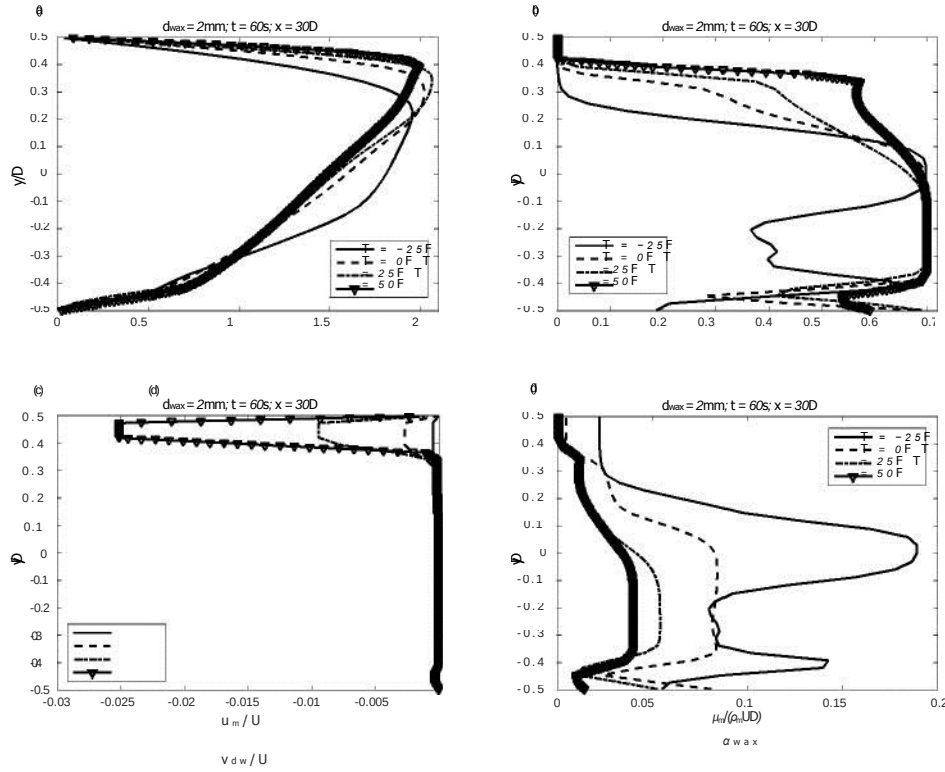


Figure 8: Profiles for $d_{wax} = 2\text{mm}$, 60 seconds after the beginning of the process and 30 diameters downstream the pig. (a) Normalized axial mixture velocity; (b) wax volume fraction; (c) Normalized vertical drift velocity; (d) Normalized Mixture Viscosity.

377 In Fig.(8,a) the mixture axial velocity scaled by the velocity U , defined
 378 in Eq.(3), is shown. The mixture axial velocity is highly dependent on the
 379 local mixture viscosity, shown in Fig.(8,d) which is scaled by $p_m U D$. The
 380 velocity gradient decreases with the increasing viscosity in order to ensure the
 381 continuity of shear stress at the boundary between the oil and the wax-in-oil
 382 slurry. As the temperature increases, the maximum velocity moves towards
 383 the pipe top wall because of the higher wax content at the bottom. In
 384 Fig.(8,c) the drift velocity scaled by U is shown. The drift velocity increases
 385 in the oil region, in agreement with Eq.(20), and decreases with the increasing
 386 temperature, in agreement with Eq.(19).

387 4.2. Results at 0.4mm wax particle diameter

388 The wax debris field in the middle section of the pipe, with a particle
 389 diameter of 0.4mm, is shown in Fig.(9). There is an increase in dispersion
 390 compared to the previous case. This is in agreement with Eq.(19), which
 391 reduces the settling velocity 25 times, compared to the previous case.

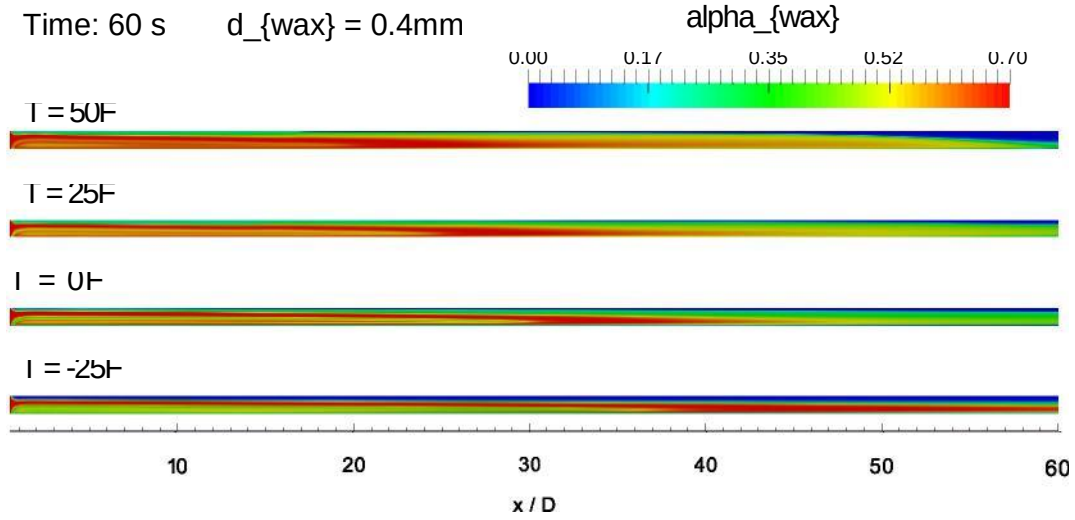


Figure 9: Wax volume fraction field for 0.4mm particle diameter at 60 seconds after the beginning of the process.

392 At $T = -25F$ the results are very similar with those shown in Fig.(3) be-
 393 cause in both cases the drift velocity is small enough to keep the particles in
 394 suspension. For the other temperatures, some differences with the previous
 395 case can be observed at the end of the domain. The near field is charac-
 396 terized by a layered structure previously observed in Fig.(3). The particle
 397 diameter seems to influence the particle deposition mostly in the far-field.
 398 This suggests that the morphology of the debris field is mostly determined
 399 by the temperature.

400 The reason for this behavior is in the nature of the settling process, which
 401 is faster in pure liquids, and slower in slurry. Therefore, the differences
 402 between Fig.(3) and Fig.(9) are more evident in the far-field, because the
 403 particles fall in the oil and the difference between the settling velocities is
 404 not negligible, while in the near-field the particles fall in the wax-in-oil slurry
 405 and in both cases the settling velocity is very small.

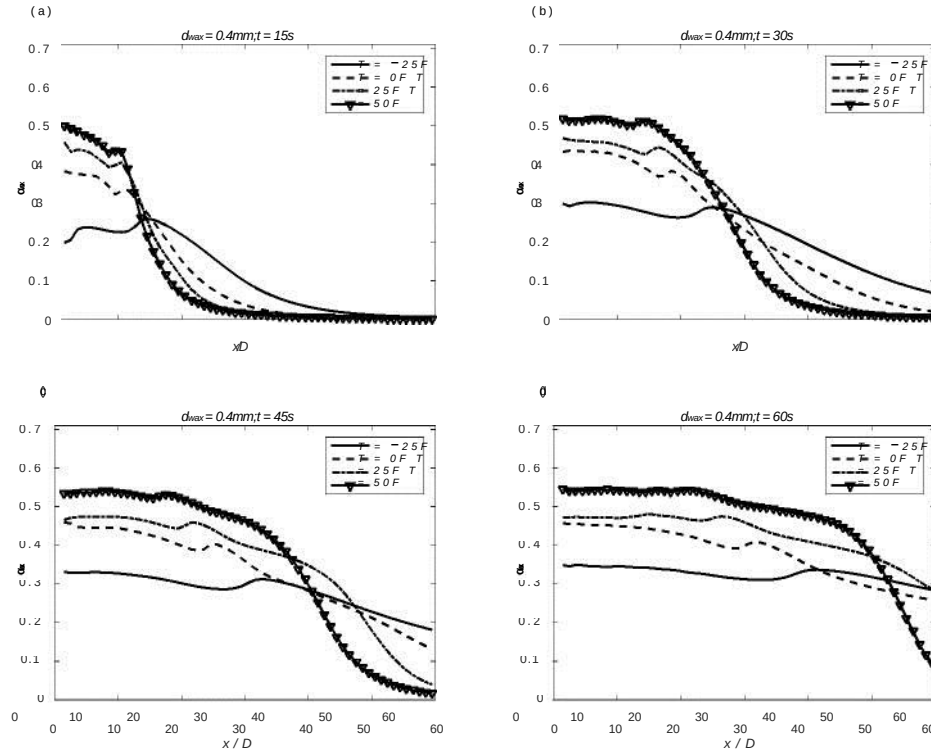


Figure 10: Section averaged cut wax volume fraction field for 2mm particle diameter. (a) $t = 15s$; (b) $t = 30s$; (c) $t = 45s$; (d) $t = 60s$.

In Fig.(10), the section averaged wax fraction at different time instants and temperatures is shown. In this case, the differences between the volume fraction field and the section averaged are less evident because the debris are more dispersed. However, the average does not show the stratification in Fig.(9) both in this case as well as in the previous one. The loss of this information could lead to a wrong estimate of velocity gradient and pressure drop.

The profiles in Fig.(10) and Fig.(4) appear to be very similar, with few differences. For $d_{wax} = 0.4mm$, the wax fraction is more uniformly distributed in the pipe compared to $d_{wax} = 2mm$. For $d_{wax} = 0.4mm$, the averaged wax fraction is lower in the near field and higher in the far-field as compared to $d_{wax} = 2mm$. This is due to the lower settling velocity which allows the particles to travel further downstream the pipe.

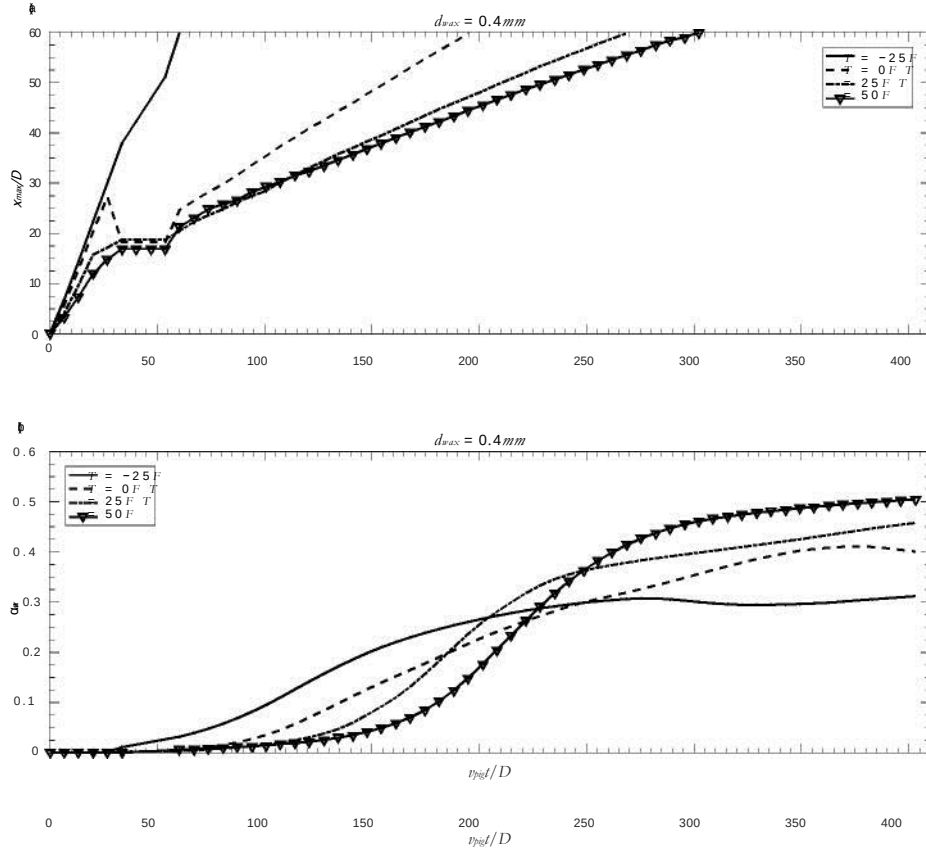


Figure 11: Time growth of wax-in-oil slurry for $d_{wax} = 0.4mm$. (a) wax-in-oil slurry length vs time; (b) wax volume fraction at $x/D = 30$ vs time.

In Fig.(11,a) the growth of the wax-in-oil slurry length in time is shown, while in Fig.(11,b) the increase of wax volume fraction at $x/D = 30$ is shown. The time has been non-dimensionalized using the time scale D/v_{pig} . As for the previous case, the growth is essentially linear in time with the slope of the curve inversely proportional to the temperature. Comparing Fig.(11,a) with Fig.(5,a) it can be seen that the growth is quicker for $d_{wax} = 0.4mm$ due to the lower settling.

As far as the wax volume fraction at $x/D = 30$ is concerned, comparing Fig.(11,b) with Fig.(5,b) it can be seen that for every temperature the growth occurs earlier, but the final volume fraction is smaller, which is also due to the reduced settling.

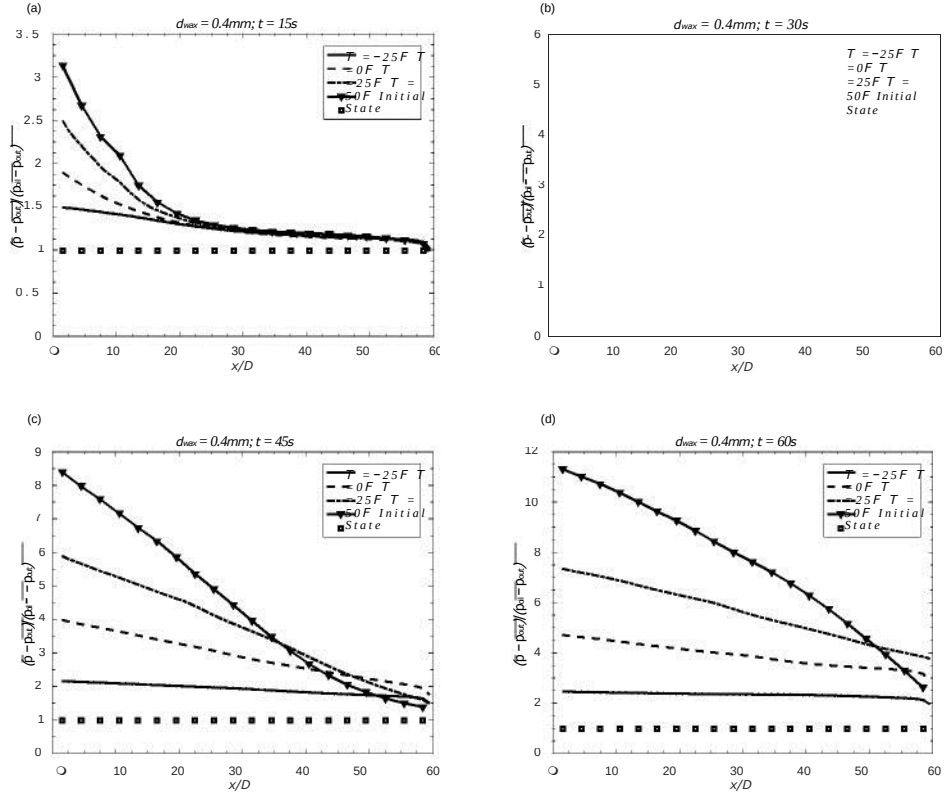


Figure 12: Ratio between the section averaged and the pure oil pressure drop for $d_{wax} = 0.4\text{mm}$ vs axial distance. (a) $t = 15\text{s}$; (b) $t = 30\text{s}$; (c) $t = 45\text{s}$; (d) $t = 60\text{s}$.

430 In Fig.(12), the ratio between the section averaged pressure drop of the
 431 mixture and the pure oil, is shown. This variable is obtained from the ratio
 432 between the expressions in Eq.(27) and Eq.(28). Comparing the profiles in
 433 Fig.(12) and Fig.(6), it can be seen that, in analogy with the previous case,
 434 the pressure drop increases in the presence of debris. Nevertheless, this effect
 435 is less pronounced as compared to Fig.(6). We can conclude that the pressure
 436 drop decreases for decreasing particle diameters. From this result, we can
 437 hypothesize that any mechanism promoting particle breakage, as a jet for
 438 instance, may reduce the pressure drop.

439 In Fig.(13) the planar velocity vectors along with the wax volume fraction
 440 field are shown. In general, the motion is more dispersed as compared to the

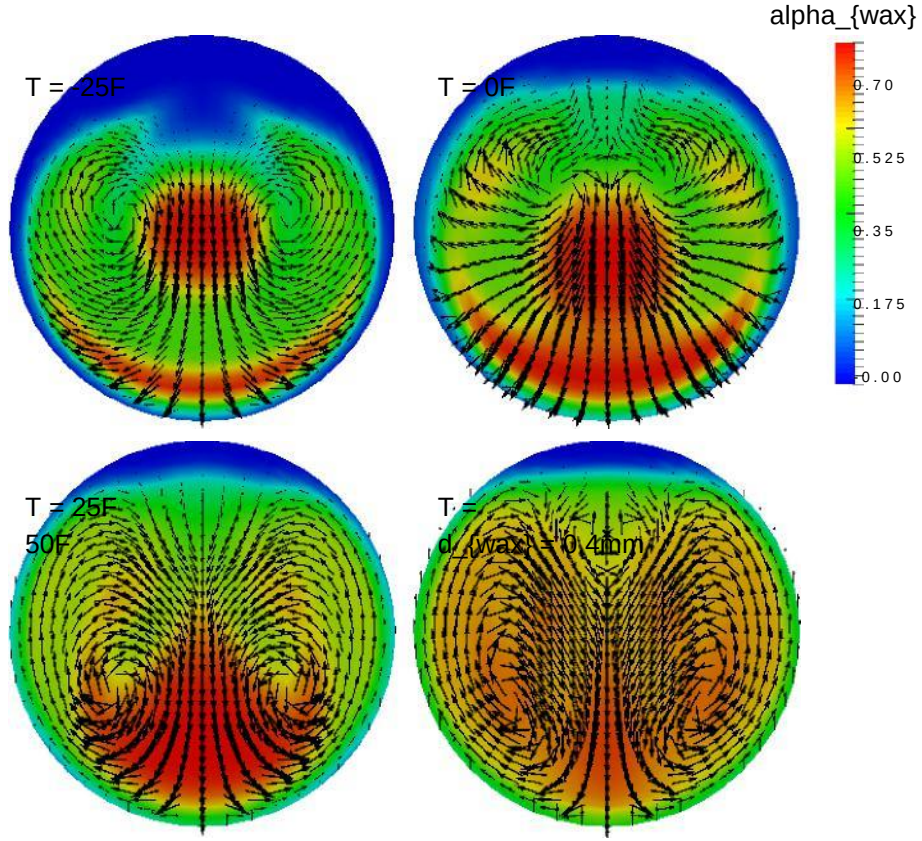


Figure 13: Cut wax planar velocity for $d_{wax} = 0.4mm$, $t = 60s$, $x/D = 30$.

441 previous case. For $T = -25F$, the particle diameter has scarce influence on
 442 the solution. For the other temperatures some differences with the previous
 443 case can be observed: the wax content is lower, as it can be deduced by
 444 comparing Fig.(10) with Fig.(4), and the counter-rotating vortexes are closer
 445 to the top of the pipe. At $T = 50F$, the velocity fields for the $d_{wax} = 2mm$
 446 and $d_{wax} = 0.4mm$ appear very different. For $d_{wax} = 0.4mm$ the vortexes are
 447 in the lower part of the pipe and their major axes are inclined with respect
 448 to the vertical axis of $\pm \pi/4$. For $d_{wax} = 2mm$, the vortexes are located at
 449 the center of the section and their major axes are parallel to the vertical axis.

450 In Fig.(14,a), the mixture axial velocity, scaled by the velocity U , defined
 451 in Eq.(3), is shown. Comparing this result with Fig.(8,a) it can be seen that

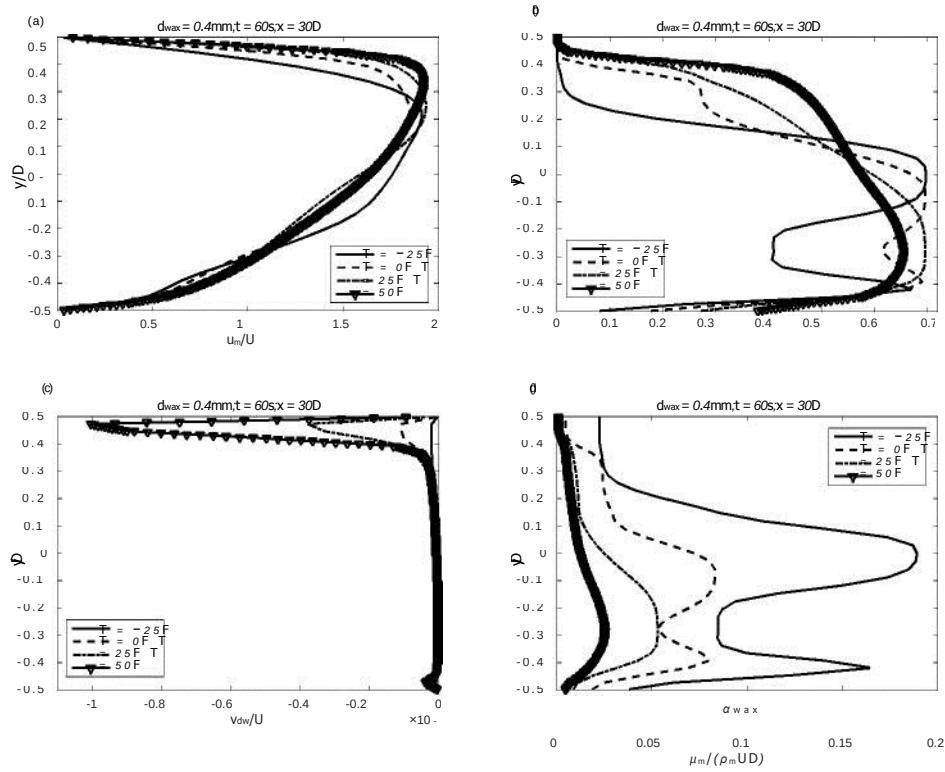


Figure 14: Profiles for $d_{wax} = 0.4\text{mm}$, 60 seconds after the beginning of the process and 30 diameters downstream the pig. (a) Normalized axial mixture velocity; (b) wax volume fraction; (c) Normalized vertical drift velocity; (d) Normalized Mixture Viscosity.

452 the profiles are smoother and the maximum velocity is lower. This is due to
 453 the fact that the wax distribution is more uniform and therefore the viscosity
 454 profile is smoother, as it can be seen comparing Fig.(8,d) with Fig.(14,d).
 455 The variable which is mostly influenced by the particle diameter is the drift
 456 velocity since is proportional to the settling velocity. Comparing Fig.(8,c)
 457 with Fig.(14,c) it can be seen that the two profiles have a similar shape,
 458 with the maximum in the oil region and decaying to zero for $a_{wax} = 0.7$.
 459 Furthermore, in agreement with Eq.(19), the drift velocity maximum is 25
 460 times smaller for $d_{wax} = 0.4\text{mm}$ as compared to $d_{wax} = 2\text{mm}$.

461 5. Discussion

462 The results of the present 3D numerical investigation reveal some im-
463 portant details about the debris flow, which could not be derived from 1D
464 analysis. Comparing Fig.(3) with Fig.(4), and Fig.(9) with Fig.(10), it can
465 be seen that the 1D information is more representative of the 3D debris field
466 at high temperatures, e.g. $T = 50^\circ\text{F}$. At lower temperatures, the information
467 concerning the stratification are lost.

468 The results of Fig.(3) and Fig.(9) show that the temperature has a greater
469 influence on the debris field than the particle diameter. In agreement with
470 Eq.(19), the debris field is more dispersed for lower temperatures and particle
471 diameters. In this work the mixture flows in laminar regime, however, in
472 larger pipelines turbulence is an important factor (Patrachari & Johannes
473 (2012)). At higher Reynolds numbers, the competition between turbulence
474 and settling could keep the particle in suspension and it is unclear if small
475 enough debris remain suspended. Answering this question is beyond the
476 purpose of this work, however, the results in Figs.(7,13), show that, in the
477 pipe cross-section there is a whirling motion which favors particle deposition.
478 Moreover, the unsteady 3D results show a very similar debris distribution for
479 the different particle diameters.

480 Despite the fact that turbulence may occur for higher oil flow rates, the
481 high wax-in-oil slurry viscosity is likely to restore the laminar flow over time.
482 In presence of a stratified flow, pure oil flows in a narrow section at the
483 top of the pipe. From the results in Fig.(8,a) and Fig.(14,a) it is clear that
484 the oil flow is laminar. The oil speed can play an important role in the
485 determination of the height of the wax-in-oil slurry, which has a “dune”
486 shape. Comparing Fig.(4) and Fig.(10), it can be seen that the height of the
487 dune is proportional to the temperatures. Since for higher temperatures the
488 oil viscosity decreases, Fig.(2,b), while the oil velocity at the top of the pipe
489 increases, Fig.(8,a) and Fig.(14,a), it seems that the height of the dune is
490 adjusted in order to have roughly the same friction for every temperature.
491 This hypothesis needs further investigation.

492 Another important information lost in the 1D analysis is the vertical
493 distribution of the different variables. What can be seen from Fig.(8,a) and
494 Fig.(14,a) is that the axial velocity profile is not flat but has a rather parabolic
495 shape, because of the low Reynolds number. If the debris field is stratified,
496 the maximum velocity is found at the top of the pipe, where the lighter fluid
497 is. If the debris field is dispersed, the velocity profile is more symmetric.

498 This is due to the fact that the shape of the velocity profile is determined by
499 the mixture viscosity, which depends on the wax volume fraction.

500 The non-uniform axial velocity field is the reason for the increase in time
501 of the wax-in-oil slurry. If the velocity profile was flat, the wax chips could
502 travel only as fast as the pig and accumulate in front of its body. However,
503 because every viscous fluid respects the no-slip condition at the wall, the
504 velocity at the center of the pipe must be higher than the mean velocity. In
505 the case of a single-phase laminar motion, the maximum velocity is twice the
506 mean one. The wax chips at the center of the pipe travel farther than the
507 pig until they settle at a certain distance. Since the velocity at the boundary
508 layer approaches zero, the fallen chips are slower than the pig, and after
509 a certain period they will be re-scraped and re-injected into the pipe. The
510 viscosity of the wax-in-oil slurry, shown in Fig.(8,a) and Fig.(14,a), influences
511 the particle deposition. A high viscosity increases the friction, slowing down
512 the chips, but reduces the settling, delaying the deposition.

513 As far as the pressure drop is concerned, the results in Fig.(6) and
514 Fig.(12), show that it is mostly influenced by the temperature rather than
515 the particle diameter. The purpose of Fig.(6) and Fig.(12) is to quantify
516 the pressure drop increase due to the debris field. Despite the pressure drop
517 being higher at lower temperatures, the debris field has a greater influence
518 for higher temperatures. The pressure drop increases with time because of
519 the increased suspended debris. This behavior must be carefully monitored
520 to estimate the risk of a wax plug. As time goes by, the pump may not be
521 able to deliver enough pressure, and the pig may slow down and stop. In the
522 present model this scenario cannot take place because of the fixed flow rate
523 boundary condition. This constraint allows the pressure to increase at will
524 in order to satisfy the boundary condition.

525 Our results show that the temperature has a fundamental importance
526 in determining the flow of the wax-in-oil slurry. In this work, the motion
527 has been considered isothermal because a short and non-heated pipeline has
528 been investigated. It would be necessary to introduce the energy equation to
529 study heated or longer pipelines in the future.

530 Improved pig and slurry viscosity models are under investigation. Further
531 experimental data are required to include the influence of non-Newtonian
532 rheology and pour point. Nevertheless, the present formulation of debris-
533 dependent viscosity is sufficient to show the qualitative mechanisms involved
534 in debris transport and deposition. The effect of a bypass at the center of
535 the pig is also under investigation.

536 6. Conclusions

537 A 3D numerical investigation of the fluid dynamics of the wax-in-oil slurry,
538 subject to pigging operations, has been conducted in this work. The *drift*
539 *flux* model has been used to simulate the flow of the slurry. The pig was
540 modeled as a cylindrical body moving at constant speed in the pipe, due to
541 the constant oil flow rate at the inlet. An injection boundary condition for
542 the wax chips, equivalent to the scraping, but numerically more efficient, has
543 been introduced. The properties of the two fluids have been experimentally
544 derived. The influence of temperature and particle dimensions on the flow
545 has been investigated.

546 The 3D simulations provide details, such as the axial velocity profiles,
547 planar velocity vectors, and wax volume fraction field, which improve our
548 comprehension of the dynamics of the process. This information can be used
549 to improve the existing 1D models. Our group is currently investigating
550 improvements of the present model as well as the influence of a bypass at the
551 center of the pig.

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